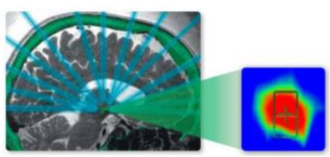
Acoustic Simulations in Transcranial MRgFUS: Prediction and Retrospective Analysis

URVI VYAS
STANFORD UNIVERSITY

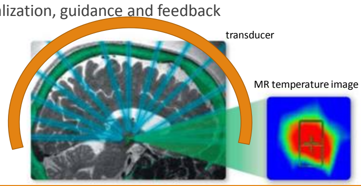
Outline

- Transcranial MRgFUS
- Clinical treatments and patient specific thermal responses
- Simulations in transcranial MRgFUS
  - Treatment planning
  - Patient selection
  - Retrospective analysis



Transcranial MRgFUS

- Non invasive selective tissue necrosis
- Focused ultrasound waves
- MR imaging for localization, guidance and feedback



Clinical tcMRgFUS Treatments

- System
  - InSightec ExAblate Neuro 4000
  - Hemispherical phased array
  - 1000 Elements, 680 kHz
  - Electronic and mechanical steering

InSightec's ExAblate Neuro "ultrasound bed" docked to a GE Discovery MR750 system

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  - Patient head shaved
  - Stereotactic frame placed
  - Transducer positioned

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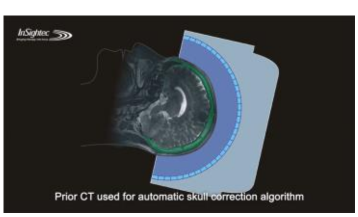
  - Transducer Positioned
  - CT and MRI registered
  - Phase aberration correction
  - Low power sonication
  - High power sonication



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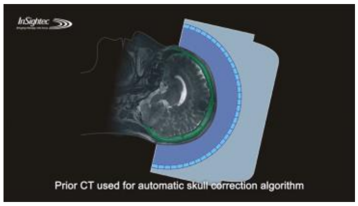
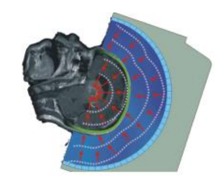


Aim: Simulations in tcMRgFUS to Improve Safety

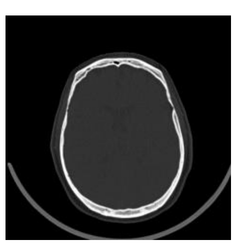
The complex propagation of the acoustic waves in the skull, which includes the effects of reflection, refraction, and attenuation, in addition to phase aberration, can be understood using simulations.

- Patient Selection
- Treatment Planning
- Retrospective Analysis



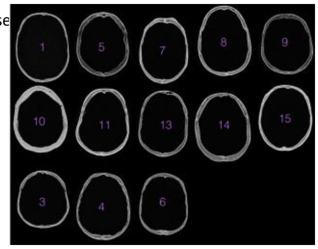
Heterogeneity in Skulls: Individual

- The presence of the skull causes
  - Phase Aberration
  - Absorption
  - Scattering
  - Reflection



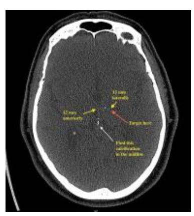
Heterogeneity in Skulls: Population

- The presence of the skull cause
  - Phase Aberration
  - Absorption
  - Scattering
  - Reflection



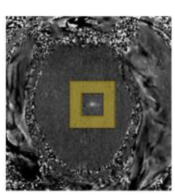
Dataset

- Seventeen datasets from two institutions : Stanford University, Stanford, CA, USA and University of Virginia, Charlottesville, VA, USA
- Aim of treating essential tremor (n = 11) or parkinsonian tremor (n = 6).
- Each subject dataset included the screening CT images and the temperature images for every sonication of the tcMRgFUS treatment.
- The dataset also included information on the applied power, duration, and focal location used for each sonication.

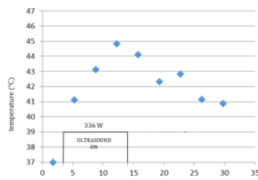


Clinical Temperature Images

- Referenceless processing with frame centered on the hotspot.
- Thermal coefficient of -0.00909 ppm/°C , inner and outer dimensions of 32 mm and 64 mm respectively.
- First sonication where the temperature was greater than 2.5 times the standard deviation.

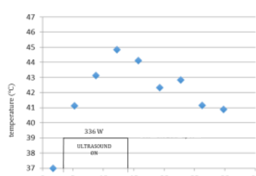


Clinical Temperature Images: Experimental SAR



Clinical Temperature Images: Experimental SAR

- Temperature increase immediately after the ultrasound power is turned on, when conduction and perfusion losses are small compared to the absorbed power losses
- Specific absorption rate (SAR) was estimated by measuring



$$Experimental\ Skull\ Efficiency = \frac{1}{Power}\frac{dtemperature}{dTime}$$

Roemer, R. B., Fletcher, A. M. & Cetas, T. C*Int. J. Radiat. Oncol.* **11,** 1539–1550 (1985).

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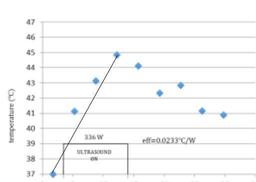

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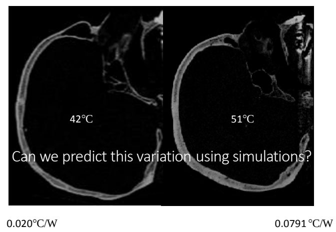
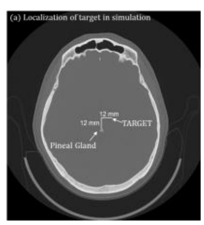
Experimental SAR: Range

- The experimentally seen variation in a subject's thermal response varies significantly.
- Between the two limits the experimental efficiency in the dataset was well distributed.



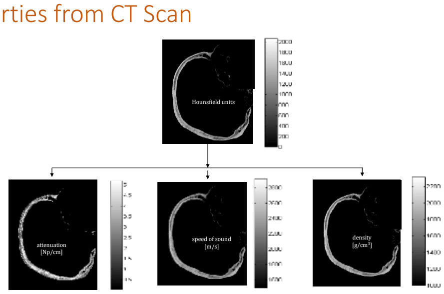
Simulations: Simulated Skull Efficiency

- Technique: Hybrid Angular Spectrum Simulations[1]
- Transducer: InSightec Brain Transducer, 680 kHz
- Phase Corrections: All simulation phase corrected using Time Reversal
- Resolution: ~0.5x0.5x0.62 mm3
- Calculation Time: Each simulation takes 20 minutes
- No of Subjects: 17 Subject x-ray CT images and Treatment Temperatures



Vyas, U. & Christensen, D. *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* **59,** 1093 –1100 (2012).

Voxel-by-Voxel Patient-Specific Tissue Acoustic Properties from CT Scan



Simulation: Density Calculation

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Aubry, J.-F., Tanter, M., Pernot, M., Thomas, J.-L. & Fink, M.. *J. Acoust. Soc. Am.* **113,** 84 (2003).

Simulations: Calculation of Speed of Sound

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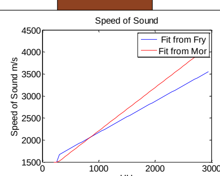

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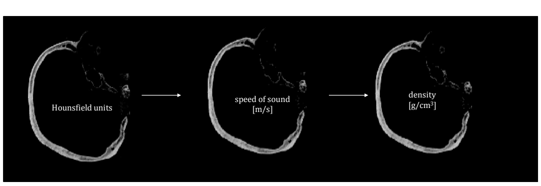

- Speed of sound and density linear with Hounsfield Units

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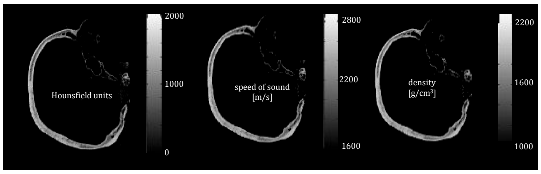

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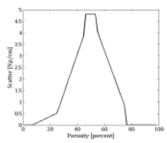

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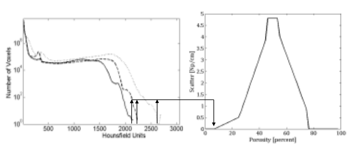

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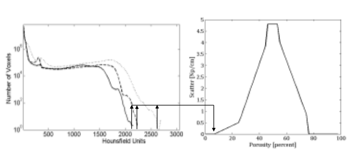

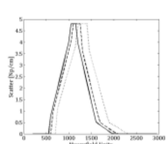

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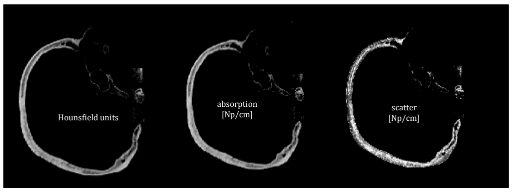
Voxel-by-Voxel Patient-Specific Tissue Acoustic Properties from CT Scan



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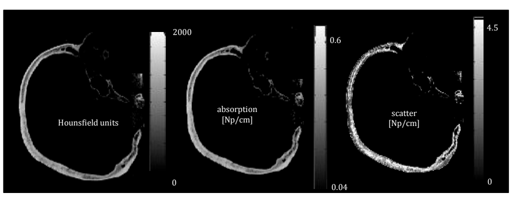

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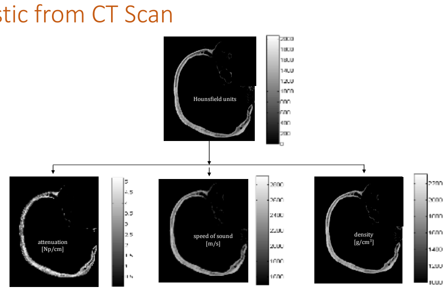
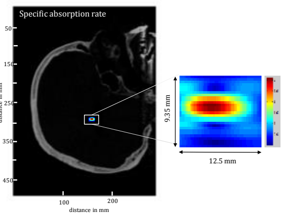
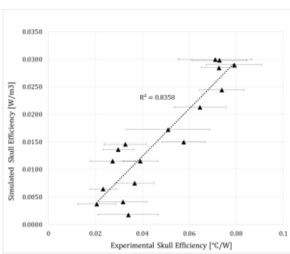


Simulations: Simulated Skull Efficiency

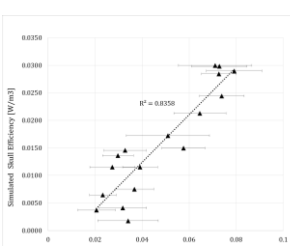
- Technique: Hybrid Angular Spectrum Simulations
- Transducer: InSightec Brain Transducer, 650 KHz (Element Locations of Stanford System).
- Phase Corrections: All simulation phase corrected using Time Reversal
- Resolution: ~0.5x0.5x0.62 mm3
- Calculation Time: Each simulation takes 20 minutes (SDR takes minutes?)
- Power: Constant 500Watts for all subjects
- No of Subjects: 17 Subject x-ray CT images and Treatment Temperatures
- SAR for each subject skull was calculated and focal SAR used as a measure of Simulated Skull Efficiency.



Results: Simulations with Experiments



Use of Simulation: Prediction of Thermal Response



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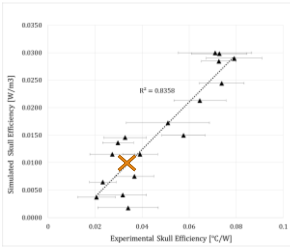

Prediction:
200 Watts, 10 seconds, temperature rise 9°C

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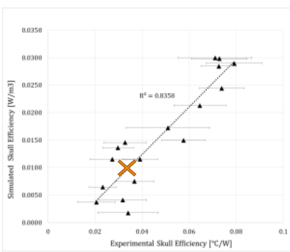

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Clinical Thermal Response:
200 Watts, 10 seconds, temperature rise 8°C

Simulating Loss Components

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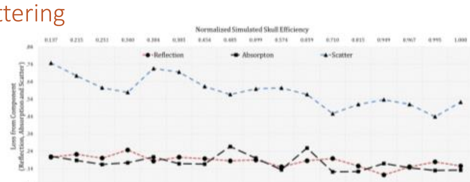
D. Absorption-only	0	α	1550	1000
E. Homogenous Model	0	0.04	1550	1000

- Each simulation modeled only one kind of acoustic loss while keeping all others equal to the losses in a homogeneous model
- We decomposed each component of the acoustic loss in the propagation of the acoustic waves in the simulation—reflection, absorption and scattering—for each individual skull.

Component Analysis: Reflection, Absorption and Scattering



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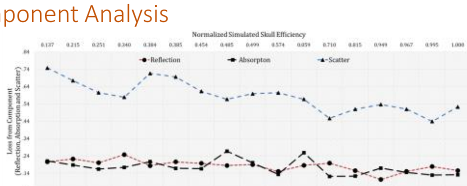
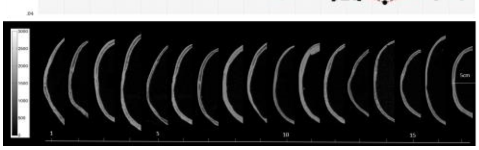
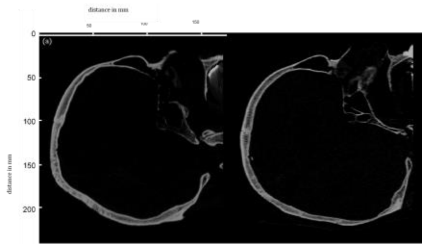




Use of Simulation: Subject Selection



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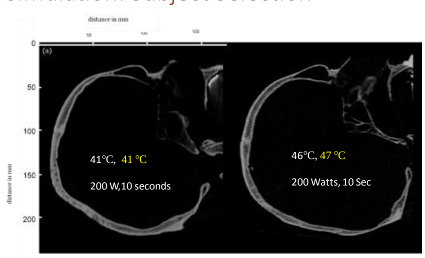

Yellow-Clinical Temp; White: Predicted Temperature

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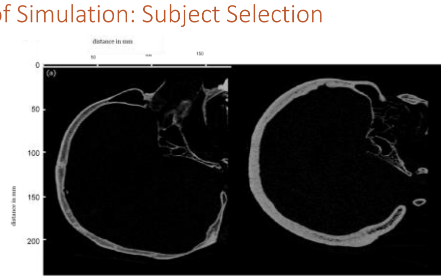

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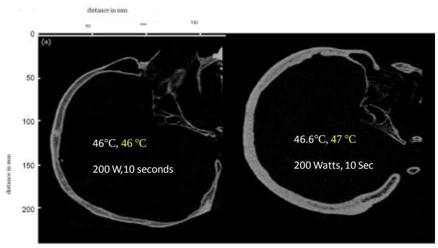
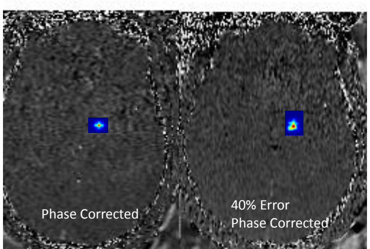


Yellow-Clinical Temp; White: Predicted Temperature

Retrospective Analysis: Phase Correction



Summary

- Simulations to predict the variation in thermal responses noticed in clinical tcMRgFUS treatments in the brain
- Simulated skull efficiency correlates strongly with experimentally seen thermal response with an **R^2 of 0.85**
- Simulations can be used for treatment planning and retrospective analysis of tcMRgFUS treatments
  - Patient Selection
  - Treatment Planning
  - Retrospective Analysis

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Thank you!

- P01 CA 159992, GE, FUSF, InSightec