Rapid Modeling of HIFU Beam Propagation through Inhomogeneous Tissues: Validation and Applications

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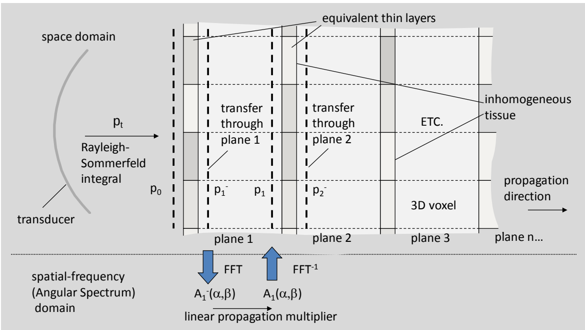
Outline

- Overview of Hybrid Angular Spectrum (HAS) method
- Validation:
  - Comparison of HAS to k-Wave simulations
  - With experimental MRI temperature imaging
- Applications:
  - Phase aberration correction in UofU Breast System
  - Characterization of scattering by the skull

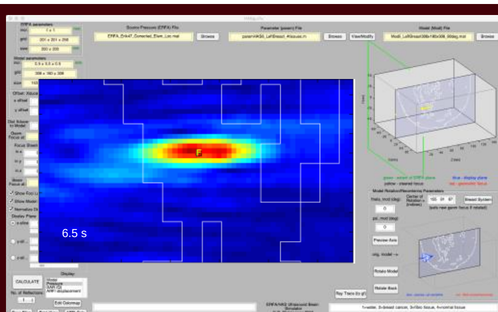
Overview of Hybrid Angular Spectrum Method*

- Extends traditional homogeneous angular spectrum method (in spatial-frequency domain) to include 3D heterogeneous media
- Leapfrogs between the space and spatial-frequency domains (next slide)
- Employs FFT commands, so very rapid
- Assumptions: steady state conditions, linearity and compressional waves only

*U. Vyas and D. A. Christensen, "Ultrasound beam simulations in inhomogeneous tissue geometries using the hybrid angular spectrum method," *IEEE Trans UFFC* 59 (6), 1093-1100, June 2012.



HAS gui - with typical pressure pattern

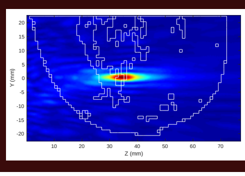


Validation

Validation 1 - Comparison of HAS to k-Wave Simulation

- k-Wave: a well-known open-source pseudospectral k-space method
- Both simulation methods modeled pressure from a phased-array transducer into a heterogeneous breast model
- HAS pattern was compared to steady-state result from k-Wave
- k-Wave: 8 hours, 32 min; HAS: 27 sec

k-Wave



309 x 181 x 308 MRI-segmented model

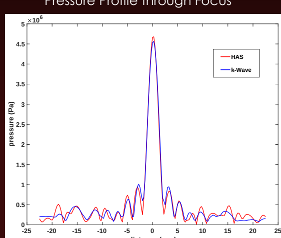
0.25-mm resolution 1.0 MHz

3 tissue types :

breast fat	1480 m/s	0.75 dB/cm
fibroglandular	1480 m/s	0.80 dB/cm
cancer	1560 m/s	1.15 dB/cm

Results – Comparison of HAS to k-Wave Simulation

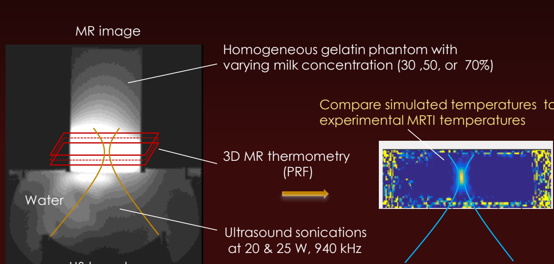
Pressure Profile through Focus



Normalized Root-Mean-Square Deviation (NRMSD)
= 2.96%

over 10 x 10 x 20-mm volume around focus

Validation 2 – With Experimental MRI Temperature Imaging



Two-fold Motivation

1. Compare simulations with experimental temperature profiles -
   - Acoustic simulations: Hybrid Angular Spectrum method (HAS)
   - Thermal simulations: Finite-Difference Time-Domain (FDTD) of Penne's Bioheat Equation (PBHE)
2. Use Monte Carlo statistical analysis to calculate expected uncertainties in the simulated temperature rise given uncertainties of input parameters -
   - Tissue-specific properties vary widely in literature

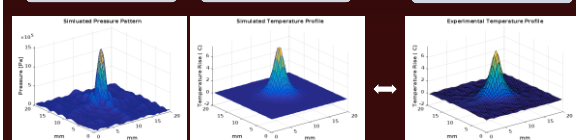
Flow Diagram

Experimentally measure acoustic and thermal properties of gelatin

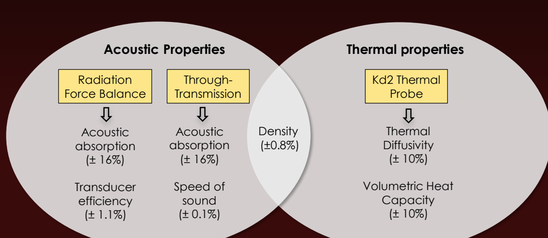
HAS: Simulate acoustic power profile → PBHE: Simulate temperature profile

compare

Experimental temperature profiles from MRTI

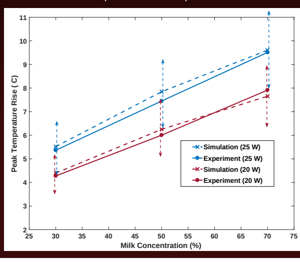


Measurements of Parameters and Their Uncertainties



Results – Peak Temperature

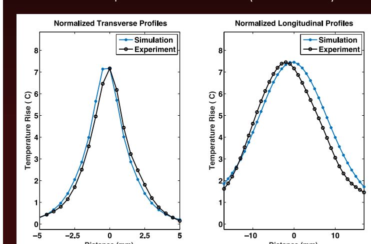
Temperature Rise (Spatial Peak Temporal Peak)
(ave of N = 3)



- Average Normalized Temperature Difference (N = 18)
  = 3.3%
- Error bars represent expected temperature range due to uncertainties in simulation input parameters (Monte Carlo)

Results – Spatial Profiles

one example: 50% milk at 25 W (ave of N = 3)

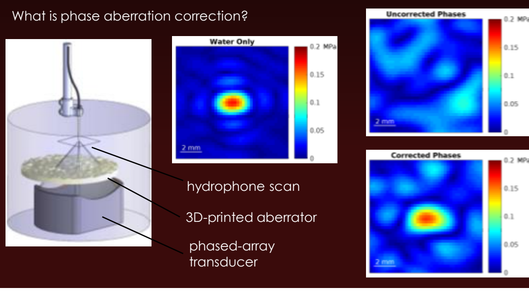


- Normalized Difference in FWHM (N = 18)
  Transverse = 4.7%
  Longitudinal = 12.1%
- Offset in location of peak (x,y,z)
  = (0,0,1.7 mm)

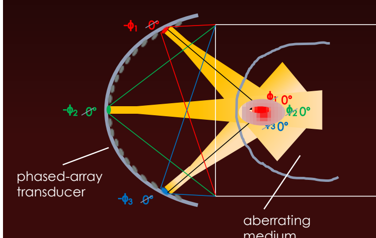
Applications

Application 1 – Phase Aberration Correction

What is phase aberration correction?



Concept : Correcting Phase Aberration with HAS Simulations



Propagate beam from each element with 0° phase

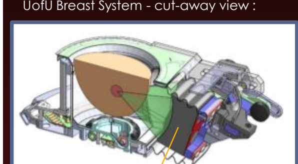
Find each phase at intended focus

Invert phase on respective elements

Achieve constructive interference at intended focus

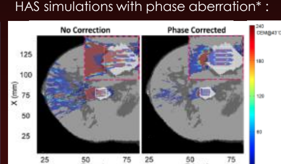
Phase Aberration Correction - in UofU Breast System

UofU Breast System - cut-away view :



laterally firing phased-array transducer

HAS simulations with phase aberration* :



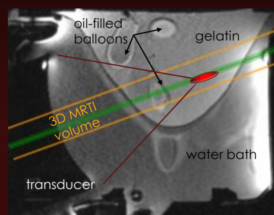
*A Farrer, et al. 2016 *Med Phys* 43(3): 1374-1384

Motivation: Experimentally demonstrate that HAS simulations can correct for phase aberrations in experimental breast-mimicking phantoms

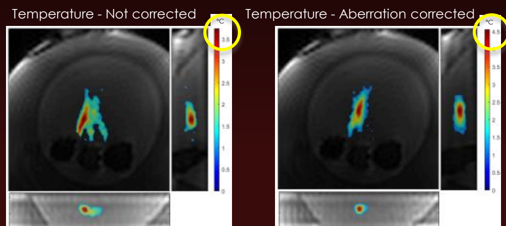
Experimental HAS-based Phase Aberration Correction

- Breast mimicking phantoms
  - 250-bloom gelatin with 50% milk
    c = 1555 m/s, α = 0.047 Np/cm MHz
    similar to fibroglandular tissue
  - canola oil (generates aberrations)
    c = 1469 m/s, α = 0.0125 Np/cm MHz
    similar to breast fat

- MRgFUS heating
  - 20 -30 s sonications,12 -24 acoustic watts
  - 3D MRTI in oblique plane
  - with and without phase aberration correction

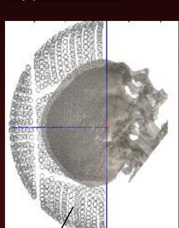


Results



➔ Average of 23% increase in temperature rise (13 unique sonication locations)

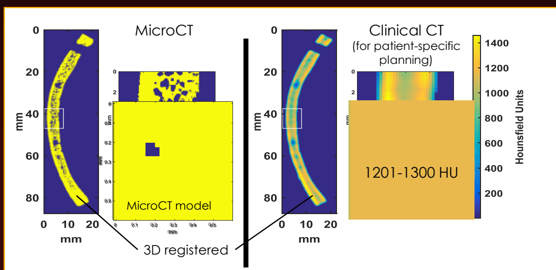
Application 2 – Characterization of Scattering by the Skull



1024-element phased-array transducer

- Attenuation = absorption (heating) + scattering
- Acoustic scattering in the skull is a significant portion of attenuation in transcranial HIFU treatments
- Attenuation varies from patient to patient, and current clinical images (from CT Hounsfield Units) do not separate out the scattering portion of attenuation
- Modeling scattering requires finer resolution than clinical CT, thus MicroCT

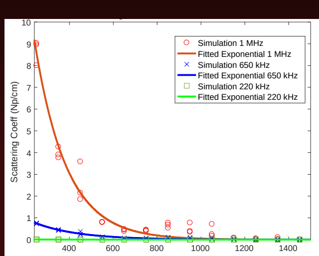
Models – Developed from Human Skull Flap



Simulating Scattering from MicroCT Models with COMSOL

- FEM iterative solver with automatic meshing
- 1 MHz, 650 kHz, 220 kHz plane wave input
- No absorption or mode conversion included (scattering only)
- Acoustic properties:
  - Bone – 2900 m/s, 1900 kg/m^3
  - Porous areas – 1500 m/s, 1000 kg/m^3
- Simulated 3 x 13 MicroCT models, 3 each of 13 100-HU ranges

Results – Scattering Coefficient vs. Hounsfield Units



- Scattering increases at low HU (more small pores)
- Scattering increases at higher frequencies
- Next: Experimental validation with several small skull pieces covering various HU ranges

Conclusions

Validation:

- Comparison of HAS to k-Wave breast model pressure patterns was within 3%
- Comparison of simulated to experimental temperatures was within 3.3% for peak temperature, and within 12.1% for spatial FWHM

Applications:

- Phase aberration correction is beneficial for many sonication locations in the UofU Breast System
- Map being developed of scattering coefficient to clinical CT Hounsfield Units

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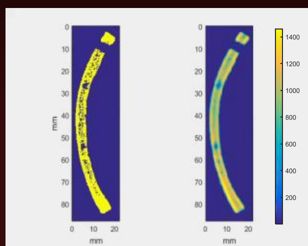
Thank you -

Any questions?

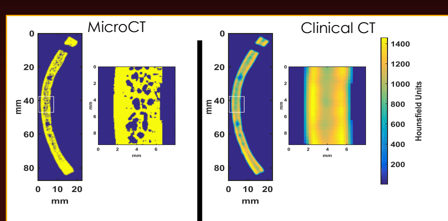
MicroCT Models - Registered to Clinical CT Voxels



~ 600 HU
~ 900 HU
~ 1300 HU

Form three samples of 3D MicroCT models over 13 HU ranges

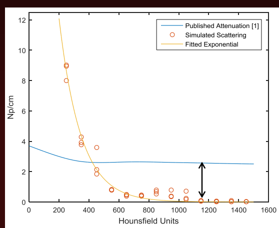
Models - Developed from a Human Skull Flap



Motivation

- Acoustic scattering in the skull is a significant portion of attenuation in transcranial treatments
- Attenuation = absorption + scattering
- Attenuation varies from patient to patient, and current clinical images (from CT Hounsfield Units) do not separate out the scattering portion of attenuation.
- Modeling scattering requires finer resolution MicroCT

Results – Scattering Coefficient vs. HU



- Scattering increases at low HU
- absorption = attenuation – scattering
- At low HU, need to differentiate between clusters of small scatterers and partial volume effect

[1] S. Pichardo, V. W. Sin, and K. Hynynen, *Phys Med Biol* 56/1, Jan 2011.