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Planning and Monitoring of MRI-Guided Ablations with Focused Ultrasound

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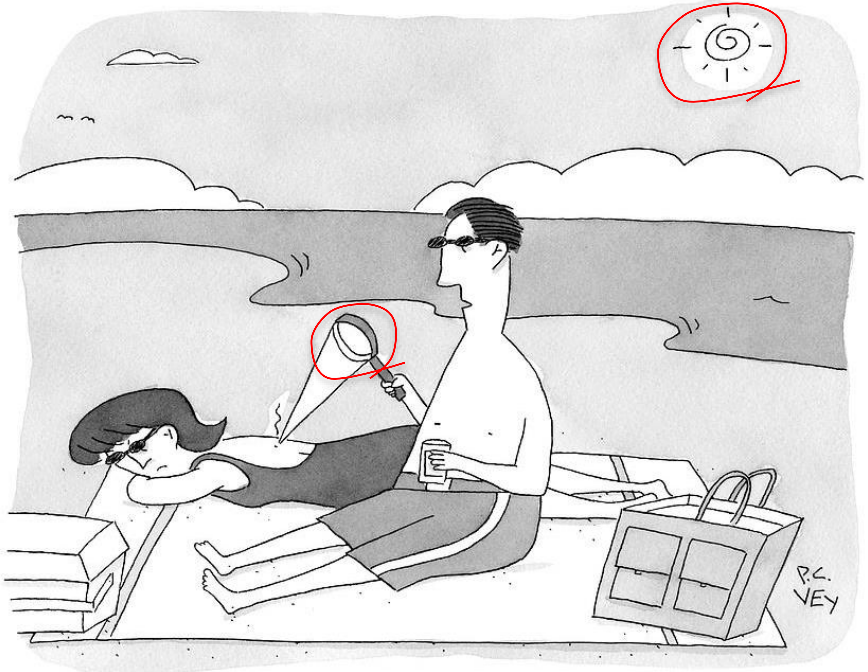
AAPM 2020

Focusing on a Problem



"Be patient. It's almost dead."

P.C. Vey, New Yorker

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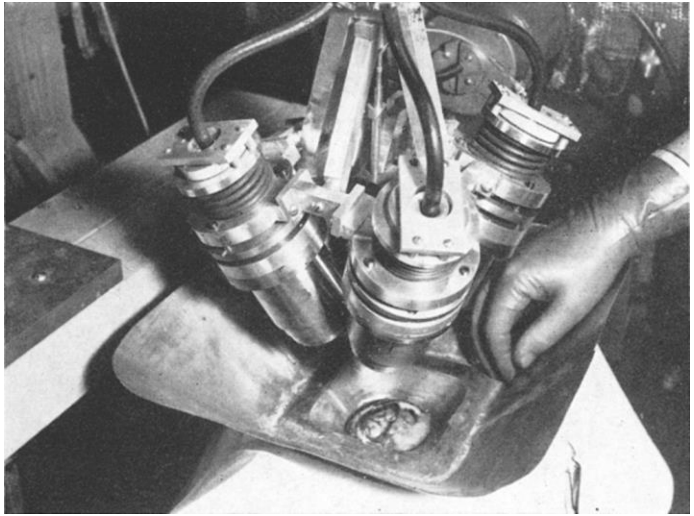
Focused Ultrasound in 1950s-60s

- William and Francis Fry demonstrated the first focused ultrasound treatments which produced localized lesions in brain without damaging intervening tissue, but with skull partially removed.
- The system was used to treat patients with Parkinson's disease successfully but not used outside of the research setting due to:
  - High complexity of the procedure
  - Difficulty in accurate target localization.



[1] WJ Fry , WH Jr Mosberg , et al. JNS, 1954

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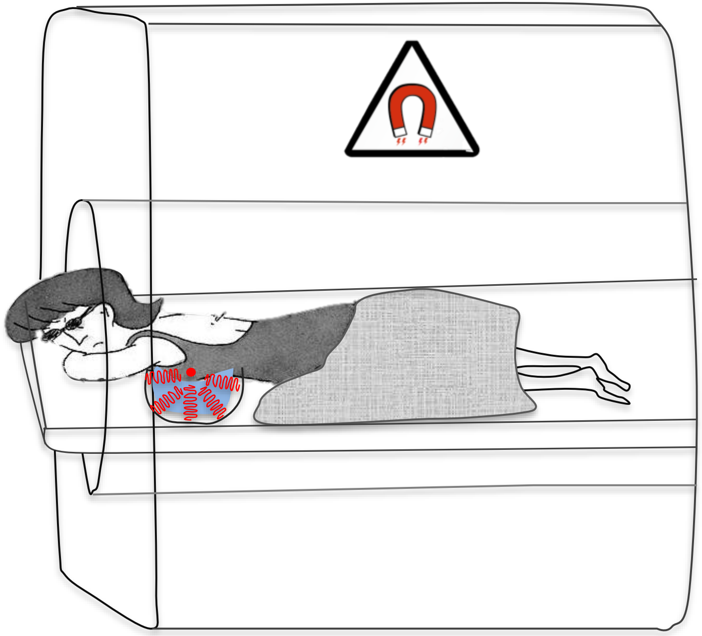
Focused Ultrasound (FUS) and MRI in 1990s

Ultrasound transducers (0.5-2.5 MHz) are built to operate at high magnetic field enabling integration with MRI scanners.

MRI ensures safety and efficacy of the FUS treatment.



[1] K Hynynen et al. Med Phys 1993, [2] A Darkazanli et al, JMRI 1993

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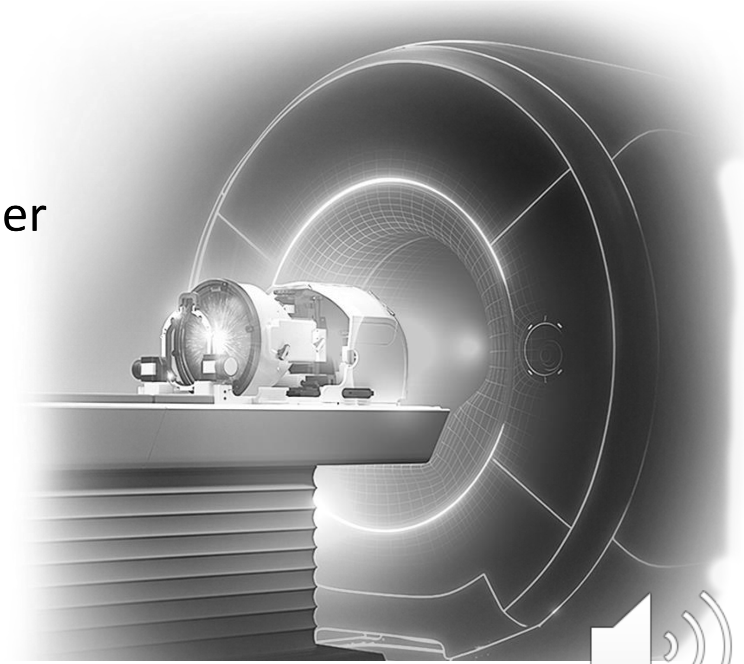
MRI-guided FUS Systems and Applications

Transcranial system

- Essential tremor and
  tremor-dominant Parkinson’s disease
- Neuropathic pain, obsessive compulsive disorder
- And more..



Exablate Neuro, InSightec

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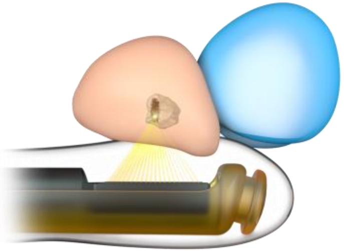
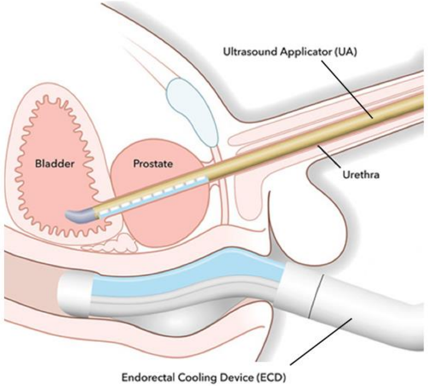
MRI-guided FUS Systems and Applications

Prostate systems





- Prostate cancer
- Benign prostatic hyperplasia

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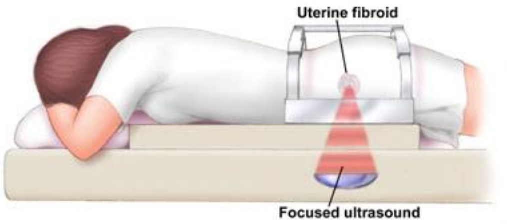
MRI-guided FUS Systems and Applications

Body systems

- Uterine fibroids
- Painful bone metastases
- And more..



Exablate, Insightec

Sonalleve, Profound

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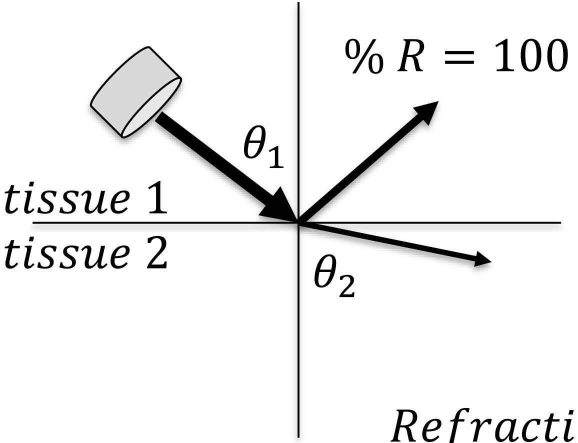
Ultrasound Propagation Considerations

- Propagating in biological tissues, ultrasound waves experience reflection, refraction and attenuation

Incident *Reflection*

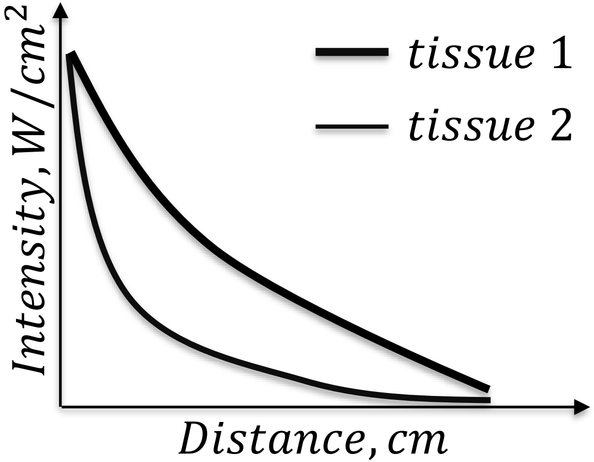
$$\% R = 100 * \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2}$$



Refraction

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{c_1}{c_2} \qquad \lambda = \frac{c_2}{f}$$

Attenuation



Attenuation increases with frequency

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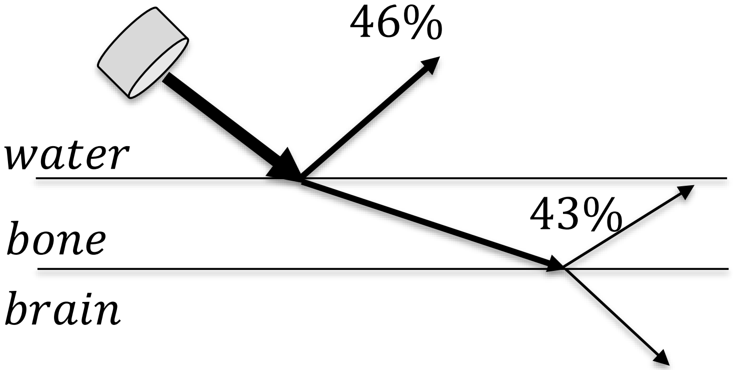
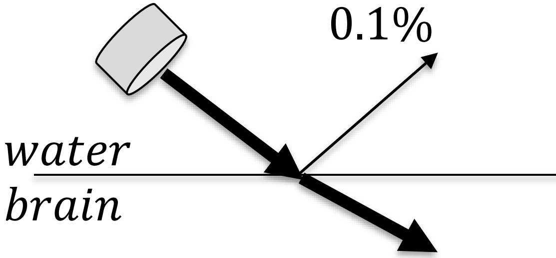
Ultrasound Propagation Considerations

	Water	Brain	Bone	Air
Speed of sound $[m/s]$	1480	1560	3000	343
Absorption [dB $(MHz\ cm)^{-1}$]	**2.5*10^-5**	**0.34**	**8**	
Impedance $[kg\ m^{-2}s^{-1}\ \times\ 10^6]$	1.48	1.6	7.8	0.0004

- Bone leads to significant **reflection**
- Bone has much higher **absorption**





[1] F Fry, J Barger, J Acoust Soc Am, 1978

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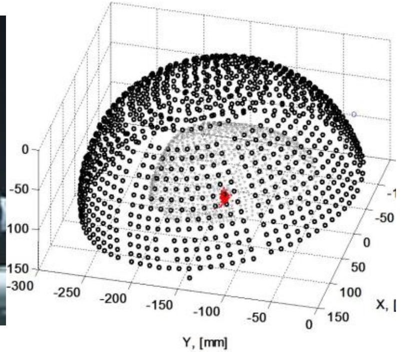
Technological Solutions: Transducers

- Lower frequency of 650 kHz
- High number of transducer elements to distribute acoustic pressure over large portion of the skull, minimize skull heating, achieve desired amplification
- Correcting for focal shift and distortion due to skull-induced aberrations using individual element’s phase and amplitude adjustment



[1] A Kyriakou et al, Int J of Hyperthermia, 2014

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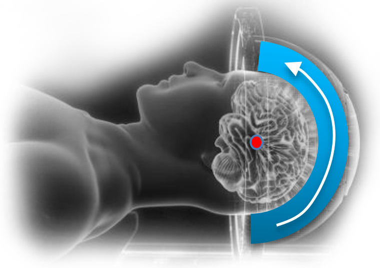
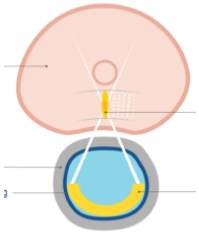
Technological Solutions: Active Cooling

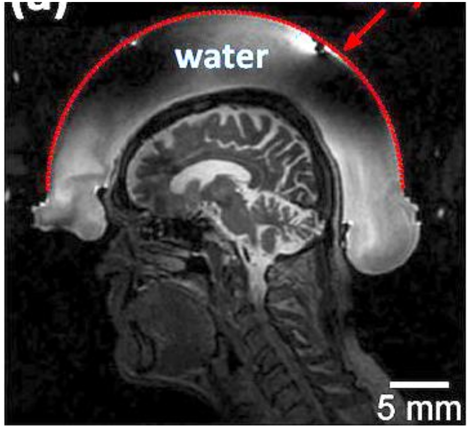
- Circulating cold water (T = 12C) reduces unwanted heating

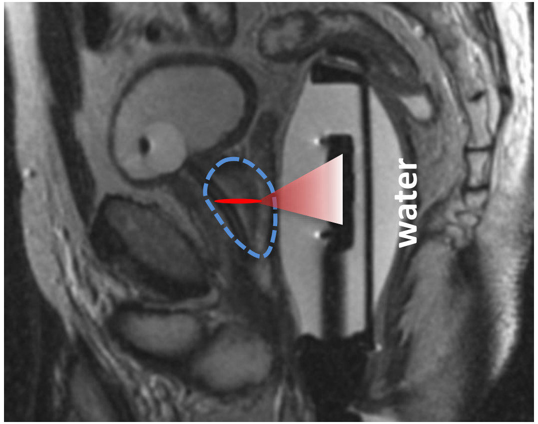


Skull cooling



Rectal cooling





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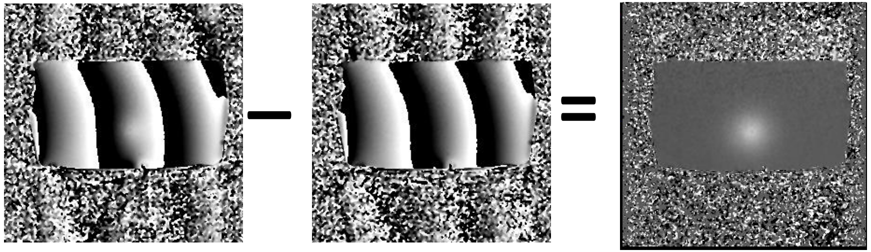
Technological Solutions: MR Thermometry

- In **water-based tissue**, proton resonant frequency linearly decreases with temperature

$$\Delta T = \frac{\Delta\varphi}{\alpha \cdot \gamma \cdot B_0 \cdot TE} \qquad \alpha = 0.01 ppm/°C$$

$TE - echo\ time$



Phase at $\boldsymbol{T_n}$

$\varphi_n = 2\pi f_n TE$

Phase at $\boldsymbol{T_0}$

$\varphi_0 = 2\pi f_0 TE$

Temperature Overlay

$\Delta\varphi = \varphi_n - \varphi_0$

By Viola Rieke, PhD

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Workflow of MRI-guided FUS

Quality Assurance
in a phantom

1

Filling water
Device positioning

2

Patient Preparation
Foley catheter
Hair removal
Frame placement

1

Patient Preparation and Device Positioning

Placement of stereotactic frame

silicone membrane

Head positioning inside the transducer

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Workflow of MRI-guided FUS

Quality Assurance
in a phantom

1

Filling water
Device positioning

2

Planning Stage
Device loc, imaging, contouring

3

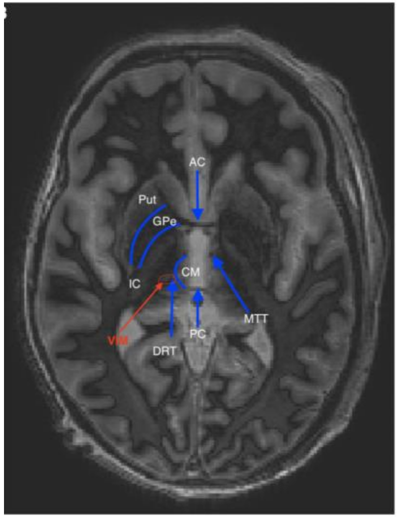
Patient Preparation
Foley catheter
Hair removal
Frame placement

1

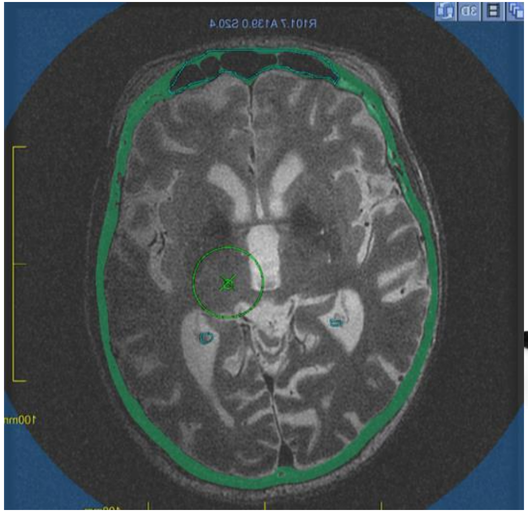
Planning Stage: Off-Line Session

- Diagnostic MR images are obtained to visualize anatomic landmarks to predict the position of the target: the ventral intermediate (VIM) nucleus of the thalamus.

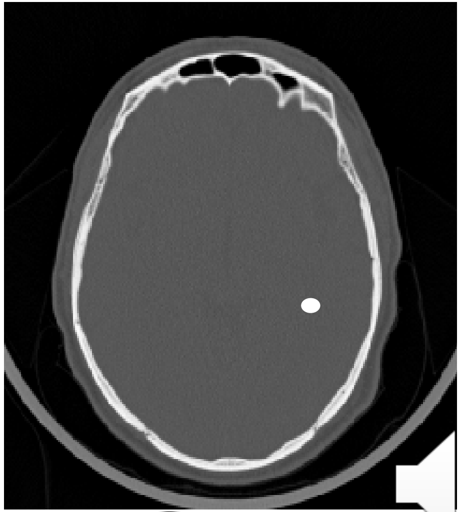
Diagnostic MRI



Treatment Workstation



Diagnostic CT



[1] BR Shah et al, Brain, 2020, [2] M Vidoretta et al, MAGNETOM, 2019

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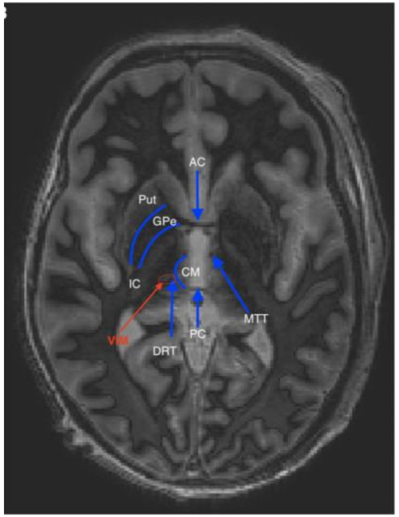
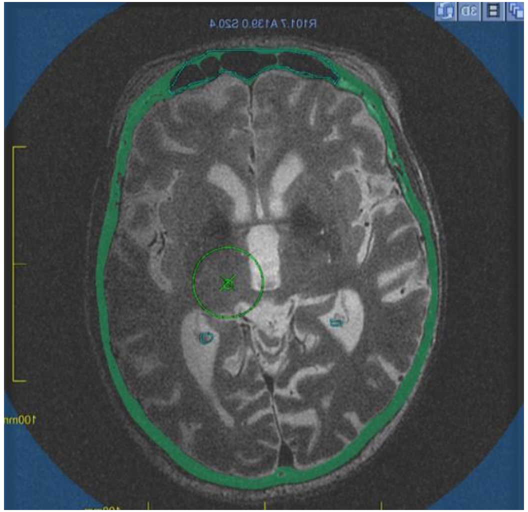
Planning Stage: Off-Line Session

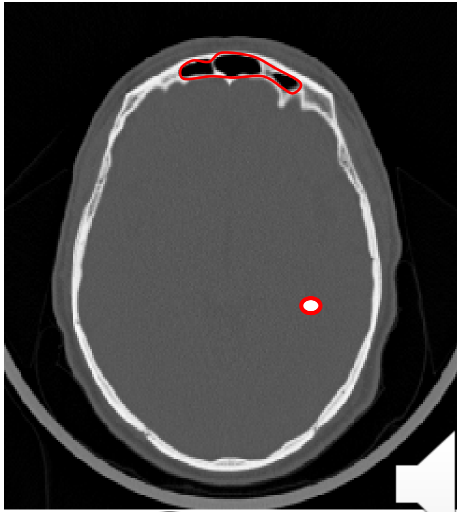
- Pre-treatment diagnostic CT and MR to registered.
- No-pass zones are outlined: calcifications, air
- Phase aberration correction is calculated

Diagnostic MRI





Diagnostic CT



E Kaye et al, Medial Physics, 2012

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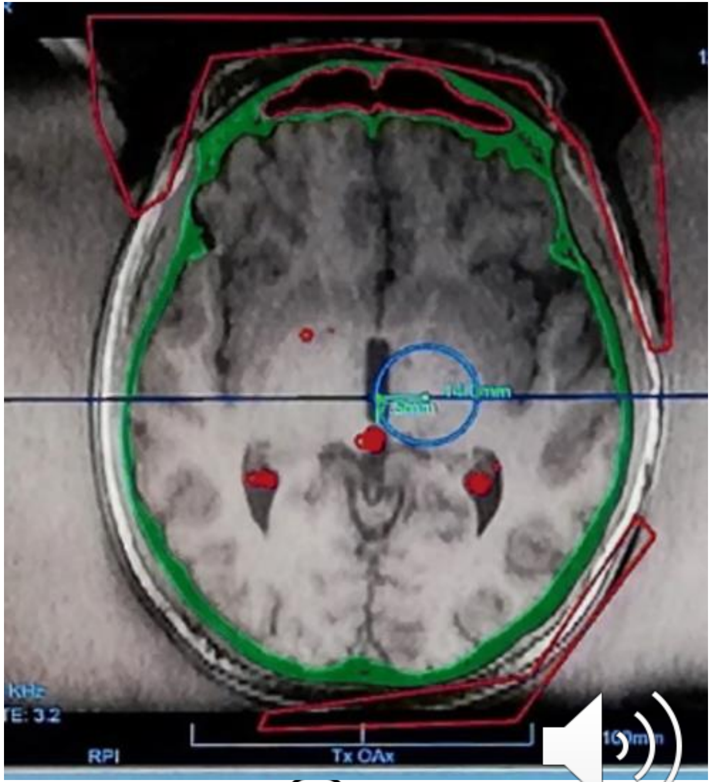
Planning Stage: Treatment Day

- Day-of-treatment MR images are registered to pre-treatment diagnostic CT and MR to align the planned target, no-pass zones
- Additional no-pass zones (folds in silicone membrane) are contoured
- Updated phase aberration correction is calculated
- Power of each element is set to normalize the intensity over the skull surface



[1] F. Bruno et al. La radiologia medica, 2020

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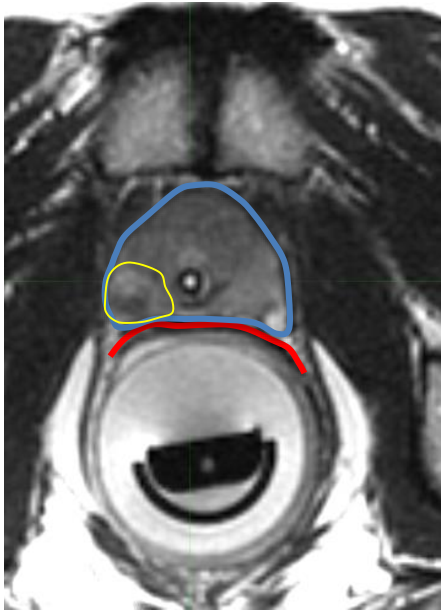
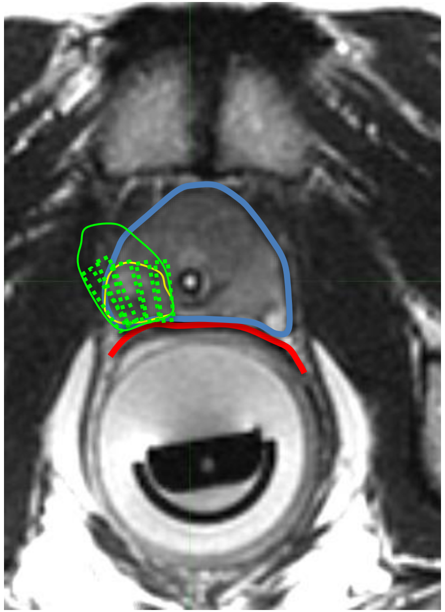
Planning Stage: Treatment Day

- T2-weighted imaging is used to contour prostate, tumor and rectal wall
- Gradient-echo imaging is used to detect air bubbles





Automated treatment plan generation:

For each sound emission (sonication) predicted position of focal zone.
And predicted extent of lethal thermal dose coverage.

Workflow of MRI-guided FUS

1

Quality Assurance
in a phantom

1

Patient Preparation
Foley catheter
Hair removal
Frame placement

2

Filling water
Device positioning

3

Planning Stage
Device loc, imaging, contouring

4

Verification Stage
Focal spot alignment
Temperature/Dose

Neurological biofeedback

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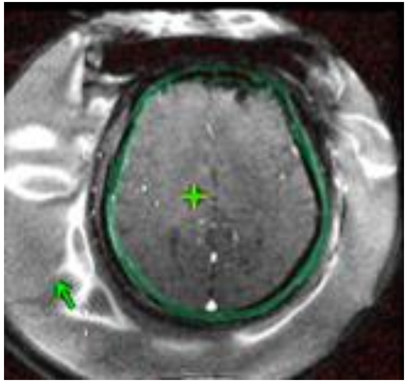
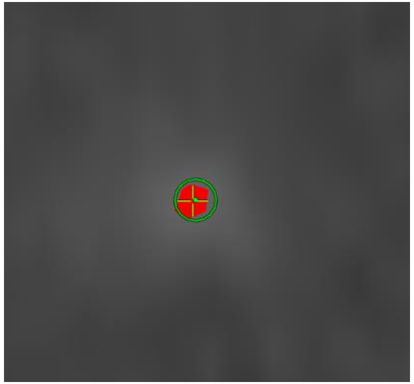
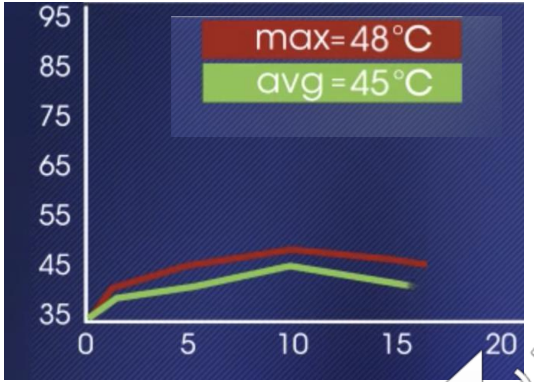
Verification Stage

- Low power ultrasound is applied, MR thermometry is used to visualize position of actual heating versus planned
- Adjustments are made to achieve good alignment
- Multiple imaging planes are used







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Neurological Biofeedback

- To refine the targeting, neurological state is monitored during delivery of sub-ablative thermal energy
- Correct targeting results in tremor suppression
- Off-target neuromodulation may elicit transient sensory changes and 'tingling' sensation in the contra-lateral fingers, hand, lips and tongue.

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Workflow of MRI-guided FUS

1 — **Quality Assurance**
in a phantom

1 — **Patient Preparation**
Foley catheter
Hair removal
Frame placement

2 — Filling water
Device positioning

3 — **Planning Stage**
Device loc, imaging, contouring

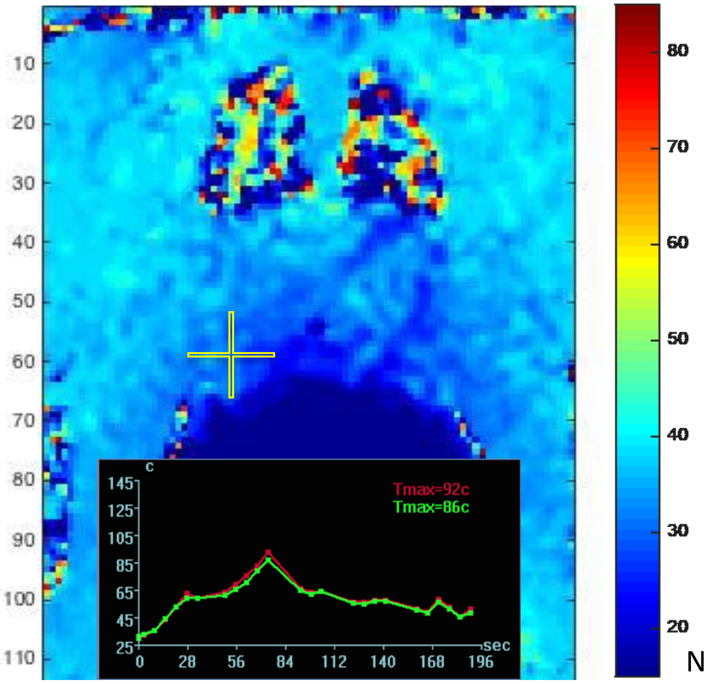
4 — **Verification Stage**
Focal spot alignment
Temperature/Dose

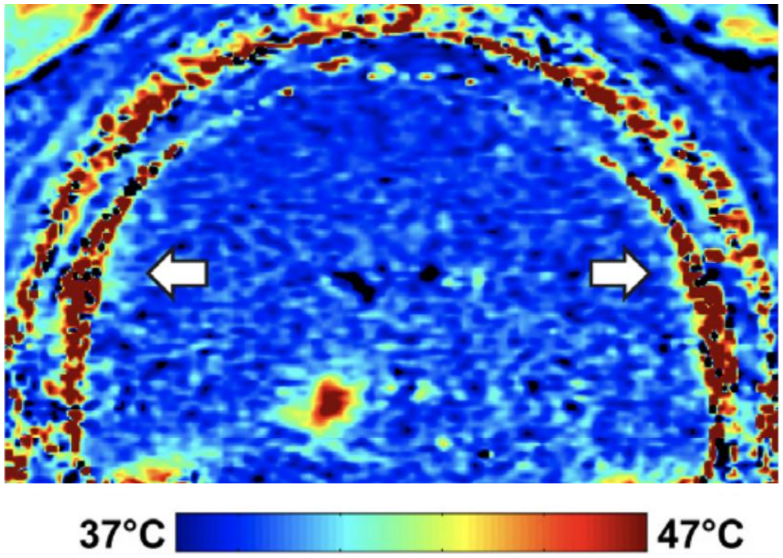
Neurological biofeedback

5 — **Treatment Stage**
Thermal ablation, thermometry

Treatment Stage: MR Thermometry

- Temperature rise is monitored during delivery of ultrasound energy.
- If unwanted heating is observed, sonication is aborted and adjusted.





N McDannold et al. Transactions of Med Img, 2020

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Workflow of MRI-guided FUS

1

Quality Assurance
in a phantom

1

Patient Preparation
Foley catheter
Hair removal
Frame placement

2

Filling water
Device positioning

3

Planning Stage
Device loc, imaging, contouring

4

Verification Stage
Focal spot alignment
Temperature/Dose

Neurological biofeedback

5

Treatment Stage
Thermal ablation, thermometry

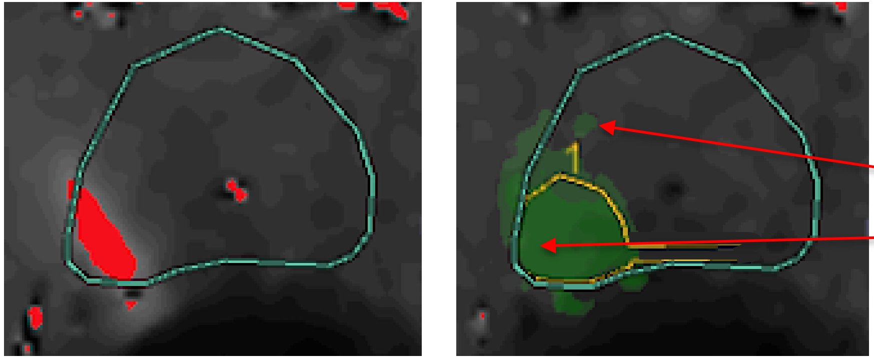
6

Assessment Stage
Multi-contrast imaging

Assessment Stage: Thermal Dose

- Lethal thermal dose coverage of the target is evaluated
- Additional treatment is delivered if needed

$$CEM_{43} = \sum_{t=0}^{t=final} R^{(43-T)} \Delta t \quad R = \begin{cases} 0.50, & T \geq 43^{\circ}\mathrm{C} \\ 0.25, & T < 43^{\circ}\mathrm{C} \end{cases}$$



$CEM_{43} = 240$

$CEM_{43} = 8000$

SA Sapareto, DC Dewey. Int J of Radiation Oncology, 1984

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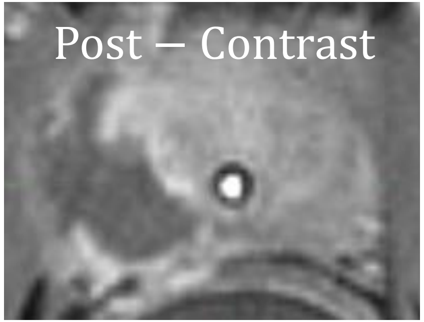
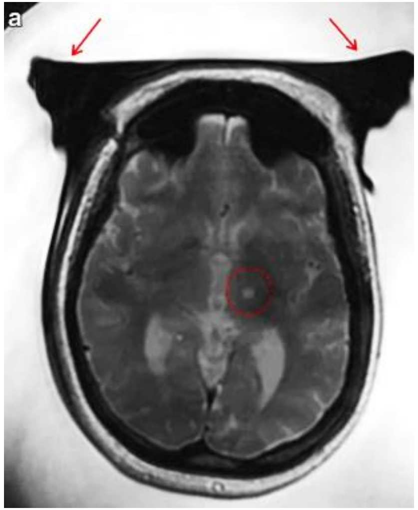
Assessment Stage: Imaging

- Non-contrast or contrast-enhanced imaging is performed
- Treatment effect visualization is confirmed

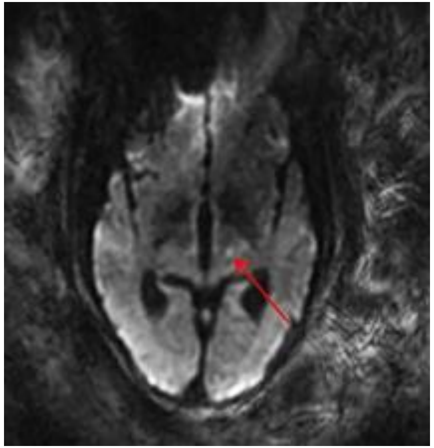


With head inside transducer

T2 – w

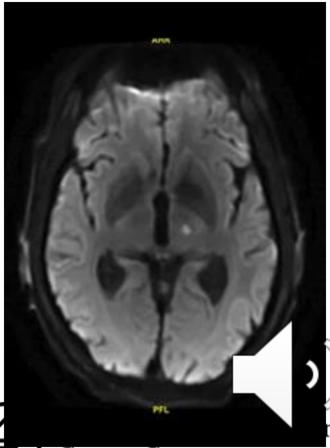


Diffusion



No transducer

Diffusion



LV Chazen et al. Clinical Neuroradiology, 2019

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Research and Development Opportunities

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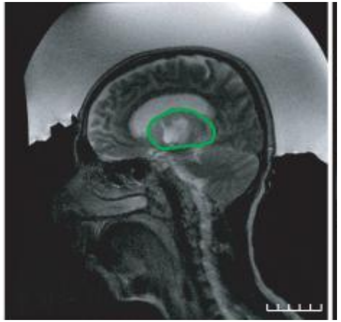
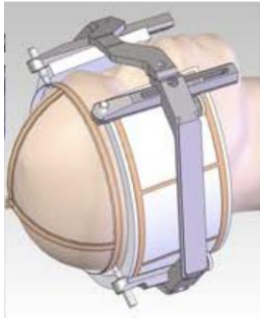
Itraprocedural Image Quality

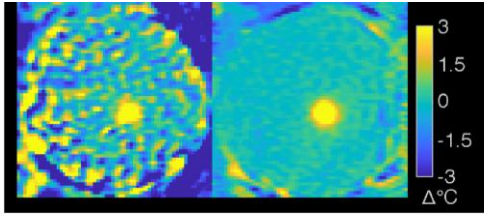
- Treatment hardware limits compatibility of RF coils and new tailored RF coils are needed





- Circulating cooling water introduces image artifacts and requires innovating imaging approaches

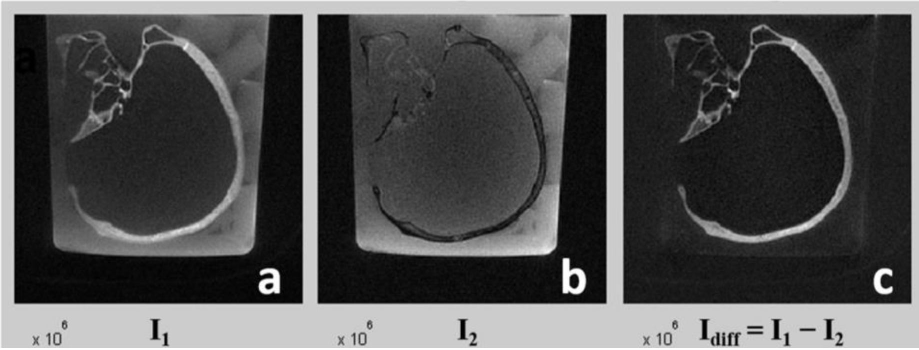
Full FOV Reduced FOV

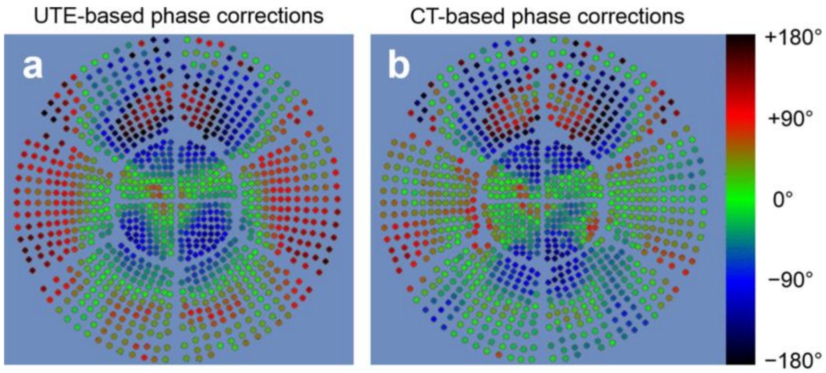


[1] N McDannold et al Neurosurgery, 2010. [2] E Minalga et al, ISMRM 2013, [3] W Grissom et al, MRM 2019

MRI-only Treatment Planning

- Accurate MRI visualization of skull bone, calcifications and air could eliminate the need for a pretreatment CT scan
- Ultra-short echo-time methods demonstrated potential





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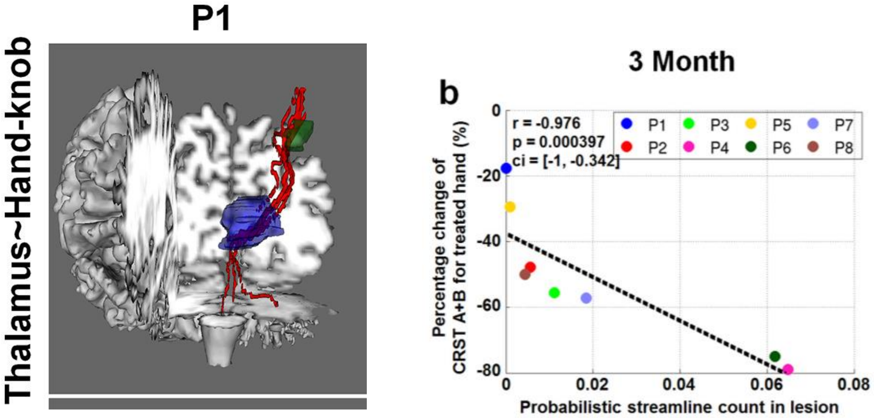
[1] GW Miller et al, Medical Physics, 2016

Advanced MRI to Improve Targeting

- Incorporation of Diffusion Tensor Imaging (which maps the white matter pathways) during treatment planning can improve targeting.



- Incorporation of Diffusion Weighted Imaging (which is used to diagnose prostate tumors) during treatment planning could improve targeting.

[1] Q Tian et al, Neuroimage: Clinical, 2018

MRI Thermometry to Monitor Skull Heating

- Skull heating leads to asymptomatic bone marrow damage in some patients[1]
- Methods to measure temperature in fat and bone can help monitor heating of the skull, leading to protocol optimization

- Methods to measure temperature in more than 1-3 slices can help monitor heating of brain tissue adjacent to the skull in the entire head[2]

3M post treatment 1

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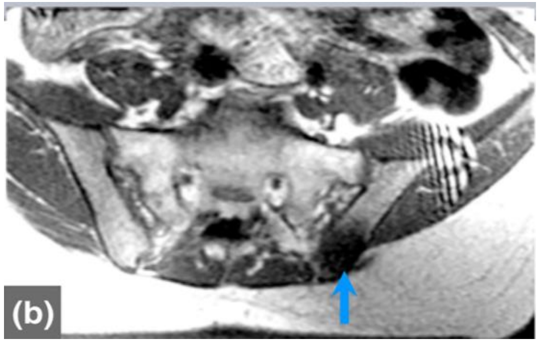
[1] N. McDannold et al. Transactions of Med Img, 2020, [2] SV Jonathan et al, MRM 2017

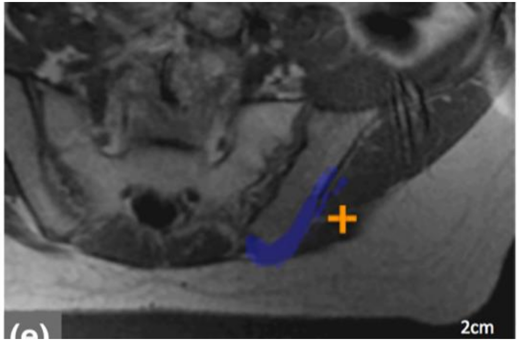
MRI Thermometry to Monitor Cooling

- Tissue near bone has longer cooling times
- Thermometry between ultrasound emissions could help monitor tissue cooling and enable optimization of cooling times and procedure time in general

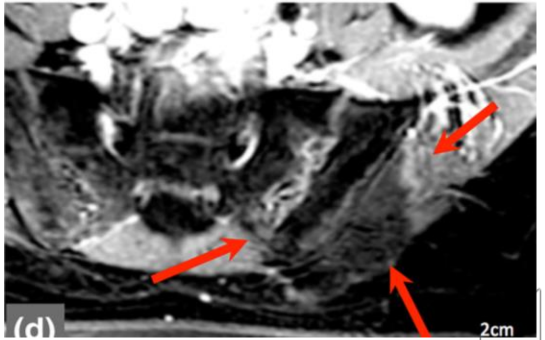
Pre Treatment



Lethal Thermal Dose



Post TreatmentAblation Zone



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[1] R Bitton et al. JMRI, 2016.[2] R Bitton et al, JMRI 2019

Summary

- Similar to radiation therapy, FUS delivers incisionless treatment but without ionizing radiation
- Similar to percutaneous laser or microwave ablation, FUS delivers heat to destroy tissue and can be monitored with MR thermometry, but it does not require insertion of electrodes or catheters through healthy tissue
- Development of MRI methods for FUS applications can reduce the risk of adverse effects, increase the efficacy of treatments and improve workflow
- MRI methodologies developed for FUS can be applicable to other MR-guided therapies

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Thank you!

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