Modeling of MR-guided HIFU for Breast and Brain Therapy

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Overview

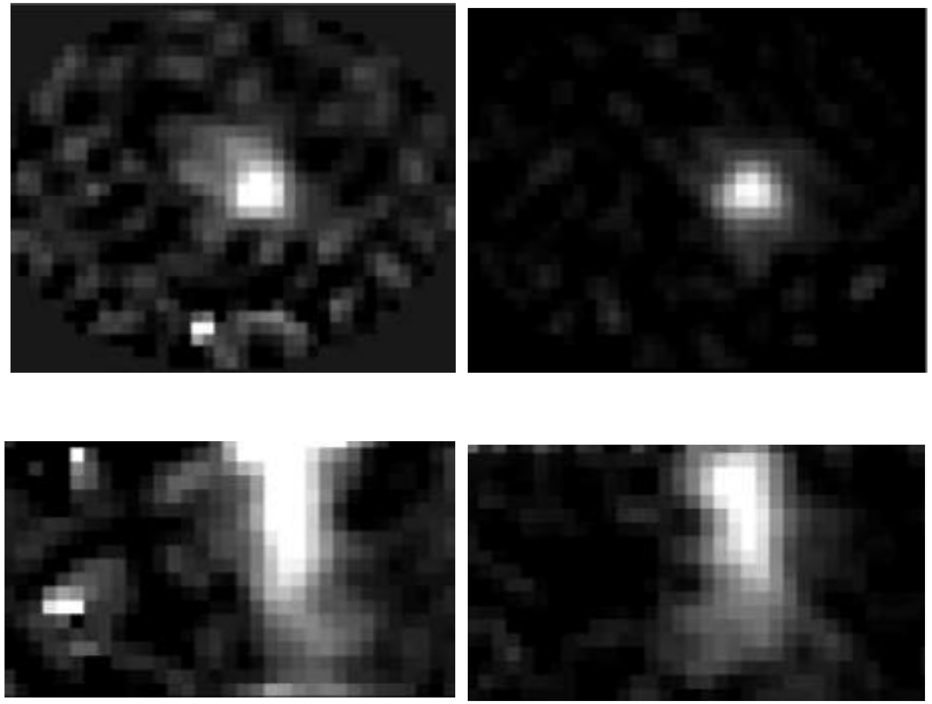
- High-Intensity Focused Ultrasound (HIFU) Surgery
  - Critical needs: locating the beam; full 3D temperature images; accurate beam modeling
- Beam Modeling with Hybrid Angular Spectrum (HAS) Method
- Application to Brain and Breast
  - Phase aberration correction
  - Incorporating absorption and scattering

Critical Need 1: Locating Beam

Use Acoustic Radiation Force Imaging (ARFI) with MRI

at geometric focus in phantom:

ARFI temperature

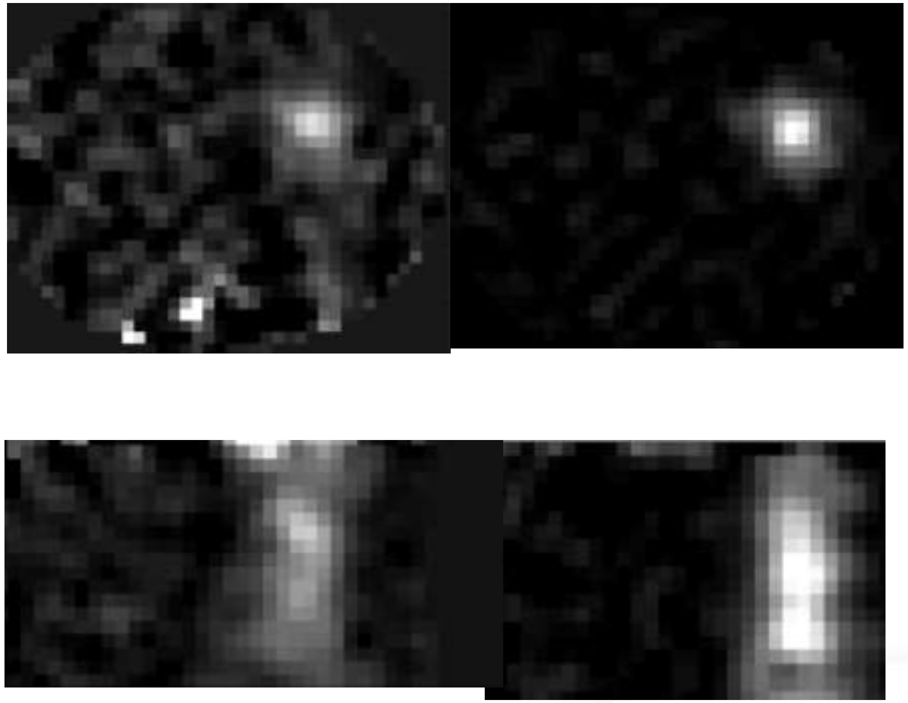


coronal

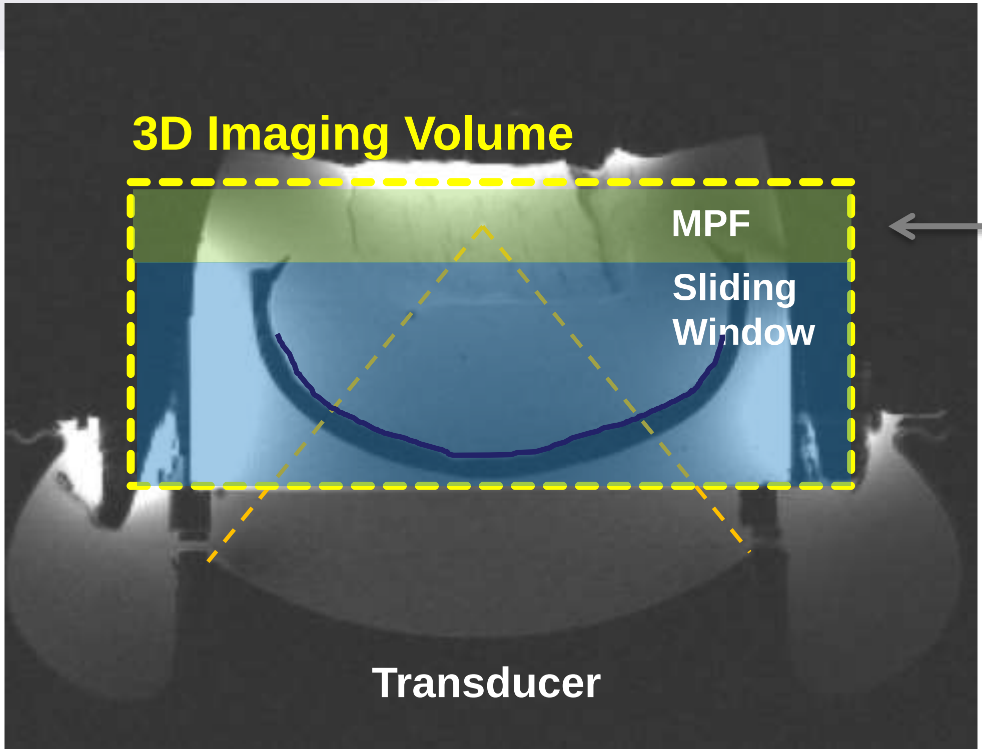
sagittal

steered 5,5,5 mm in phantom:

ARFI temperature



Critical Need 2: Measure Temperature throughout Full 3D Volume



Use Model Predictive Filtering with an acoustic and thermal model

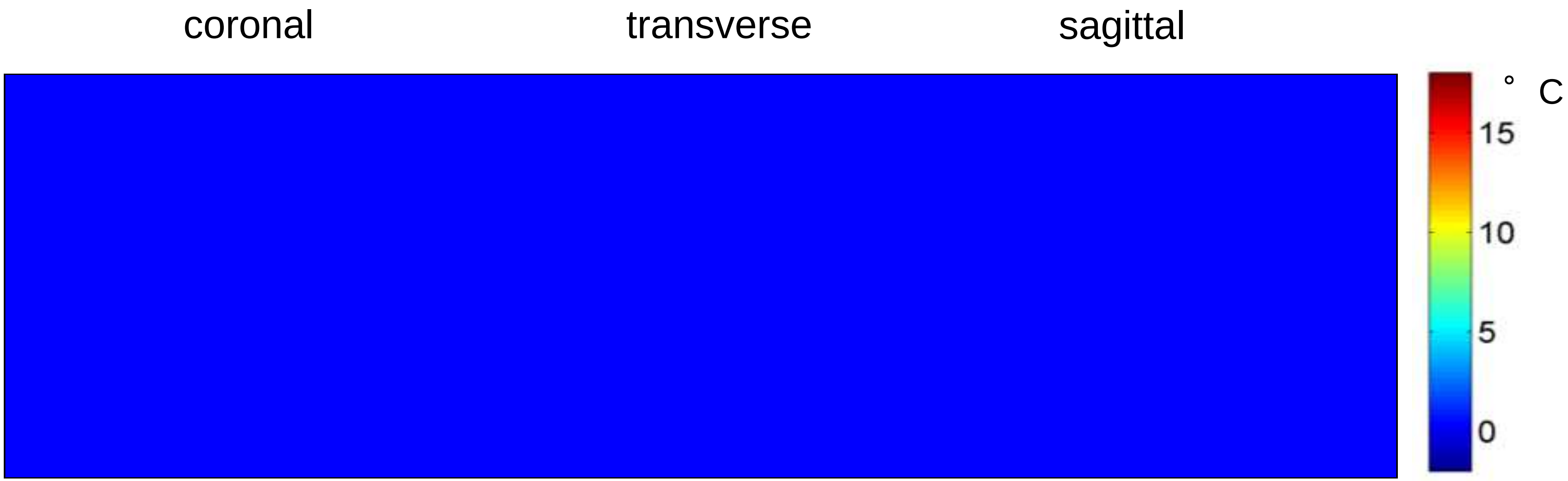
Ultrasound Parameters:

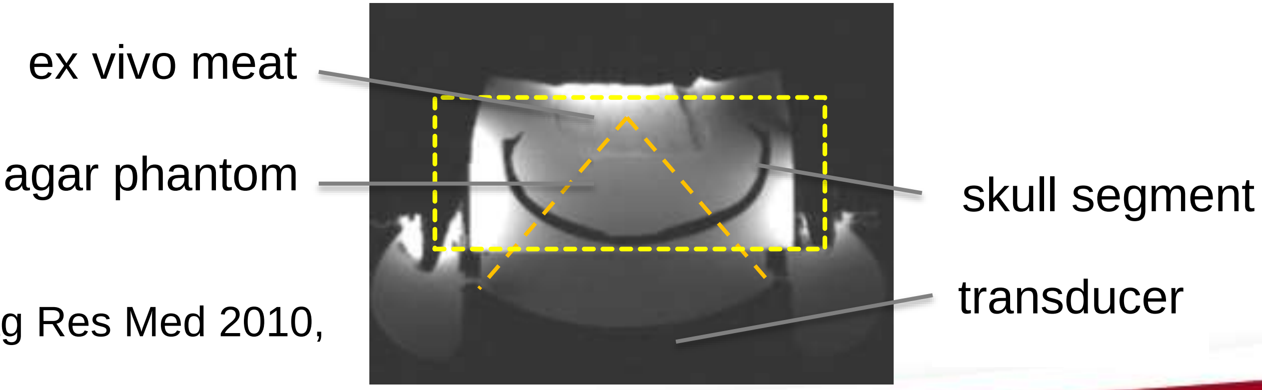
- 256-element transducer
- 30-s single point sonication
- 48 W

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

Experimental Results: 3D Temperature Measurements



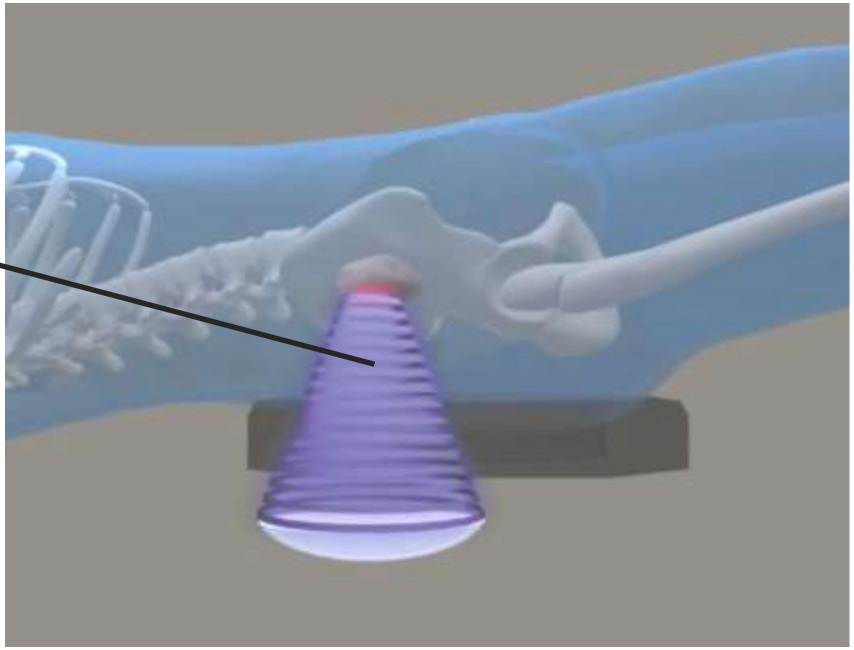


Nick Todd et al., Mag Res Med 2010,
63(5),1269-1279

Critical Need 3: Accurate Ultrasound Beam Simulations

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

Bone metastases:

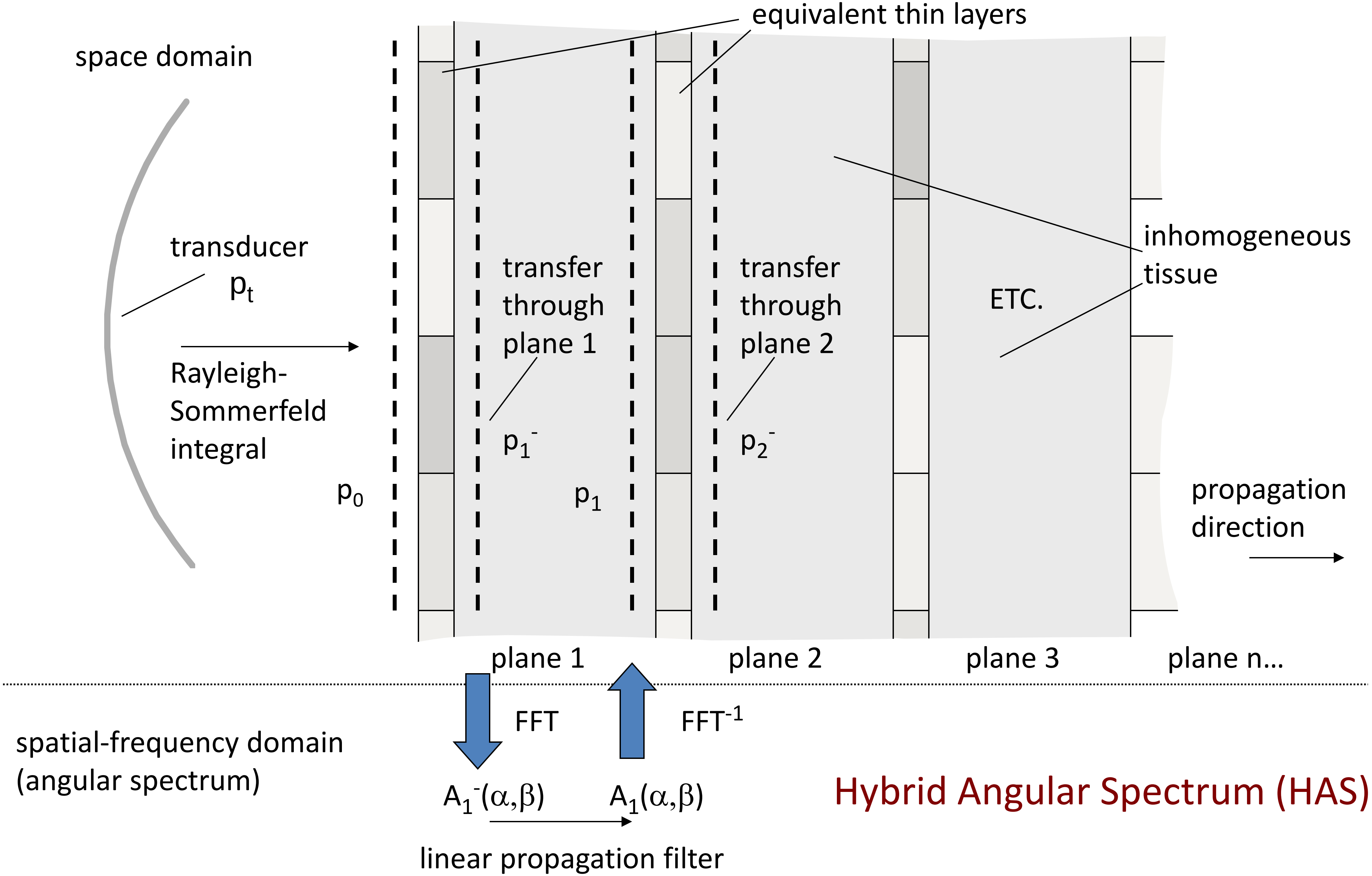


InSightec Ltd, Israel

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

Hybrid Angular Spectrum (HAS)



space domain

equivalent thin layers

transducer

p_t

Rayleigh-Sommerfeld integral

p_0

transfer through plane 1

p_1^-

p_1

transfer through plane 2

p_2^-

ETC.

inhomogeneous tissue

propagation direction

plane 1

plane 2

plane 3

plane n…

FFT

FFT^{-1}

spatial-frequency domain (angular spectrum)

$A_1^-(\alpha,\beta)$

$A_1(\alpha,\beta)$

linear propagation filter

HAS Method

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

- Two orders of magnitude faster:

  FDTD – 67 min HAS – 9.5 sec

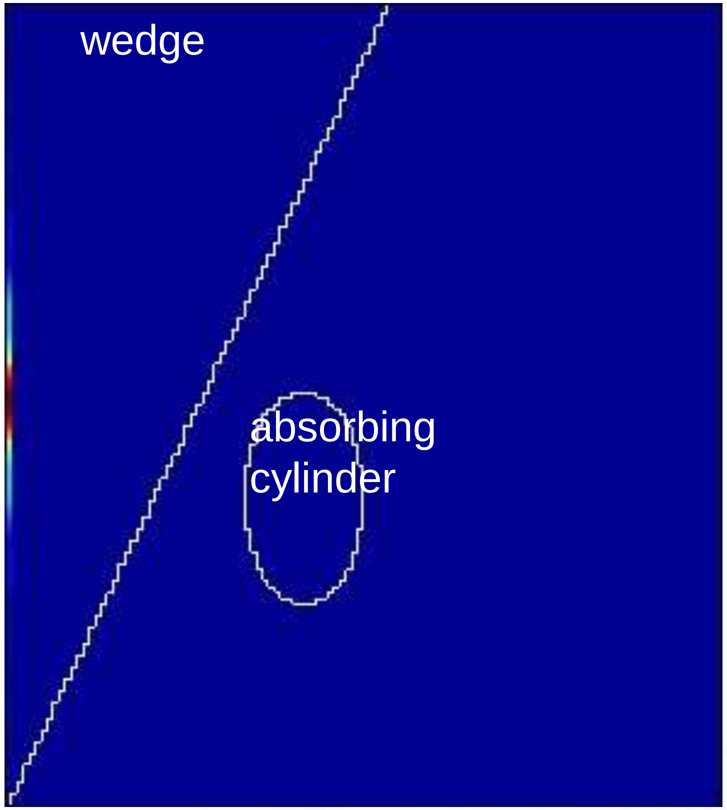
- Example simulation:

  transducer: 1.5 MHz

  3D model: 141 x 141 x 161

beam direction →

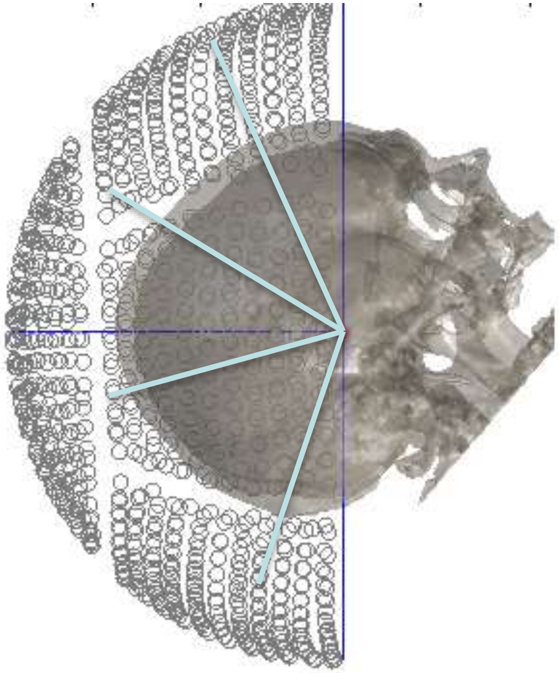
3D pressure pattern:



*Vyas, U. and Christensen, D.,
IEEE Trans UFFC, **59** (6), 1093-1100 (2012)

Application of Beam Modeling to Transcranial Treatments

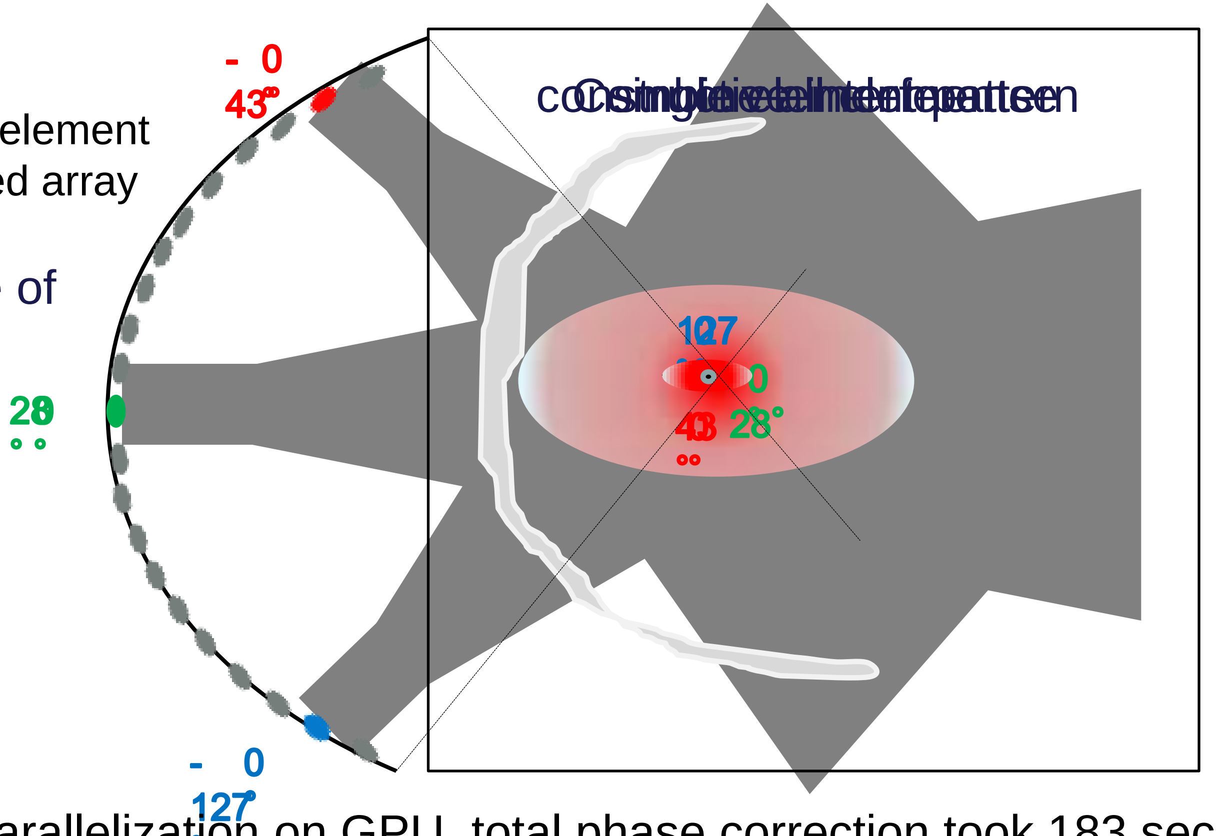
InSightec 650-kHz ExAblateNeuro



Variable skull thickness in beam path leads to phase aberration

Phase Aberration Correction through Skull

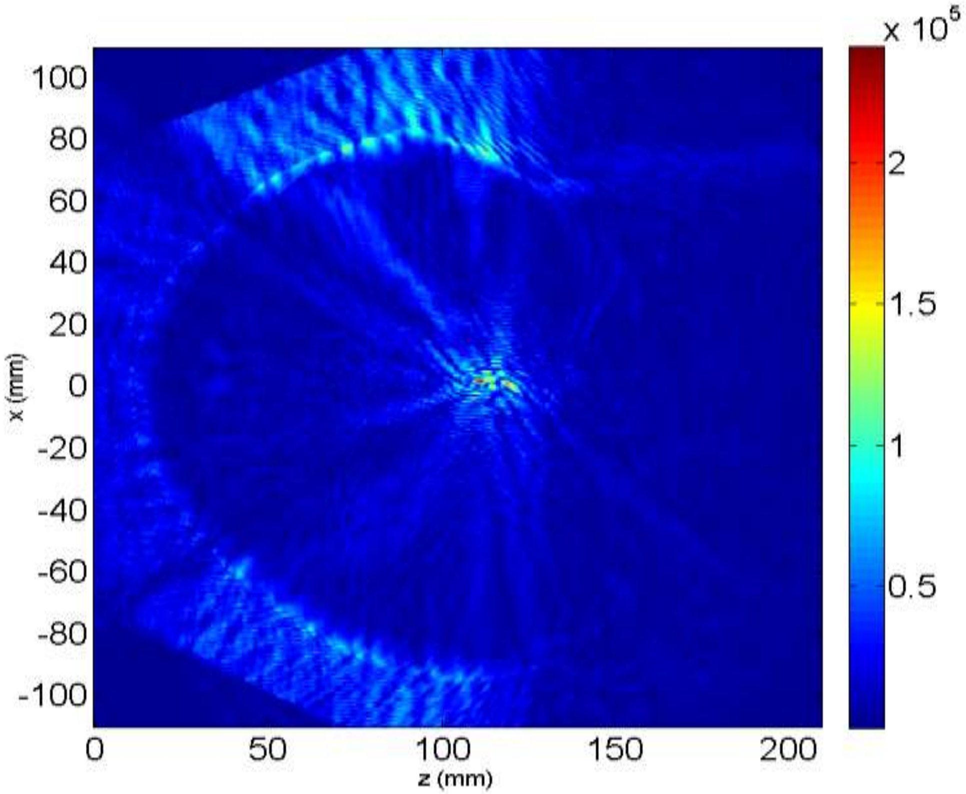
512 x 348 x 488 model
0.6 x 0.43 x 0.43-mm resolution



With parallelization on GPU, total phase correction took 183 seconds

Pressure Patterns through Skull

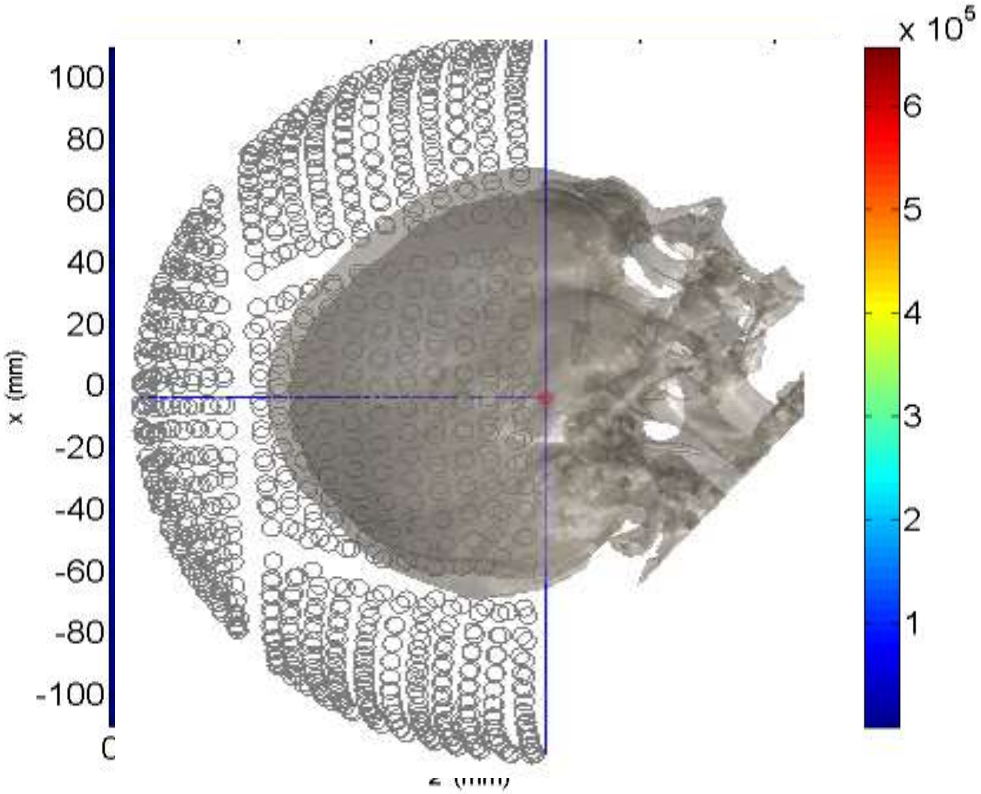
no phase correction



Max pressure at focus- 2.4x10^5 Pa

normalized to 8 W total

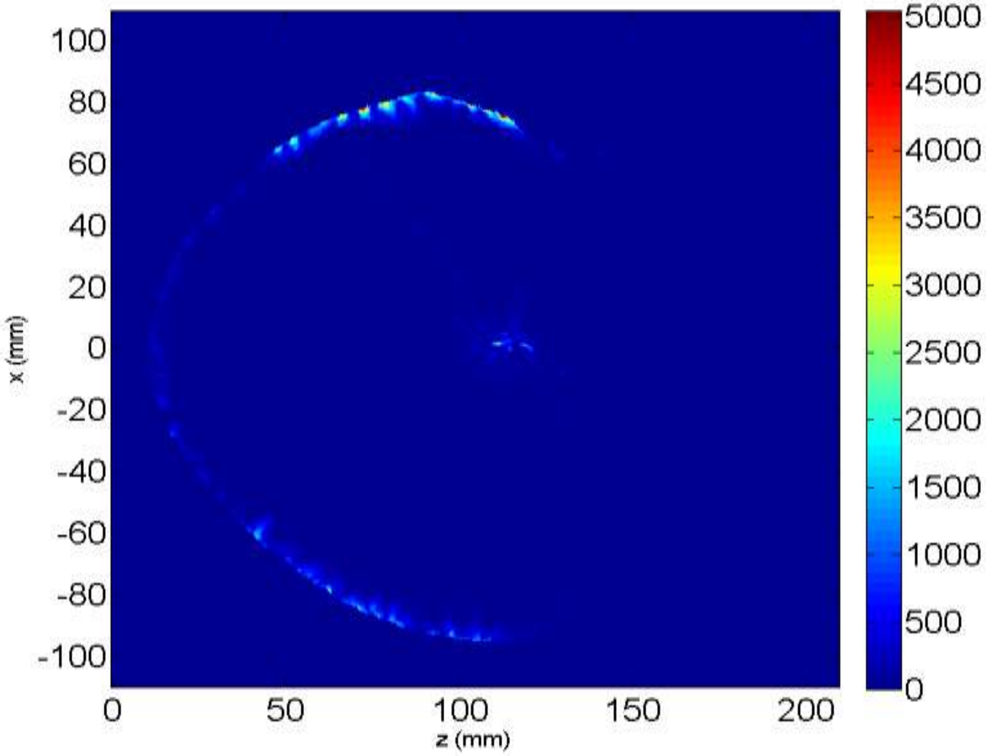
phase correction



Max pressure at focus- 6.6x10^5 Pa

Power Deposition Q Patterns through Skull

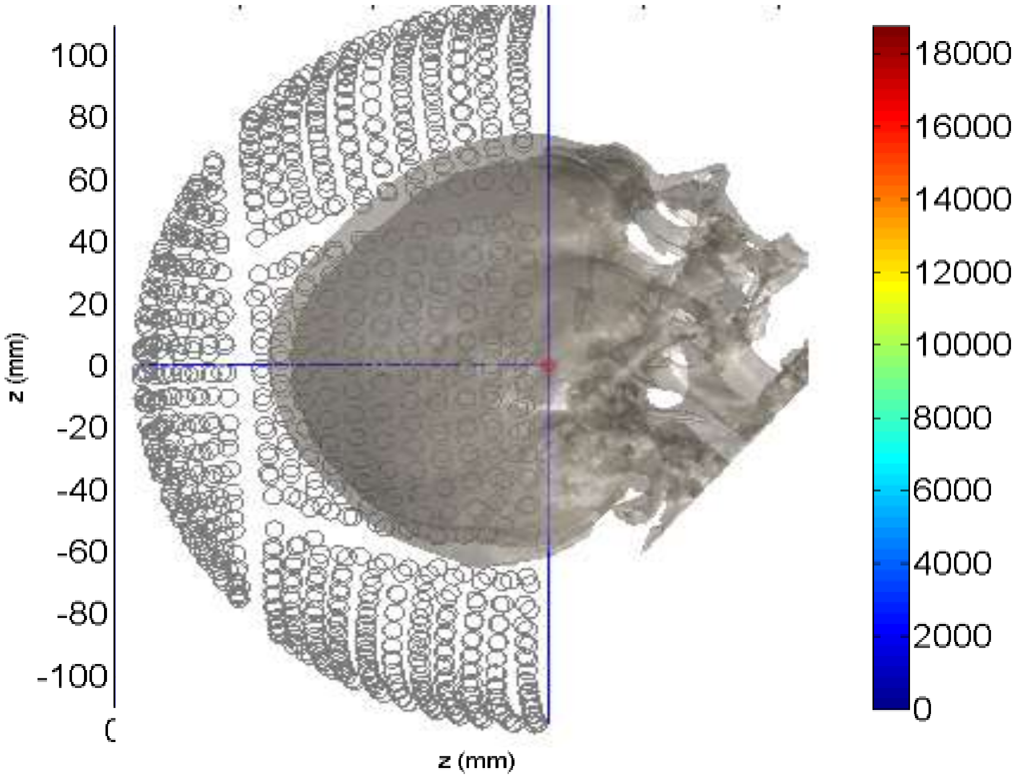
no phase correction



Max Q at focus- 2500 W/m^3

Ratio Q_{focus}/Q_{skull}- 0.51

phase correction

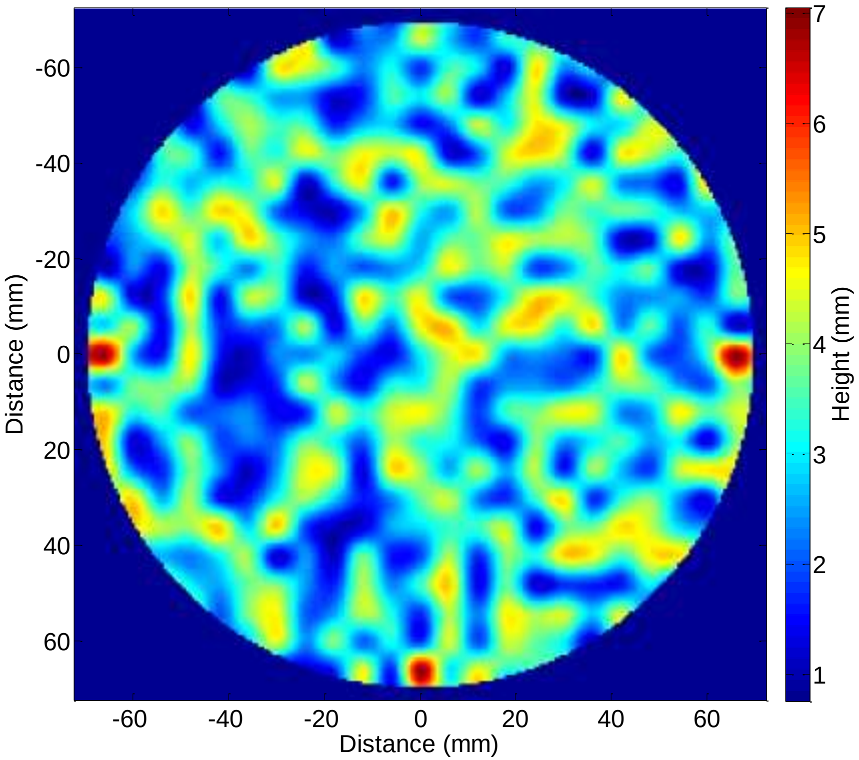


Max Q at focus- 18,000 W/m^3

Ratio Q_{focus}/Q_{skull}- 2.4

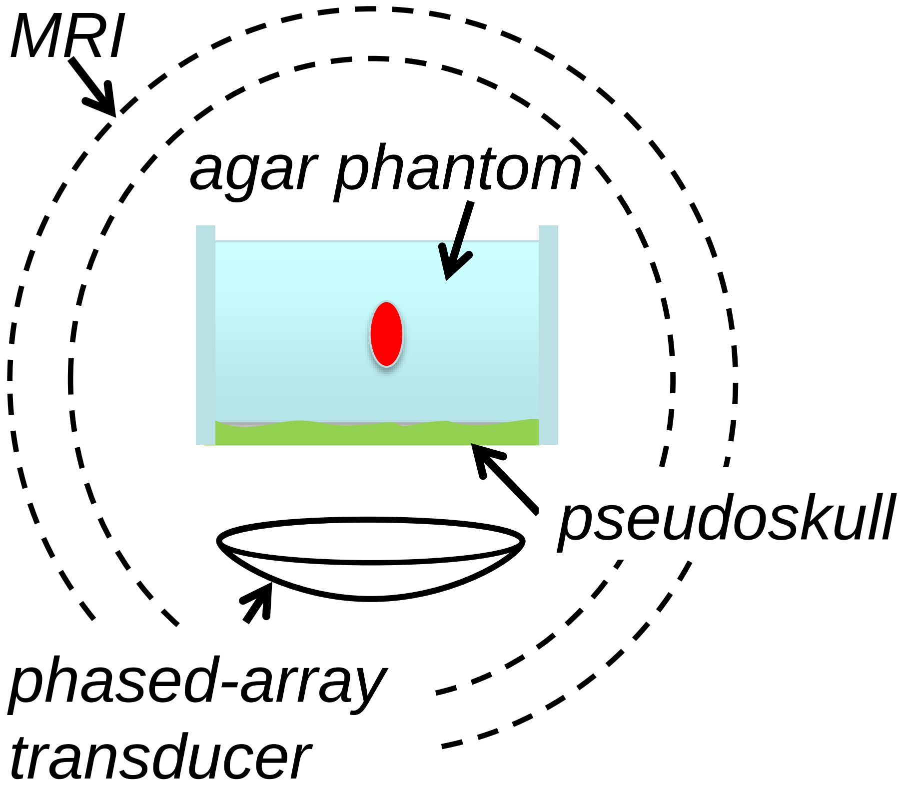
Experimental Results for Phase Correction

- Experimental setup:
    - 3D-printed plastic skull model
    - Random variations in thickness
    - Phase shifts up to 2π



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

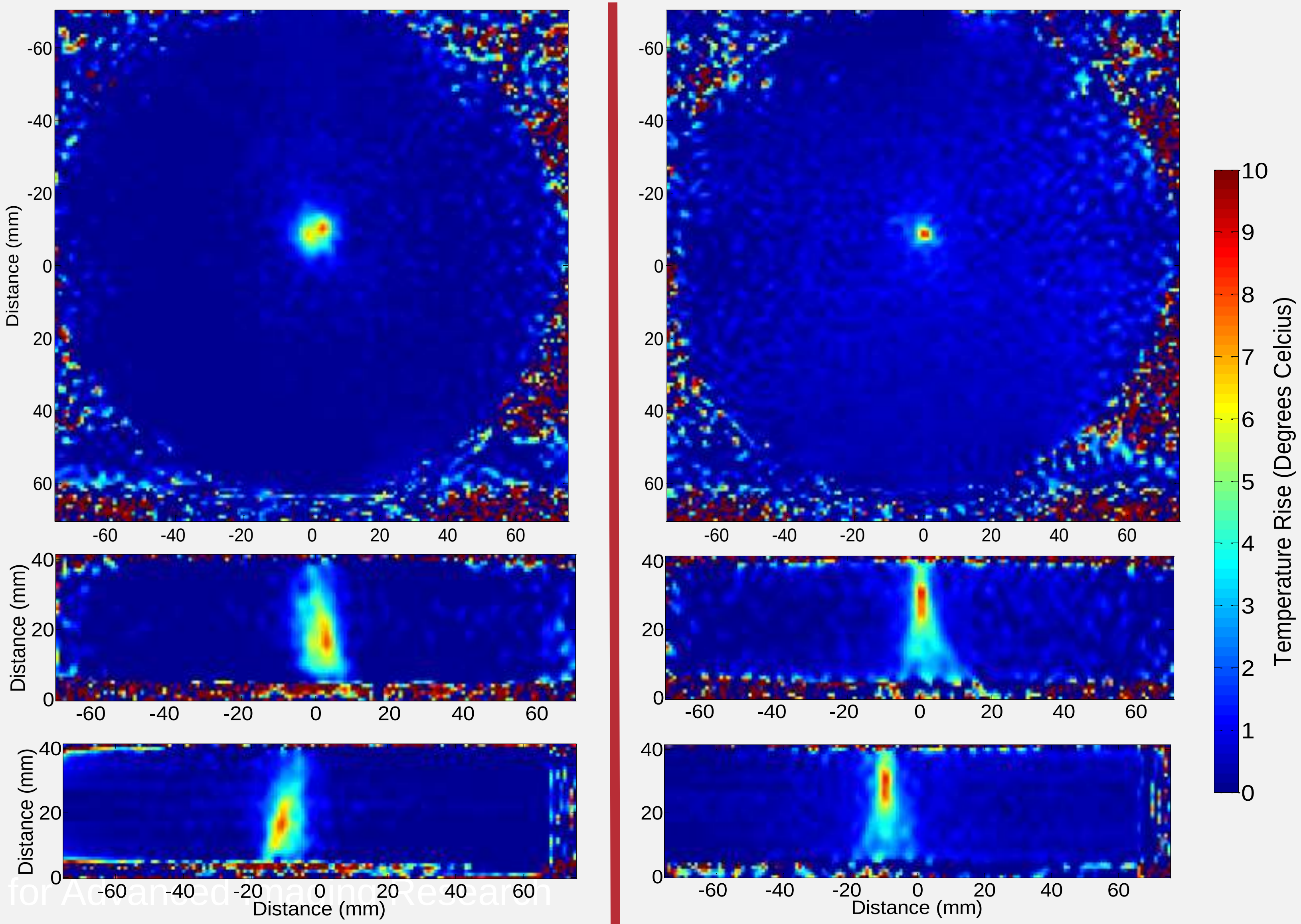
no phase correction

phase correction

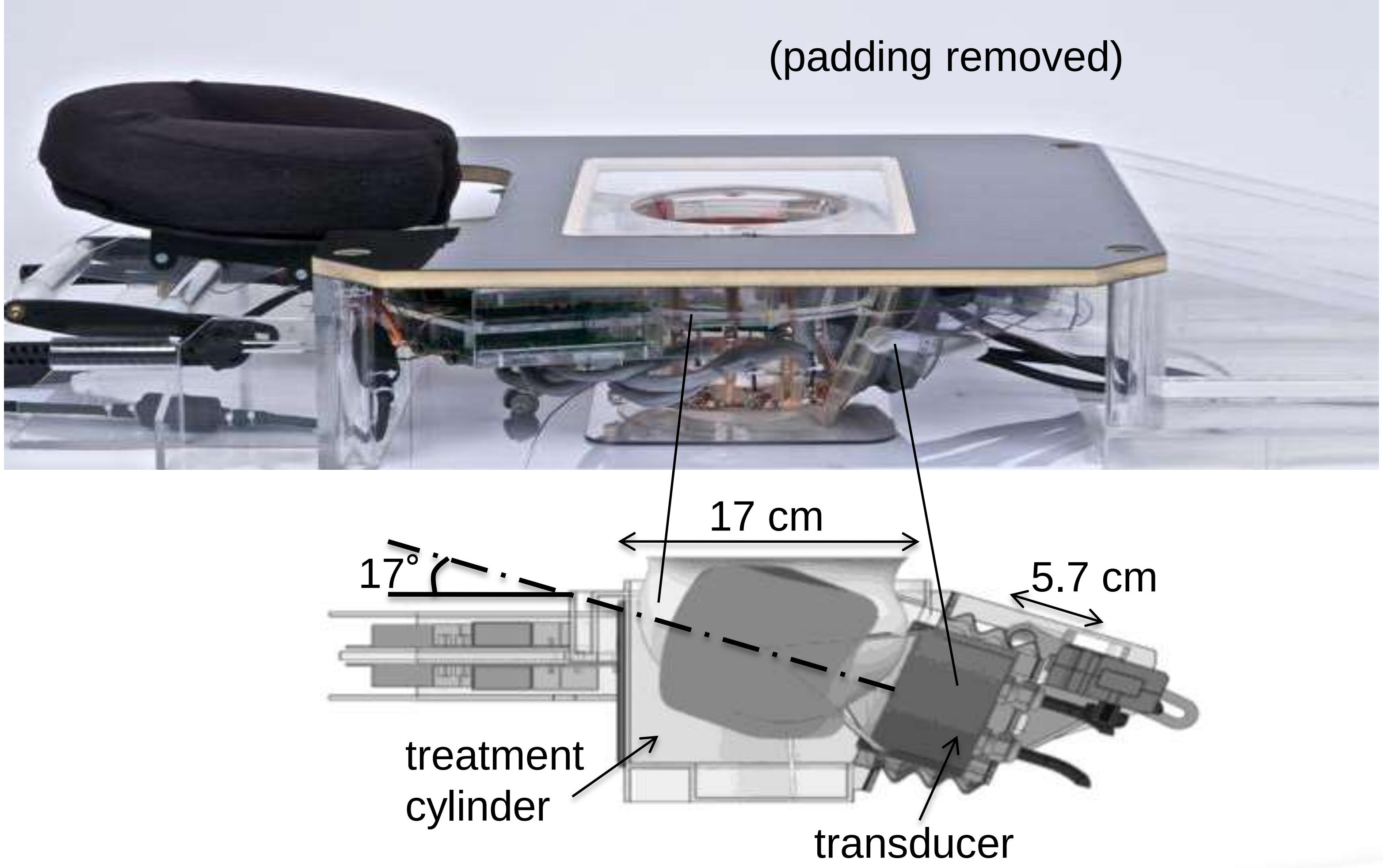
coronal

transverse

sagittal

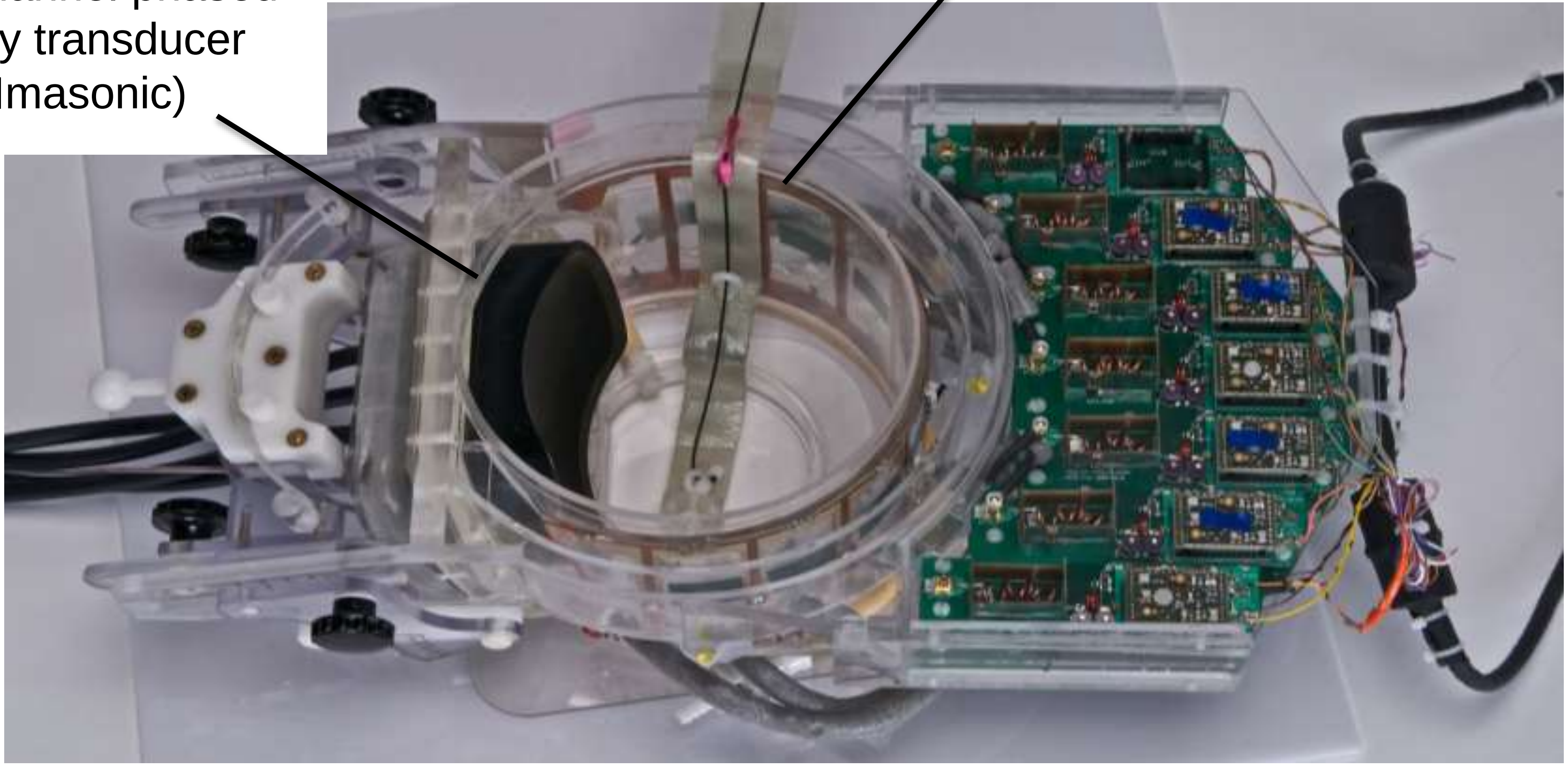


Application to Univ. of Utah Breast HIFU System



Allison Payne, et al., Med Phys 2012; 39(3):1552-1560

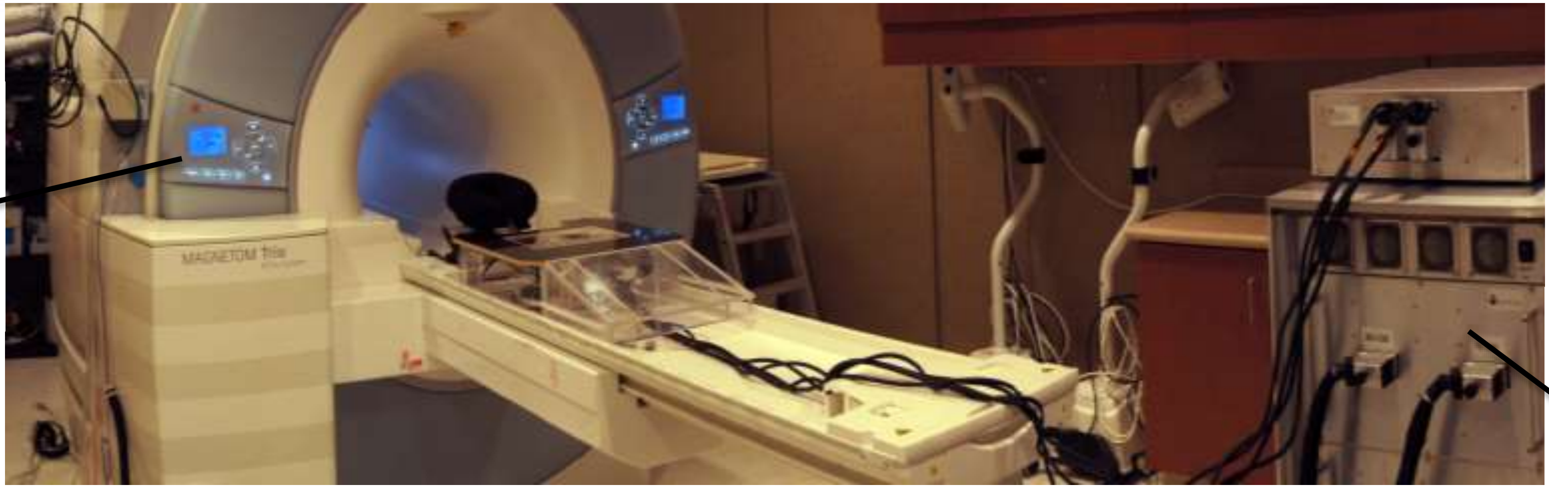
Univ. of Utah Breast-Specific Treatment Cylinder


256-channel phased-array transducer (Imasonic)

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

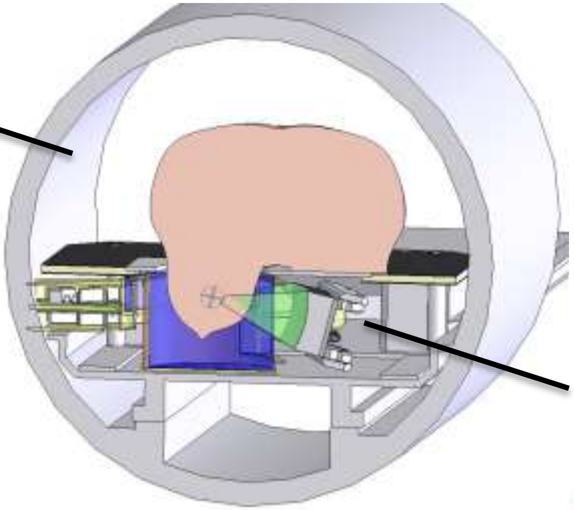
* Emilee Minalga, et al., Magn Reson Med 2013 Jan;69(1):295-302

Univ. of Utah Breast-Specific HIFU System



Siemens Trio 3T MRI

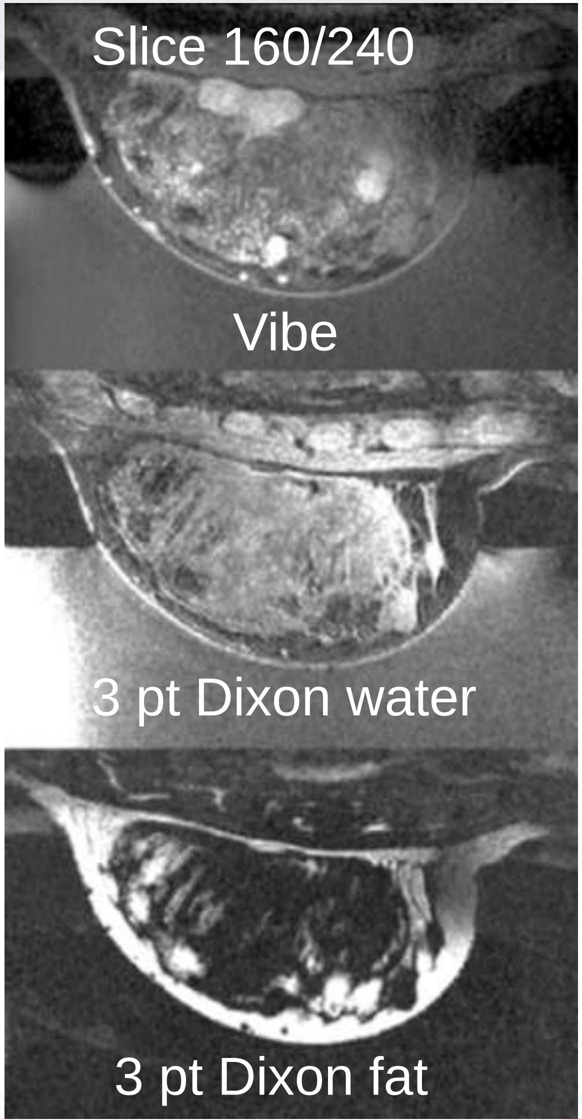
ultrasound power drivers

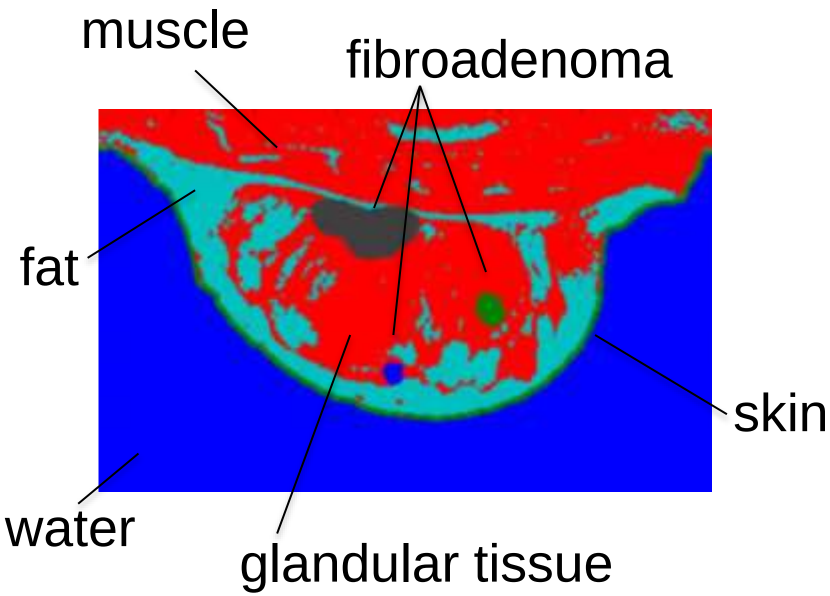


MRI bore

phased-array transducer

Phase Aberration Correction in Breast



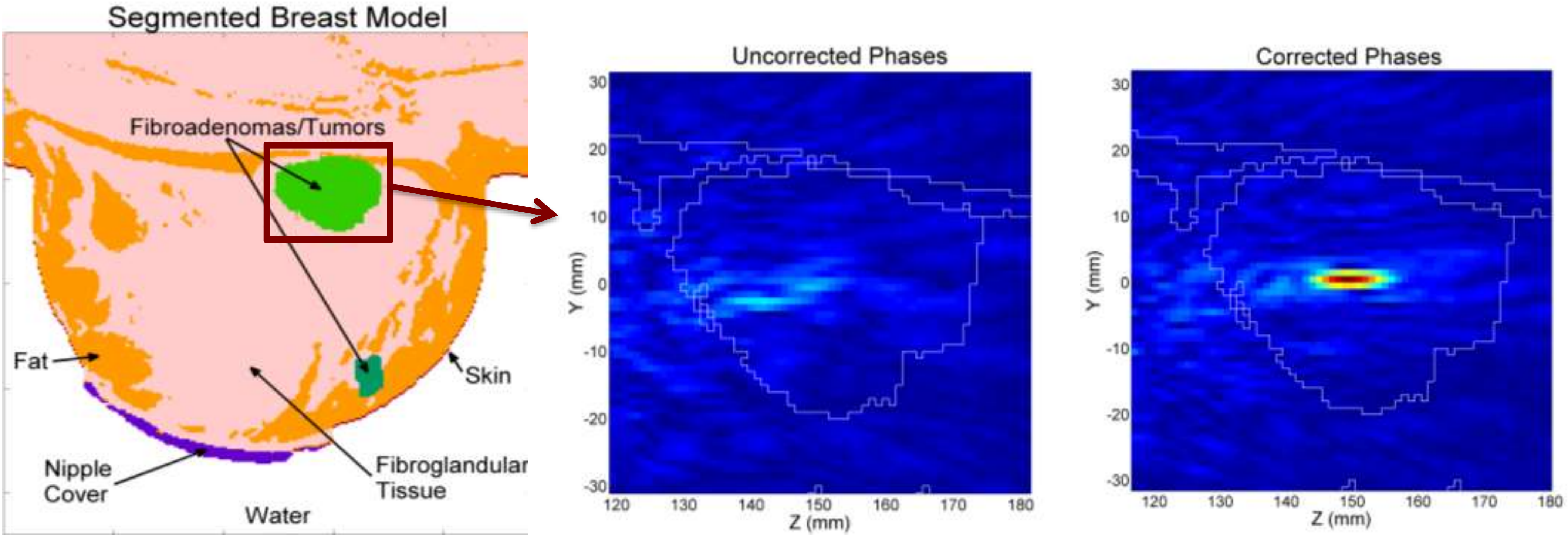


- Develop full 3D tissue model
  - Segment tissues with multiple contrasts
  - Estimate acoustic properties for each tissue type
  - Model beam propagation using HAS
  - Adjust transducer element phases

Alexis Farrer, ISTU 2013, poster 28

Example of Phase Correction in Breast

Pressure patterns



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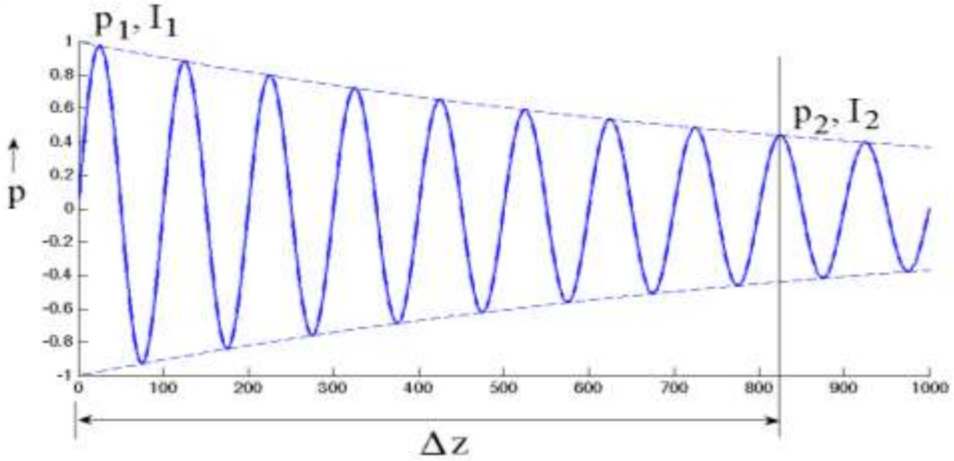
Adding Scattering to HAS Algorithms

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

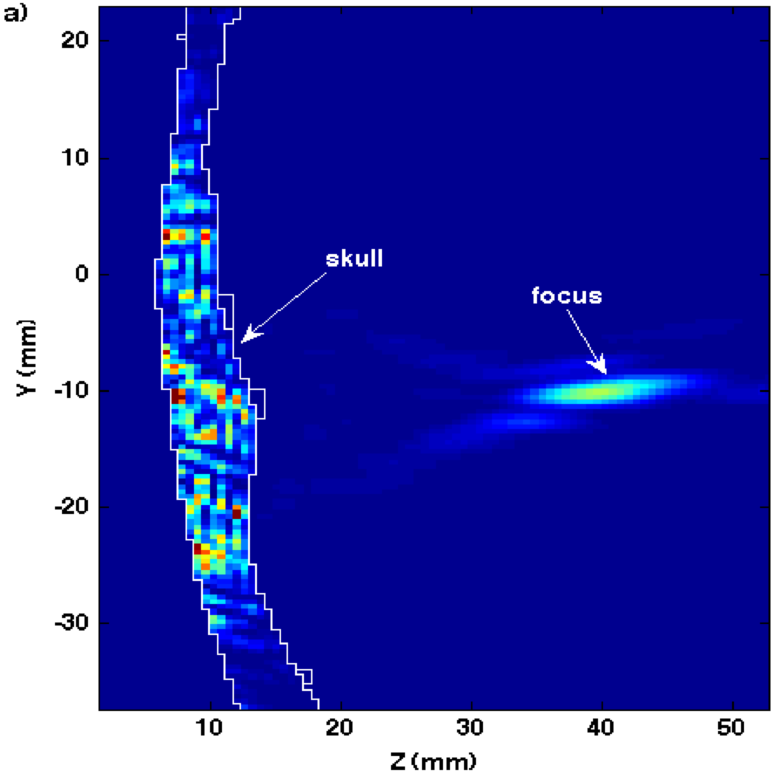
$$p_2 = p_1 e^{-a_{total} Dz}$$

Improved : attenuation = absorption + scattering

$$p_2 = p_1 e^{-a_{total} Dz} = p_1 e^{-\left(\underset{\text{heat}}{a_{abs}} + \underset{\text{scattered power}}{a_{scatt}}\right) Dz}$$

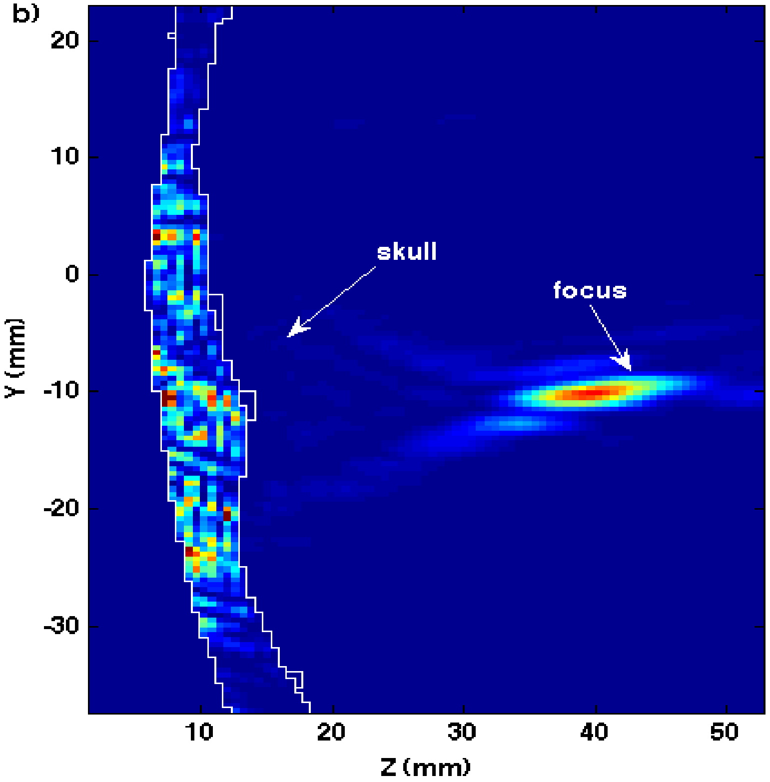
A. Implicit: Transcranial Power Deposition Patterns

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



peak power brain/peak power skull = 0.29

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

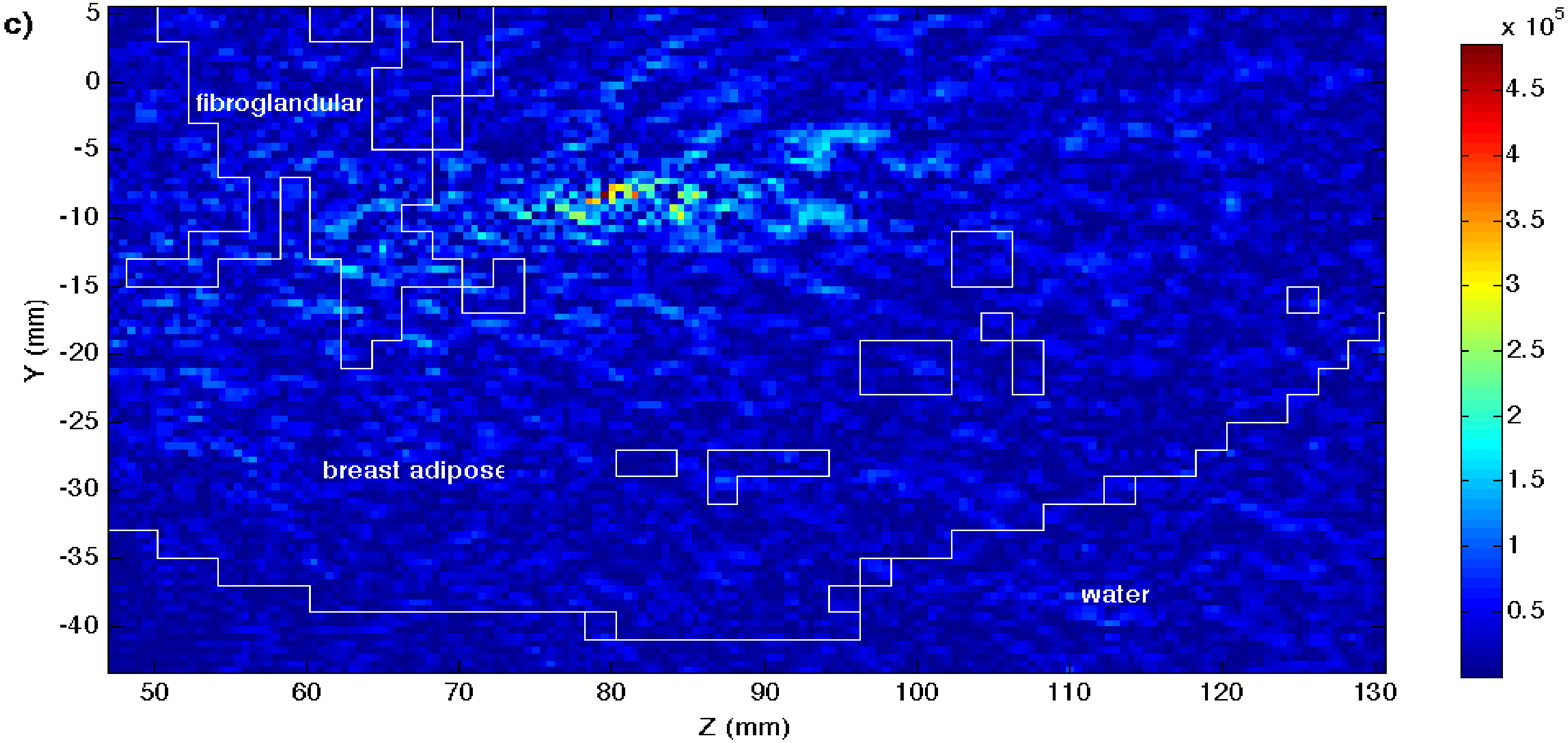


peak power brain/peak power skull = 0.47

*Pinton, G. et al., Med Phys **39**, 299 (2012)

B. Explicit: Small Scatterers within Each Voxel

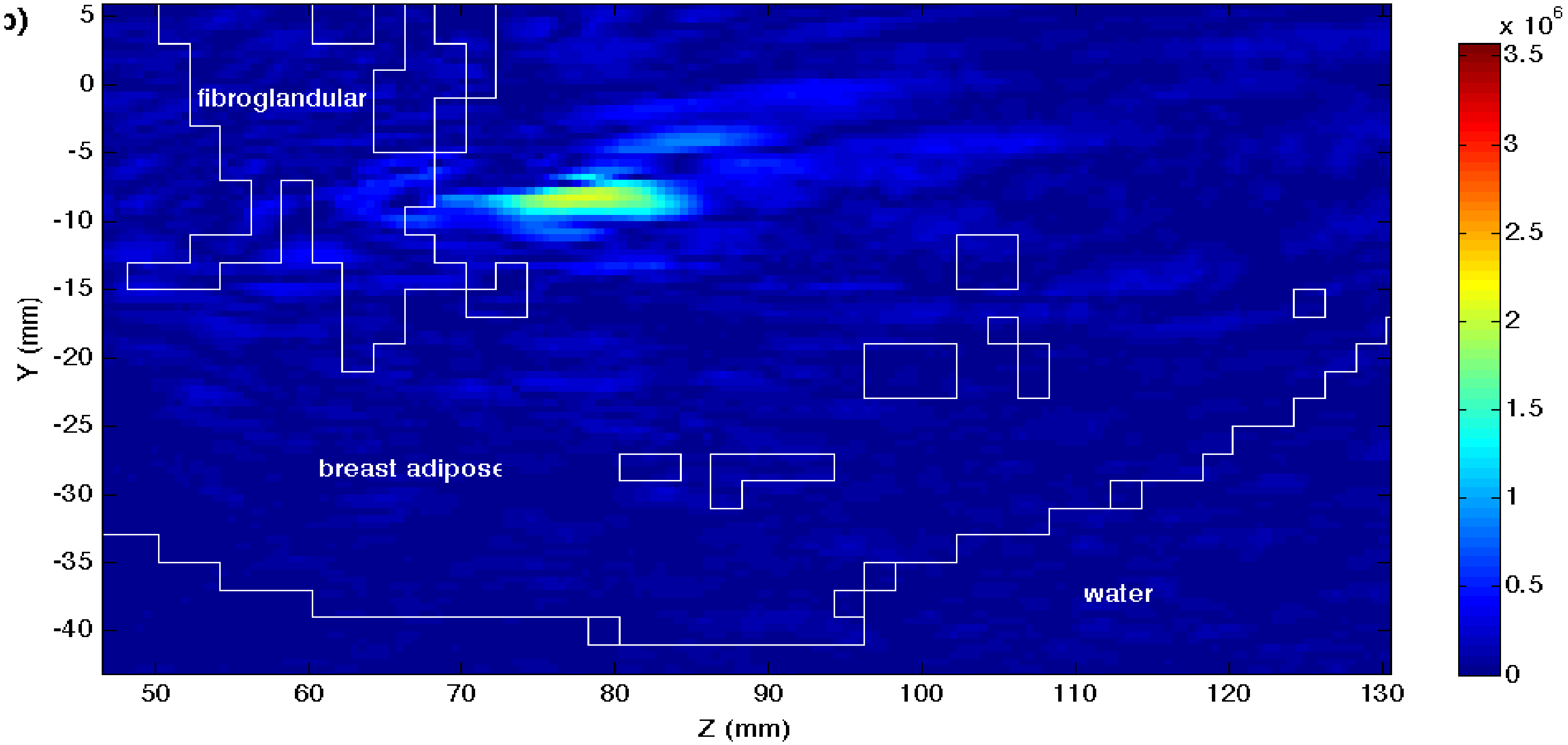
Scattered beam pressure pattern alone in breast
(volume with scattering – volume without scattering)



$\alpha_{\text{scatter}} = 40\% \ \alpha_{\text{total}}$

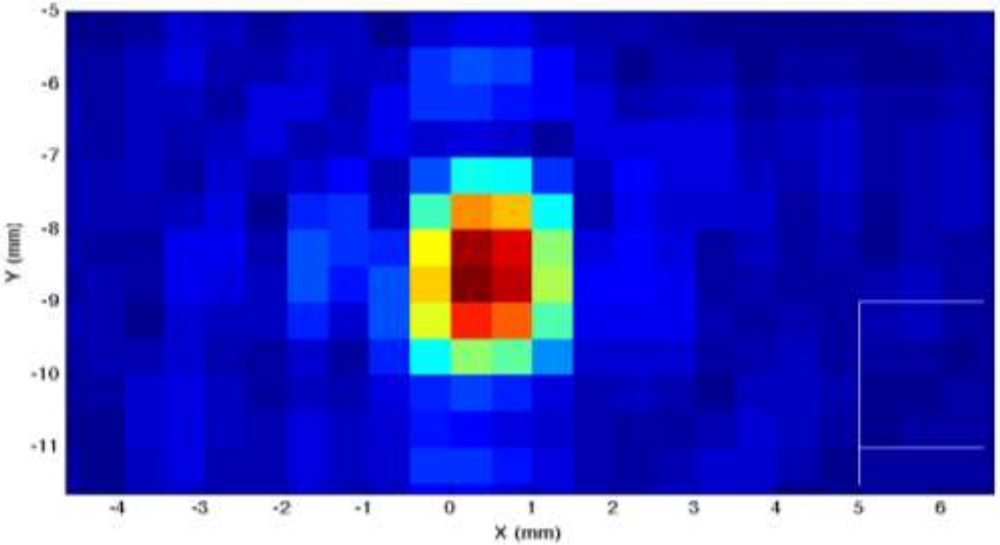
C. Explicit: Larger Property Variation across Voxels

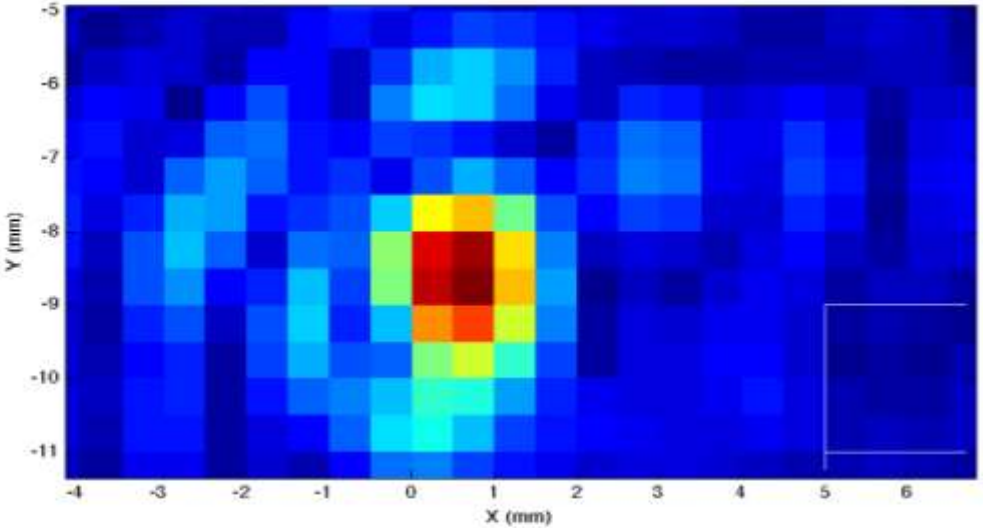
Scattered beam pressure pattern alone in breast
(volume with scattering – volume without scattering)



standard deviation = 2%, correlation length = 6 mm

C. Explicit – Effect of Scattering on Focused Spot


no scattering


2% std dev of acoustic parameters

- 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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The UCAIR group

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The Margolis Foundation,
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NIH R01s:
CA87785, CA134599, EB013433

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Thank you -

Any questions?

High-Intensity Focused Ultrasound (HIFU) Surgery
Critical needs:

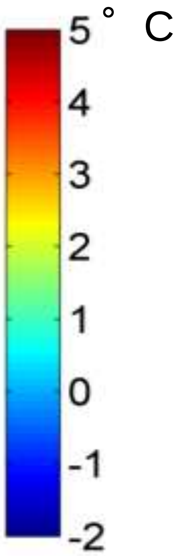
- Treatment planning
  - Beam localization **3D MR-ARFI; 3D MRTI**
  - Beam modeling
    - Phase and attenuation correction
    - Beam profile/SAR prediction: Optimize delivery of energy to treatment position
    - Minimize heating of adjacent and near-field tissues
- Treatment Control
  - 3D Temperature monitoring **3D MRTI (MR Temperature Imaging)**
  - Tissue damage assessment (Todd et al., ISTU 2013 Tuesday)

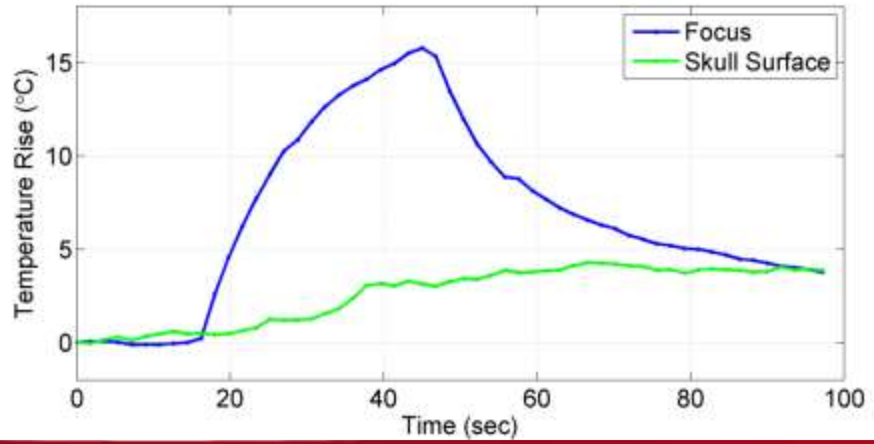
3D MRI temperature measurements

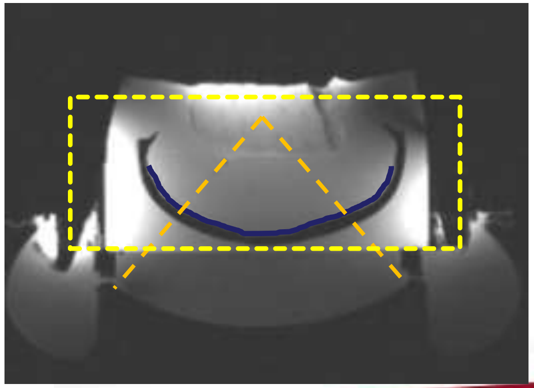
MPF: Experimental results

Coronal

2-D Skull Surface Projection







High-Intensity Focused Ultrasound (HIFU) Surgery
Critical needs:

- Treatment planning
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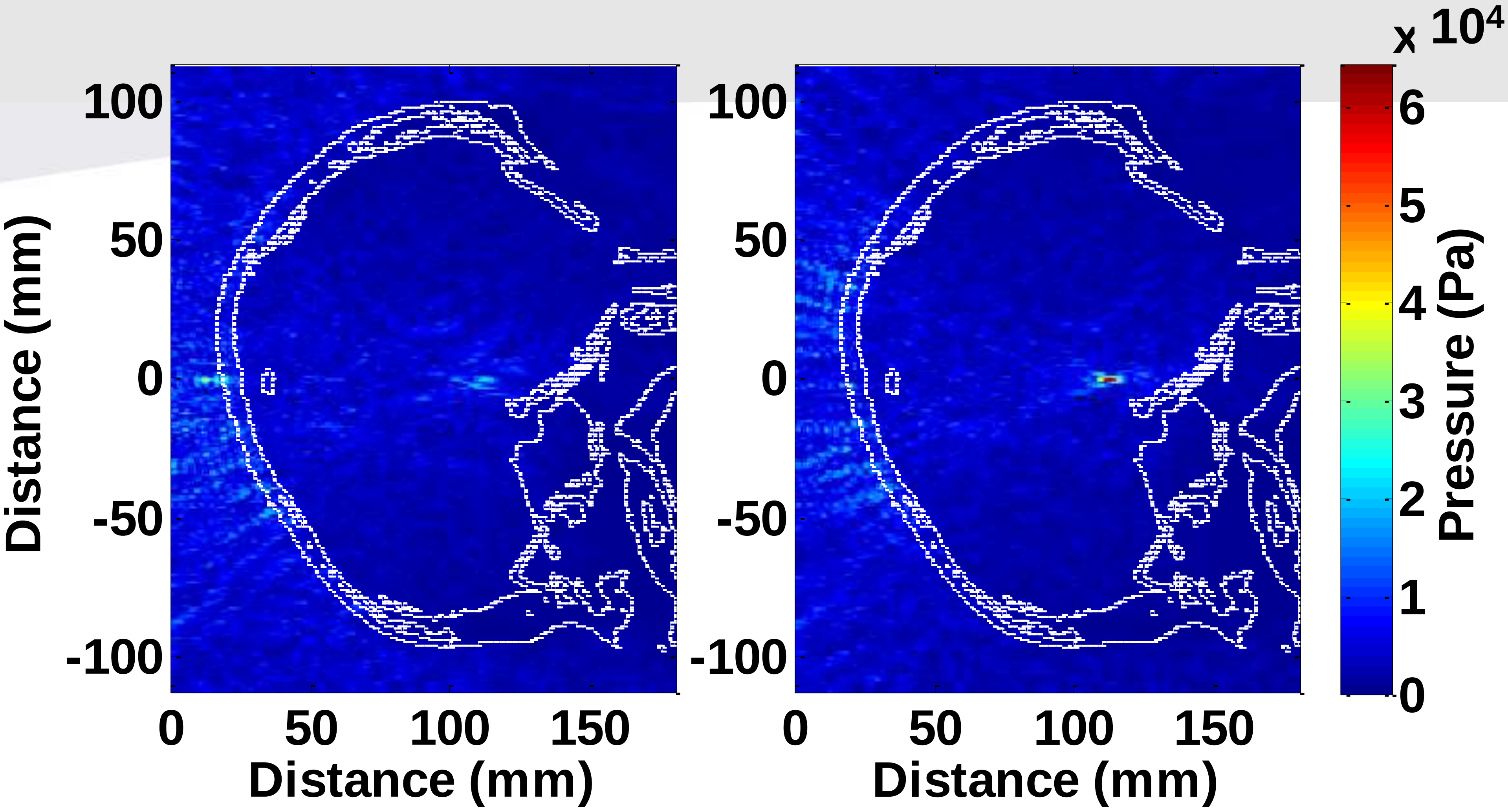
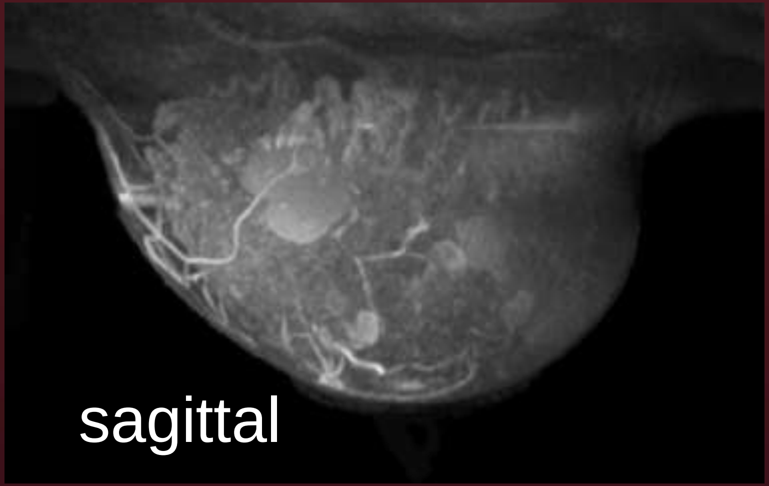

100
50
0
-50
-100
Distance (mm)
0
50
100
150
Distance (mm)
100
50
0
-50
-100
0
50
100
150
Distance (mm)
x 10^4
6
5
4
3
2
1
0
Pressure (Pa)

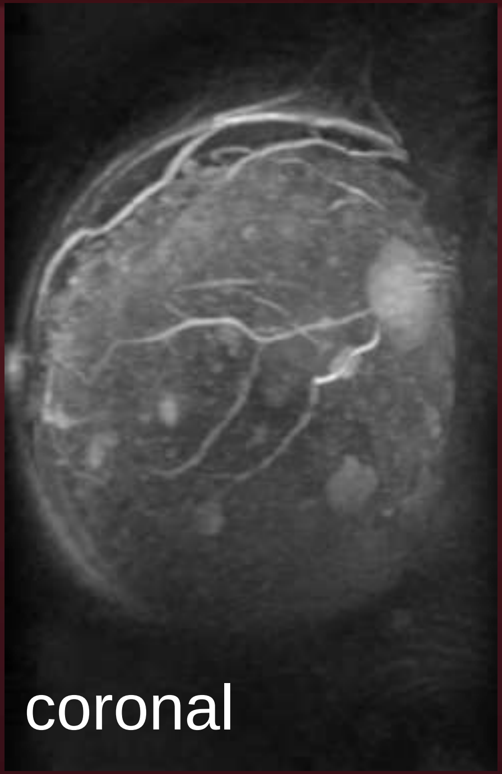
High-Intensity Focused Ultrasound (HIFU) Surgery Critical needs:

- Treatment planning
  - Beam localization **3D MR-ARFI**
  - Beam modeling **Hybrid Angular Spectrum (HAS)**
    - 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

HAS for beam phase correction

3D Vibe with Contrast

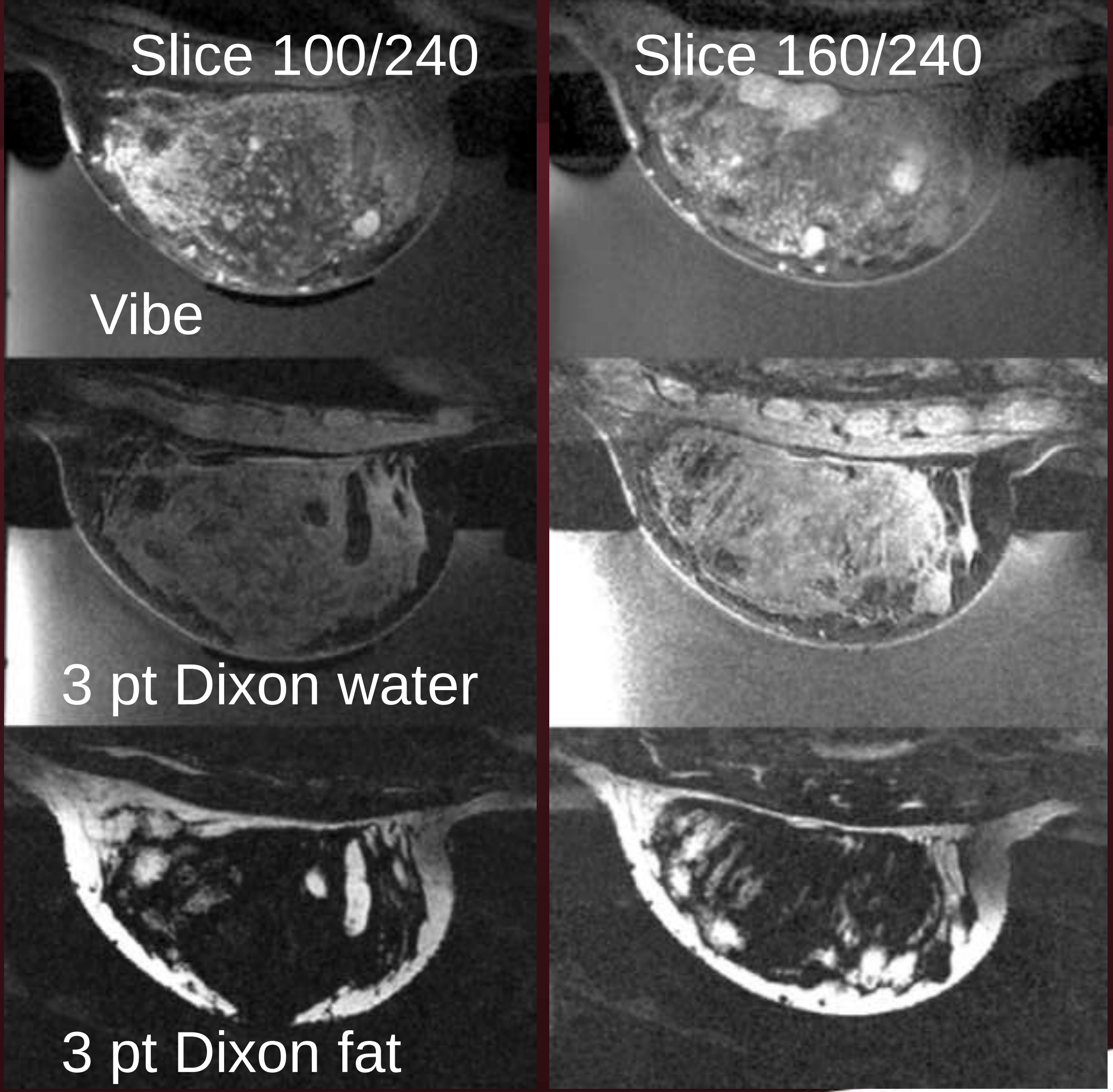




- Develop fully 3D tissue model
  - 3D MRI covering full volume
  - 1-mm isotropic resolution, ZFI to 0.5 mm spacing

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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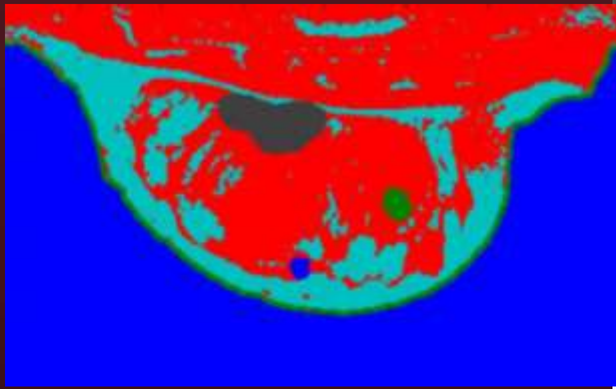
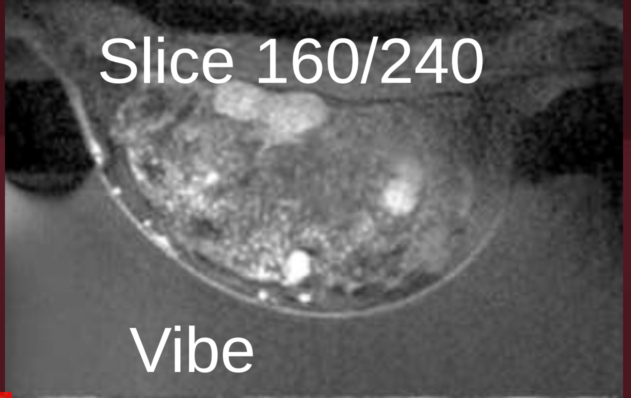
HAS for beam phase correction

- Develop fully 3D tissue model
  - Segment tissues

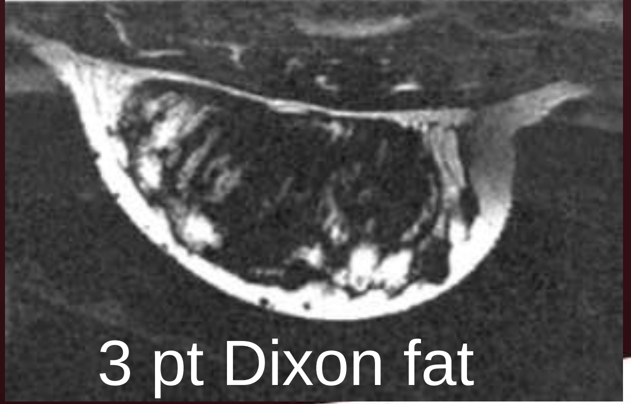




Slice 160/240

Vibe

3 pt Dixon water



3 pt Dixon fat

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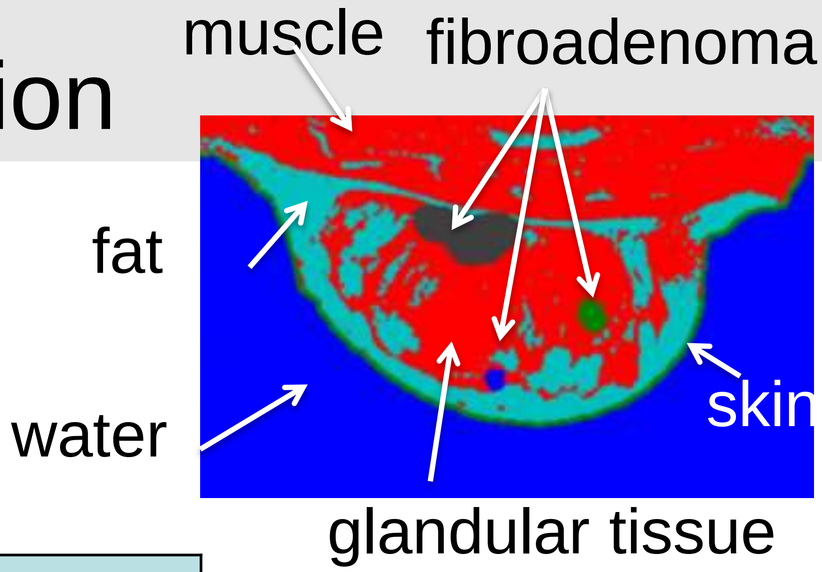
HAS for beam phase correction



- Estimate acoustic properties

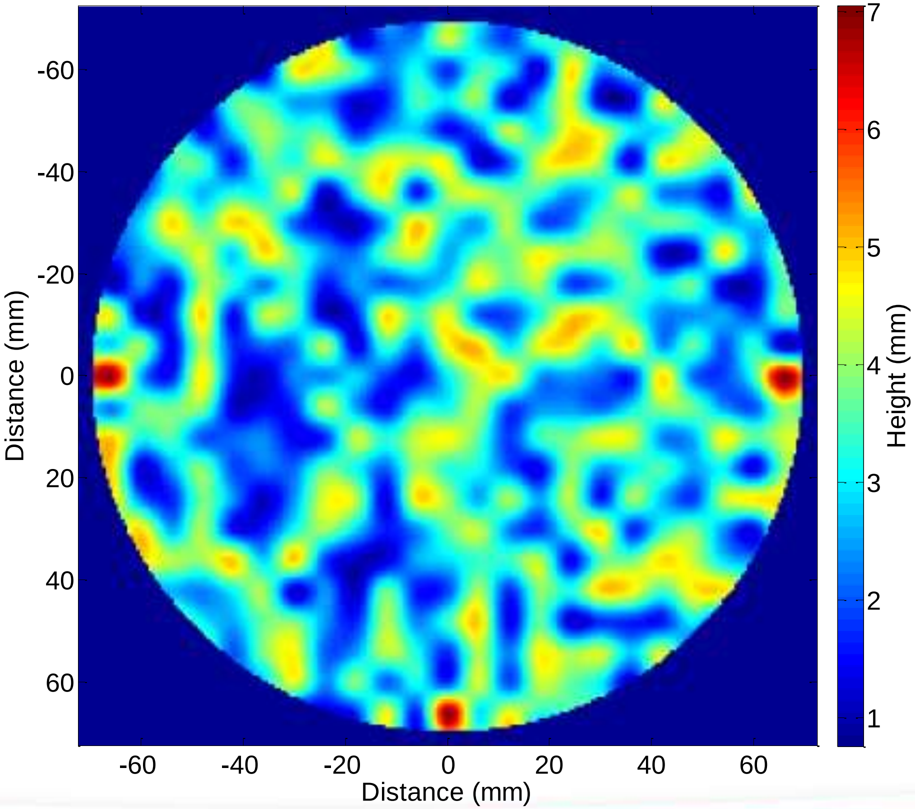
  for each tissue type

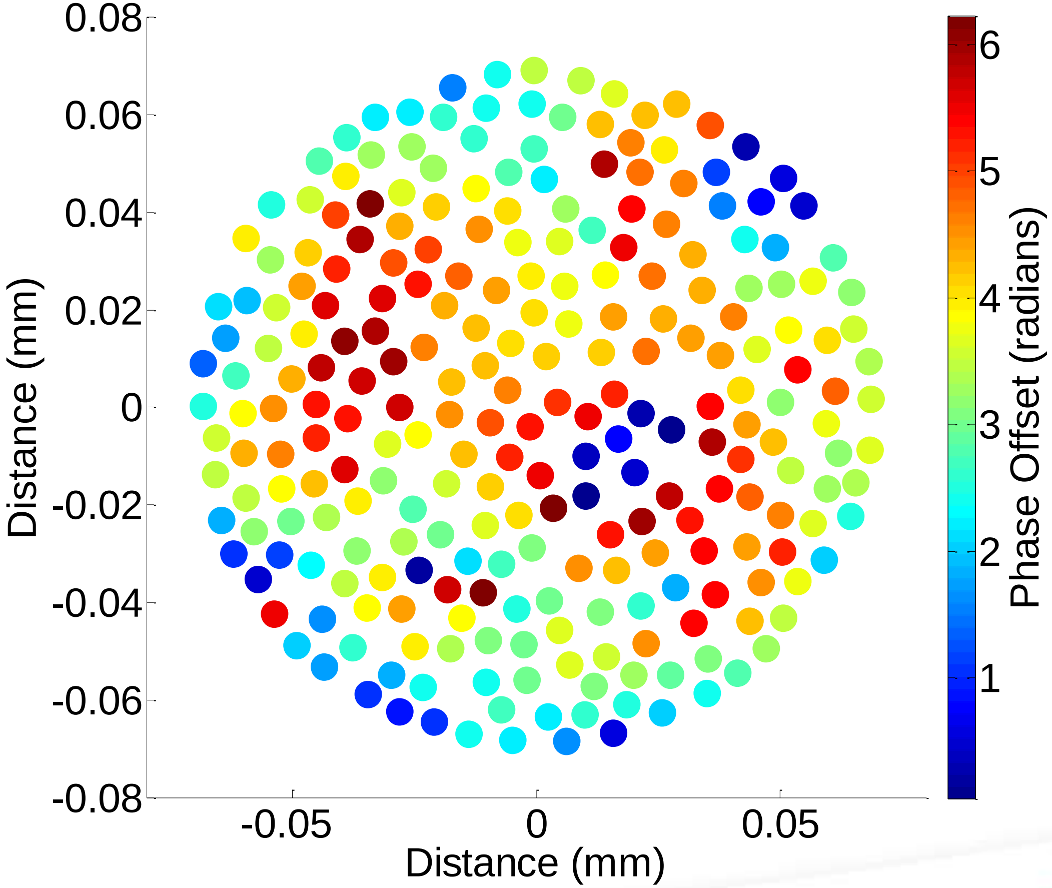
5. F. Duck. **Physical Properties of Tissue.** Academic, New York, 1990:

	Density (kg/m^3)	**Speed of Sound (m/s)**	**Attenuation (Np/cm*MHz)**
Water	1000	1500	0
Skin	1100	1537	0.28
Breast fat	928	1436	007
Fibroglandular tissue	1058	1514	0.09
Tumors/Fibroadenoma	1041	1584	0.081
Nipple cover	937	1480	0.086

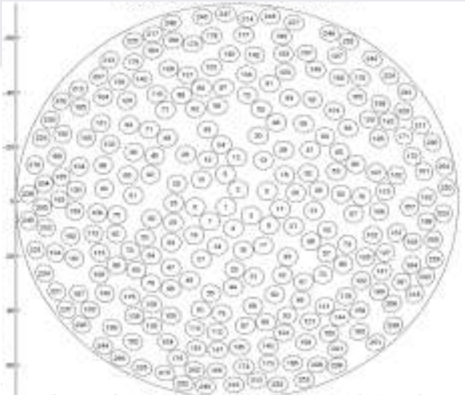
HAS phase aberration correction in pseudoskull

- Calculated phase offsets to match measured thickness from HAS model



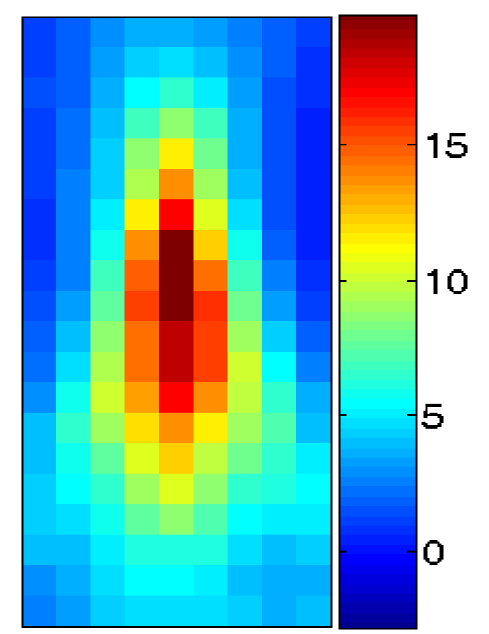


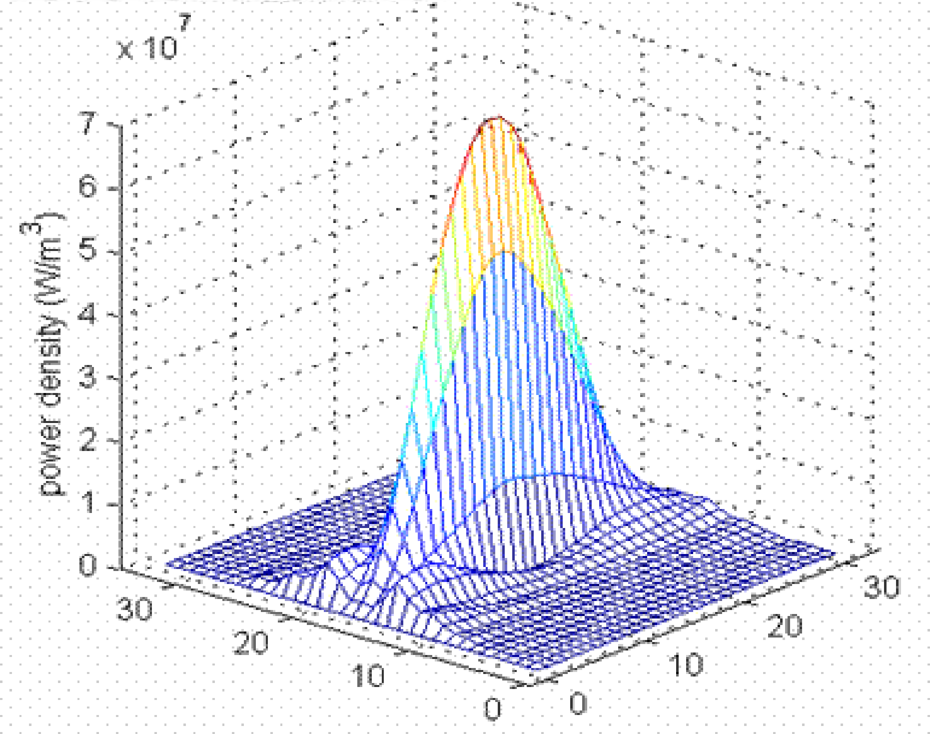
HAS beam modeling

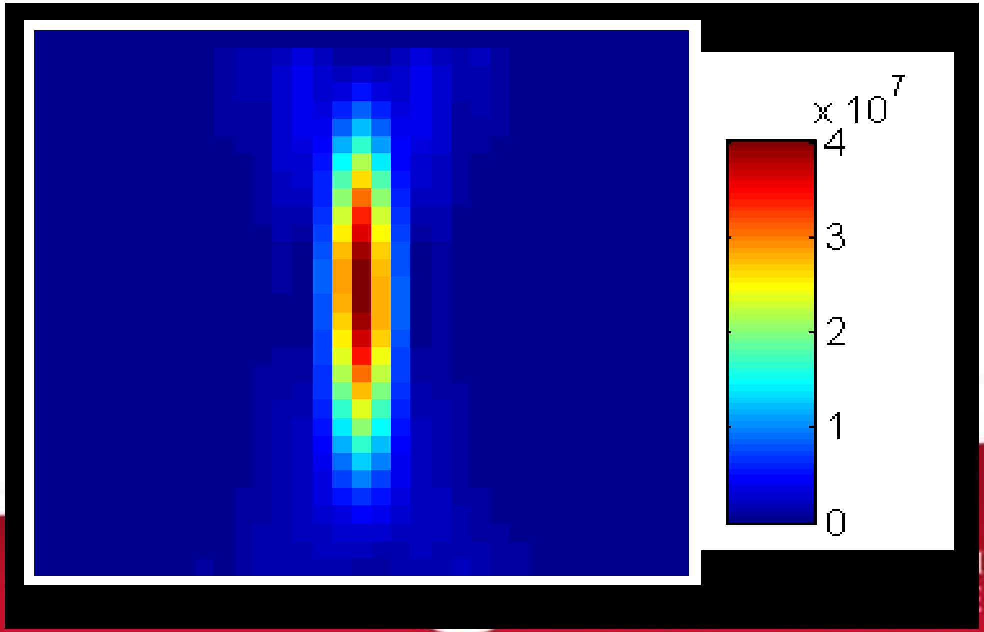


256 element phased array (Imasonics, Inc.)
1 MHz, 13cm radius of curvature
Hybrid Angular Spectrum (HAS) method
Focal spot ~ 2mm x 13mm

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