# Modeling of MR-guided HIFU for Breast and Brain Therapy

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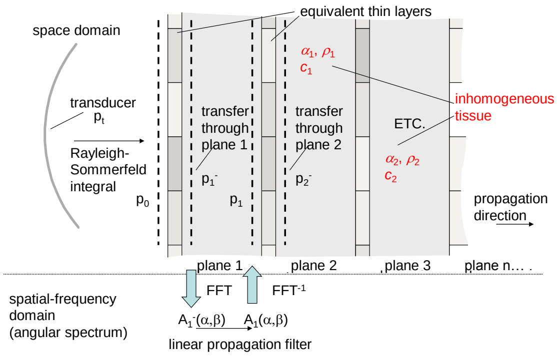
## Outline of Talk

- Overview of Hybrid Angular Spectrum (HAS) method
- Three examples of use:
  1. Modeling of acoustic radiation force imaging (ARFI)
  2. Determining extent of phase aberration in breast treatments
  3. Predicting heating efficiency in transcranial treatments (on-going)

## Concept of Hybrid Angular Spectrum Method*

- Extends traditional angular spectrum method (in spatial-frequency domain) to include inhomogeneous 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

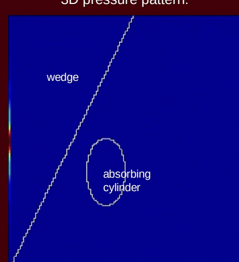
*U. Vyas and D. A. Christensen, "Ultrasound beam simulations in inhomogeneous tissue geometries using the hybrid angular spectrum method," *IEEE Trans UFFC* 59 (6), 1093-1100, June 2012.




## HAS Method Overview

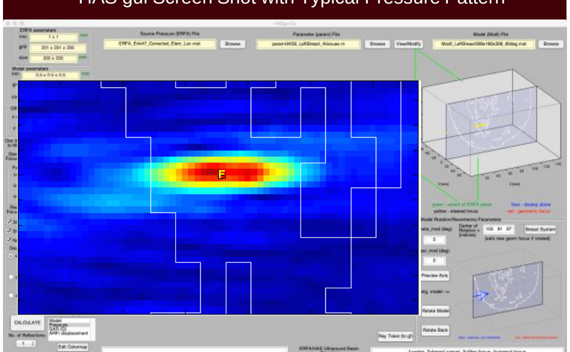
- Comparable to FDTD results within 2.8% (3D breast model)*
- Two orders of magnitude faster*:
  FDTD – 67 min HAS – 9.6 s
- Example simulation:
  3.5 MHz beam →
  3D model 141 x 141 x 161

3D pressure pattern:




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

## HAS gui Screen Shot with Typical Pressure Pattern



## Example 1 – ARFI Modeling

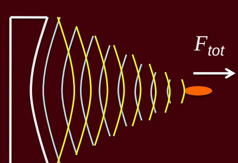
Study by Allison Payne with Josh de Bever et al.*

Uses –

- Finding location of beam focus in any tissue
  (e.g., replaces thermal test shot in fatty tissue)
- Determining mechanical properties of tissue
  (e.g., for treatment assessment)

*A. Payne, J. de Bever, A. Farrer, B. Coats, D. Parker and D. Christensen, "A simulation technique for 3D MR-guided acoustic radiation force imaging," *Med. Phys.* 21(2), Feb 2015.

## Origin of Radiation Force




$$\bar{F}_{abs} = \frac{2\alpha I}{c} \quad [\mathrm{N/m^3}]$$

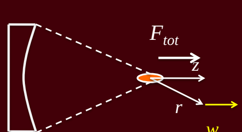
$$\bar{F}_{ref} = \frac{2IR^2}{c} \quad [\mathrm{N/m^2}]$$

$I$ = intensity from HAS calculation
$\alpha$ = tissue absorption coefficient
$R$ = interface reflection coefficient
$c$ = speed of sound

$$F_{tot} = \Delta x \, \Delta y \, \Delta z \, \bar{F}_{abs} + \Delta x \, \Delta y \, \bar{F}_{ref} \quad [\mathrm{N}]$$

## Generation of Displacement $w$ due to Distributed Force

Simplifications: Poisson's ratio … 0.5 so $\lambda >> \mu$




*g(r)*

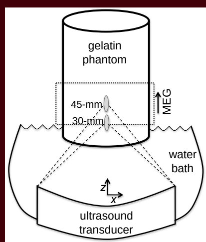
*distributed force field*

$$w = \frac{1}{8\pi\mu}\left[\frac{z^2}{r^3} + \frac{1}{r}\right] \otimes F_{tot}$$

$\lambda$ = first Lame coefficient
$\mu$ = Lame shear coefficient

- 3D green's function *g(r)* is convolved with distributed force field (computed using the HAS technique)
- Carried out in frequency domain

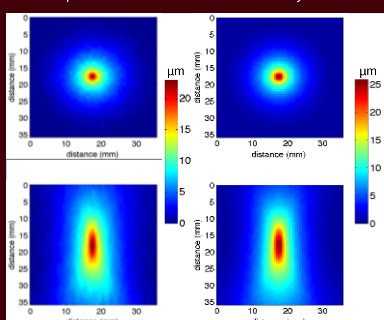
## Experimental Validation with MRI




- Three different values of gelatin stiffness (Young's modulus) used: 125, 175 and 250 bloom
- Young's modulus, speed of sound and attenuation independently measured (similar to soft tissue values)
- Displacement in 3D volume determined by MR phase measurements*
- Ultrasound on for 10 ms at 66 W.

* J. de Bever, N. Todd, M. Diakite, D. Parker, Proceedings of the ISMRM 21st Scientific Meeting, Salt Lake City, USA, 20–26 Apr., 2013.

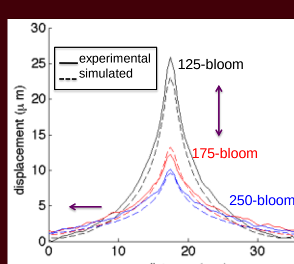
## Results – Displacement for 125 bloom




## Results – All three bloom values

Notes:

- Peak displacement inversely related to Young's modulus (bloom value)
- Displacement shape broadens for faster shear wave speed (higher Lame coefficient)




transverse slice, 30-mm focus depth

## Example 2 – Determining Extent of Phase Aberration in Breast Treatments

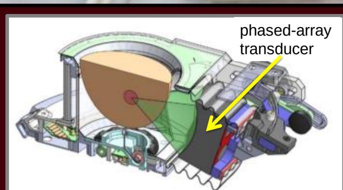
Study by Allison Payne with Alexis Farrer and Chris Dillon et al.*

Motivation –

- Phase aberration is a known issue in HIFU with large-aperture transducers (e.g., transcranial)
- Extent of phase aberration is unknown for smaller aperture transducers (e.g., Utah breast system)

*A. Farrer, S. Almquist, C. Dillon, D. Parker, D. Christensen and A. Payne, "Phase aberration simulation study of MRgFUS breast treatments," 15th International Symposium on Therapeutic Ultrasound, Utrecht, Apr. 15-18, 2015

## Utah MRgFUS Breast System



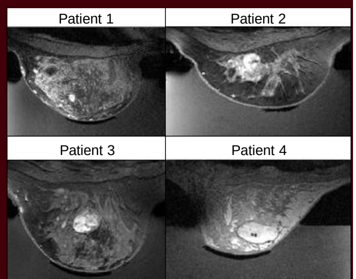

## Goals of Breast Study

- Determine if phase aberrations will be present for our smaller aperture transducer through HAS-simulated treatments
- Investigate how the treatment will benefit from phase aberration correction in the presence of various degrees of breast heterogeneity

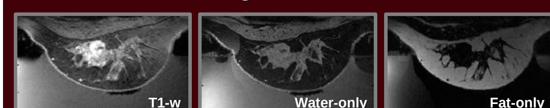
## MRI Patient Data

4 female volunteers with fibroadenoma(s)

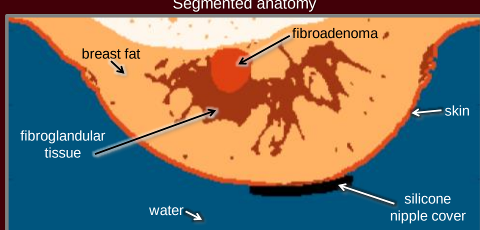
- 18 to 45 years old
- 1 to 8 fibroadenomas per patient
- 3-point Dixon acquisition
- Contrast-enhanced T1-weighted images



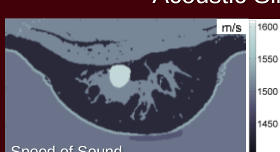

## Segmentation

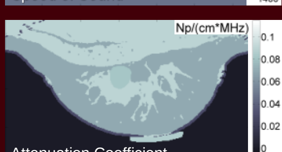



Segmented anatomy




## Acoustic Simulations




- Acoustic properties determined from Duck et al. 1990*
- 0.5-mm isotropic resolution
- Hybrid Angular Spectrum (HAS) method employed to give SAR pattern

* FA Duck, *Physical Properties of Tissues*. Academic Press: Harcourt Brace Jovanovich,1990.

## Treatment Simulation Set-Up

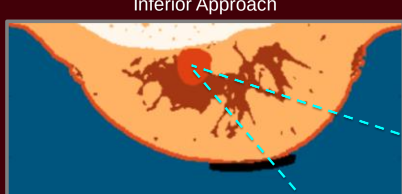
Superior Approach

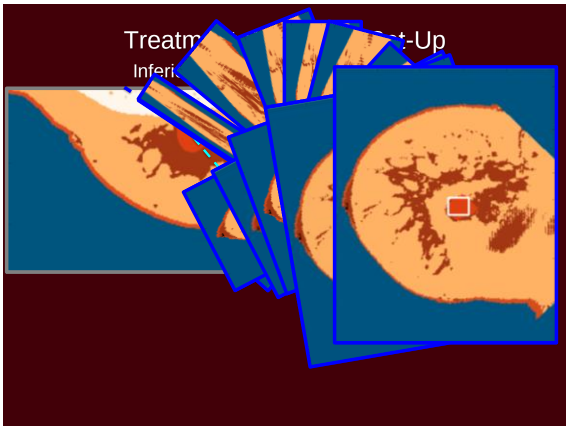
## Treatment Simulation Set-Up

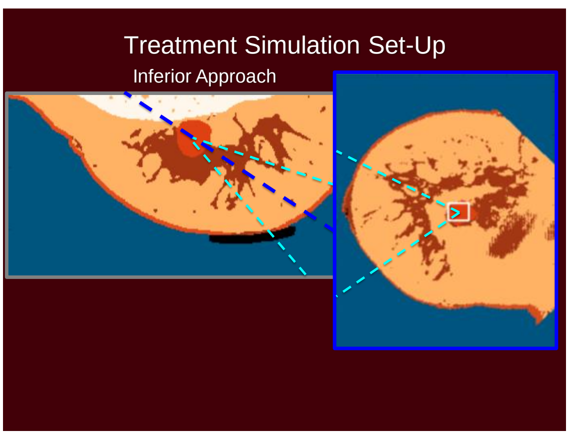
Inferior Approach

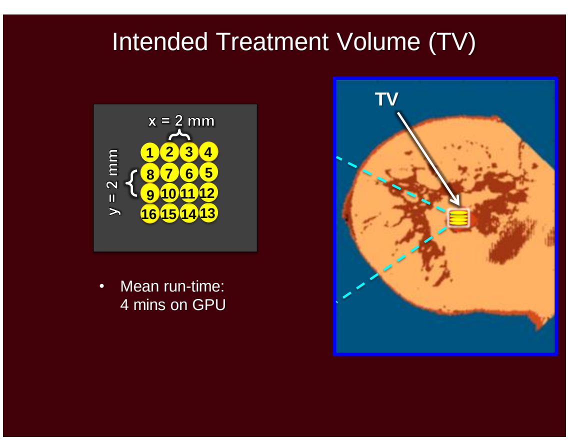
## Treatment Simulation Set-Up

Inferior Approach

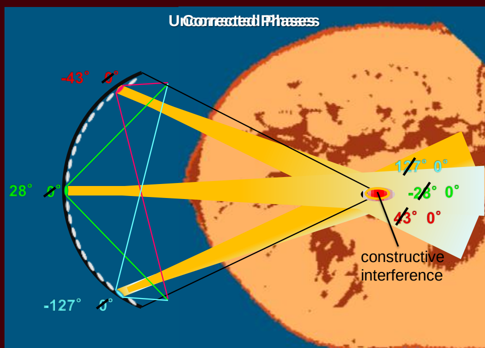





Treatment Simulation Set-Up
Inferior Approach

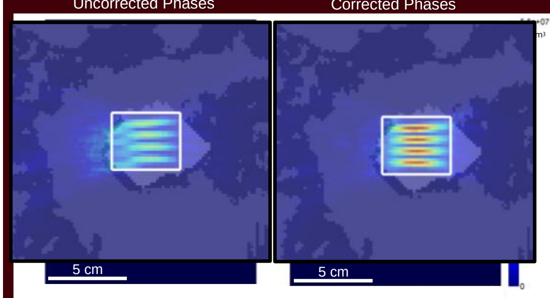

Intended Treatment Volume (TV)
x = 2 mm
y = 2 mm
1 2 3 4
8 7 6 5
9 10 11 12
16 15 14 13
• Mean run-time: 4 mins on GPU
TV

## Phase Correction Approach

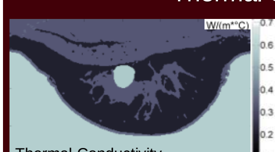


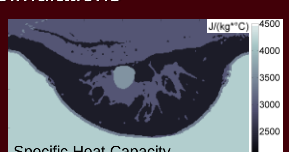

## Results: Power Deposition

Uncorrected Phases | Corrected Phases




## Thermal Simulations



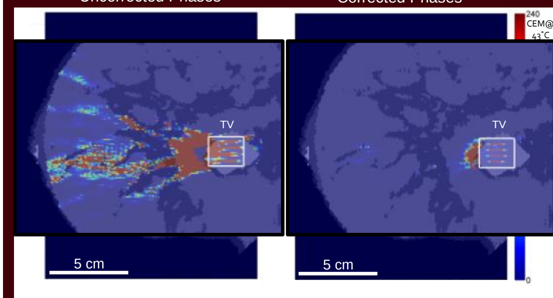





- Pennes Bioheat Equation – FDTD simulation
- Heating: 15 s/location; no cooling between locations
- Power output adjusted to achieve a 20 °C rise at first treatment location

## Results: Thermal Dose*

Uncorrected Phases | Corrected Phases




*S. A. Sapareto and W. C. Dewey, "Thermal dose determination in cancer therapy," Int. J. Radiat. Oncol., Biol., Phys. 10(6), 787–800 (1984).

## Dose Volume Ratio Metric

Uncorrected Phases — *DVR* = 9.1

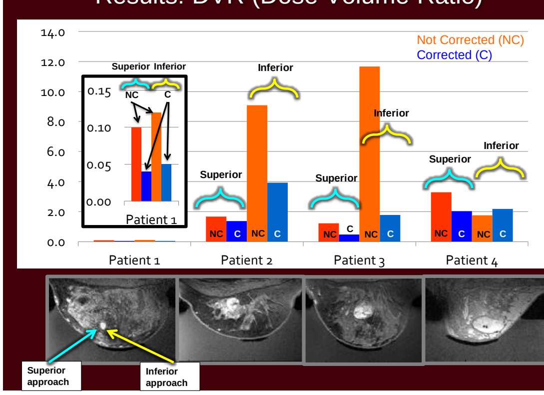
Corrected Phases — *DVR* = 3.9


*Dose Volume Ratio (DVR):*

*DVR = Volume Outside TV ≥ $240_{CEM}$ / Volume Inside TV ≥ $240_{CEM}$*

*(smaller is better)*

## Results: DVR (Dose Volume Ratio)



## Example 3 – Predicting Heating Efficiency in Transcranial Treatments

Study by Dennis Parker with Scott Almquist and Henrik Odeen et al.* (on-going)

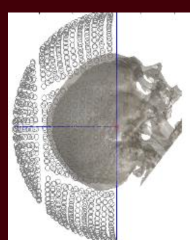
Background –

- Temperature profiles (space and time) available for 14 patients undergoing transcranial essential tremor treatments
- Perform retrospective analysis of temperature as a function of applied acoustic energy to determine efficiency of heating

*S. Almquist, N. Todd, J. de Bever, D. Parker and D. Christensen, "Correcting Phase Aberrations in Transcranial High Intensity Focused Ultrasound," International Society for Therapeutic Ultrasound Symposium, Heidelberg, Germany, June 11-13, 2012.

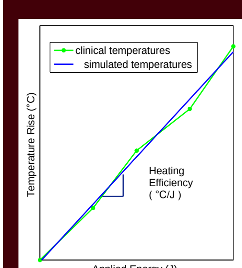
## Modeling of Transcranial Treatments

InSightec 650-kHz ExAblateNeuro



1024-element applicator in place

## Modeling of Transcranial Treatments

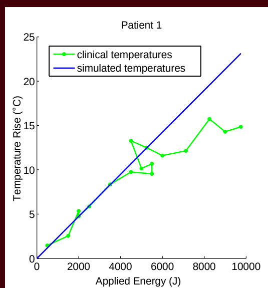



* S. Pichardo, V. W. Sin, and K. Hynynen, *Phys. Med. Biol.*, 56 (1) 219, Jan 2011

### Modeling Steps:

- Model skull from CT scan with acoustic values based on Hounsfield Units*
- Propagate beam into brain with HAS using clinically found element amplitudes and phases
- From HAS SAR pattern, find peak temperature with bioheat equation (FDTD)
- Plot peak temperature as a function of exposure energy: slope = Heating Efficiency (° C/J)

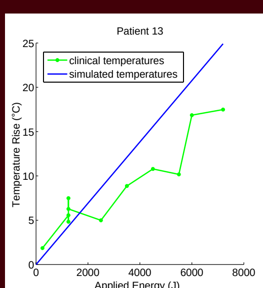
## Patient 1



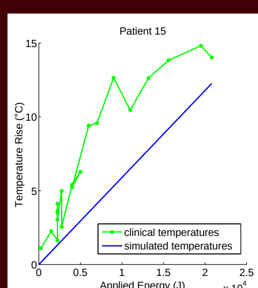

Notes:

- Some clinical searching for optimum temperature imaging plane
- Bending over of clinical plot at higher temperatures
- Reasonable simulation match at lower energy levels

## Patient 13 — Patient 15

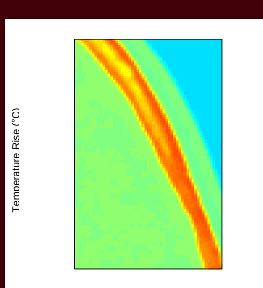



Overpredicted

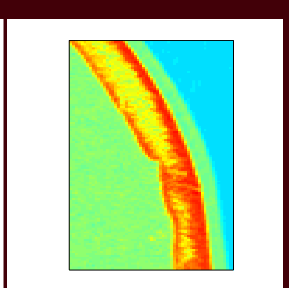



Underpredicted

## Patient 13 — Patient 15




Overpredicted



Underpredicted

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Image Guided Therapy
FUS Foundation

Thank You

Any Questions?

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## Numerical Modeling of Focused Ultrasound

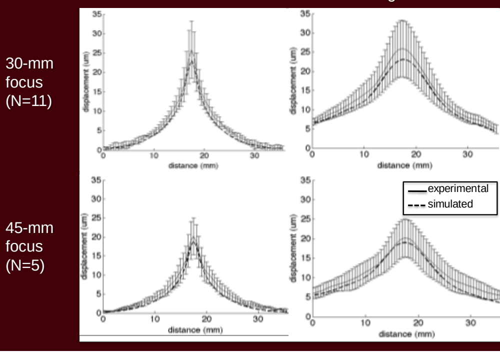
Uses -

- Predicting beam and heating patterns
- Determining phases for aberration correction
- Retrospective analysis of treatments
- Designing custom applicators
- Potential for patient treatment planning

Limitations -

- Only as valid as model parameters
- Simplifications reduce accuracy
- Need experimental validation

## Results – Displacement (µm) for 125 bloom




## Summary – HAS Technique

- HAS method allows rapid beam calculations of pressure, intensity and SAR patterns.
- Includes refraction, attenuation and reflection effects.
- MATLAB gui provides convenient user interface.

Future work:

- Including shear waves and multiple reflections.
- Adding scattering component to attenuation.

## Summary – ARFI Modeling (Example 1)

- Developed a numerical model for ARFI displacements
- Force field calculated by the HAS technique
- Validated with 3D MRI displacement measurements
- Model estimates displacements to within 2.8-12 % accuracy

## Summary – Breast System (Example 2)

- Phase aberration correction improved most treatments for our smaller aperture breast specific system.
- The degree of improvement depends on the amount of tissue heterogeneity in the beam path.

Future Work:
- Determine a figure of merit for clinicians that indicates how beneficial patient-specific phase correction will be.

## Summary – Transcranial (Example 3)

- aaa
- Bbb

Future Work:
- ccc