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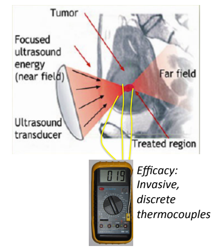
Advancing the role of MRI in high intensity focused ultrasound treatments

Allison Payne, Henrik Odeen, Dennis Parker

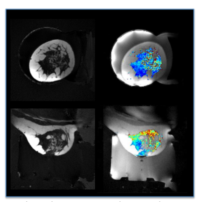
NON-INVASIVE THERAPEUTIC MODALITY

- HIFU non-invasively changes tissues at the cellular level
  - Thermal: tissue heating due to the absorption of ultrasound energy
  - Mechanical: cavitation
- Image guidance used for treatment planning, monitoring, and assessment should be non-invasive as well



MAGNETIC RESONANCE IMAGING

- Generally qualitative images weighted by tissue properties
- Quantitative information rapidly increasing
- Rapid advancement of MRI sequences and reconstructive techniques



Svedin et al., Mag Reson Med 2017, Early view

OBJECTIVE

Review current and developing MRI techniques that are used in MRI guided high intensity focused ultrasound therapies for treatment

- ***Planning***
- ***Monitoring***
- ***Assessment***

MRI in treatment planning

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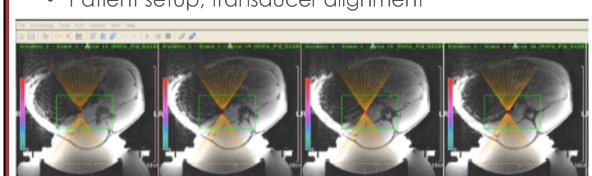
TREATMENT PLANNING

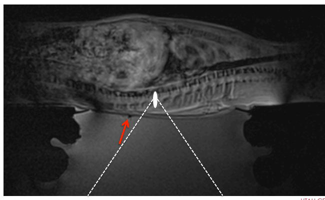
- Patient setup, transducer alignment



Thermoguide, Image Guided Therapy, Bordeaux France

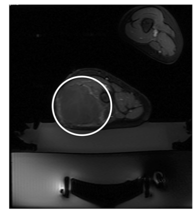
TREATMENT PLANNING

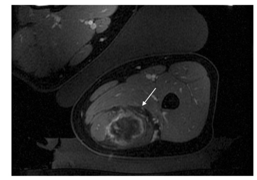
- Evaluation of acoustic window
  - Gas bubbles



TREATMENT PLANNING

- Evaluation of acoustic window
  - Far-field considerations



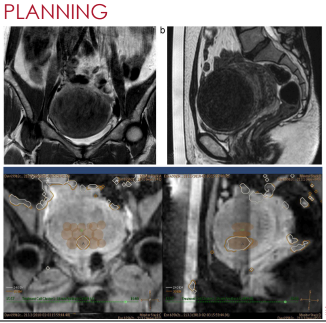


Bucknor et al., J Ther Ultrasound 2017 5:4

TREATMENT PLANNING

T2w

T1w

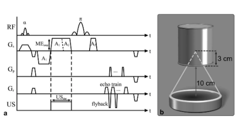


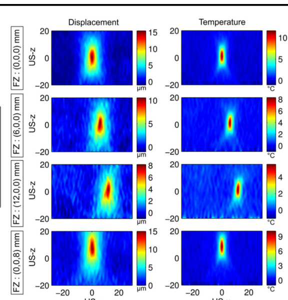
BEAM LOCALIZATION

- Test sonications are often performed to localize and calibrate the ultrasound beam
- Repeated multiple times to adjust positioning and align MR slices
- Potential unwanted thermal buildup
- Alternative is MR Acoustic Radiation Force Imaging

Ghanouni et al., Am J Roentgenol 2015, 205:150-159
McDannold et al., Med Phys 2008, 35(8):3748-58

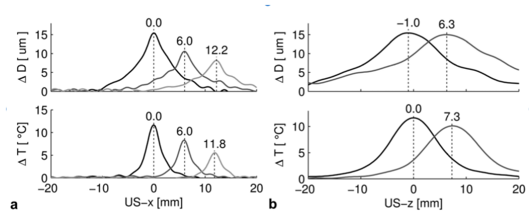
BEAM LOCALIZATION





de Bever et al., Mag Reson Med, 2016, 76:803-813

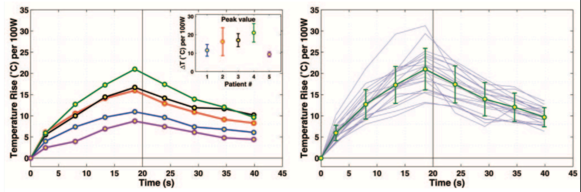
BEAM LOCALIZATION



de Bever et al., Mag Reson Med, 2016, 76:803-813

PATIENT-SPECIFIC TISSUE PROPERTIES

- Known intra- and inter-patient variability



McDannold et al., Radiology, 2006, 240(1)

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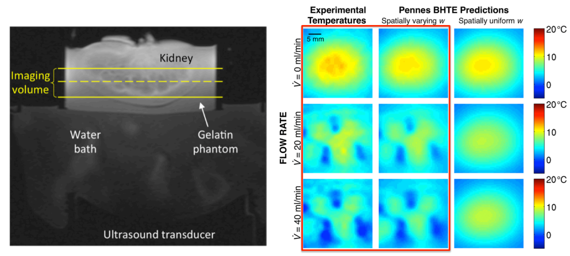
THERMAL TISSUE PROPERTIES



Dillon et al., NMR Biomed, 2015, 28:803-813

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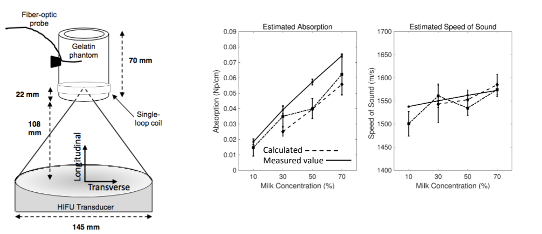
ACOUSTIC TISSUE PROPERTIES



Johnson et al., Int J Hyperthermia, 2015, 32(7)

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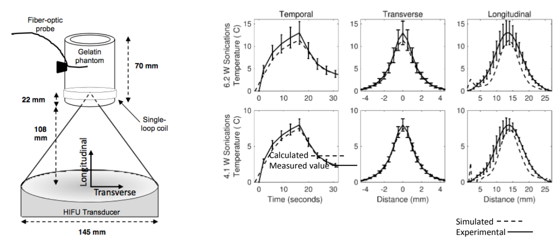
ACOUSTIC TISSUE PROPERTIES



Johnson et al., Int J Hyperthermia, 2015, 32(7)

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MRI treatment monitoring techniques

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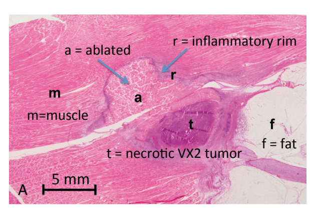
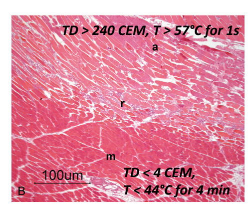
TYPICAL ABLATION REGIONS



21 days after treatment



3 days after treatment

Wijlemans et al., Inv Radiol, 2013

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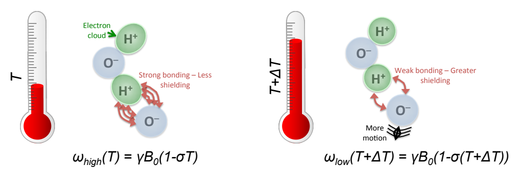
MR THERMOMETRY: PROTON RESONANCE FREQUENCY



$\omega_{high}(T) = \gamma B_0(1-\sigma T)$ $\omega_{low}(T+\Delta T) = \gamma B_0(1-\sigma(T+\Delta T))$

- Linear with the temperature range of interest
  - α=dω/dT
- Calculated from the phase image

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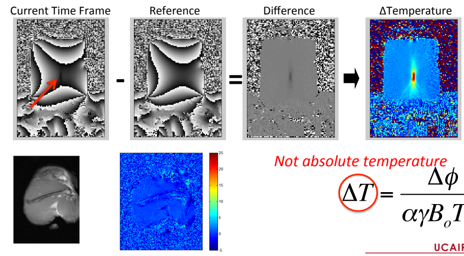
MR THERMOMETRY: PROTON RESONANCE FREQUENCY

The proton resonance frequency (PRF) decreases with temperature increase



Not absolute temperature

$$\Delta T = \frac{\Delta\phi}{\alpha\gamma B_o TE}$$

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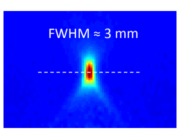
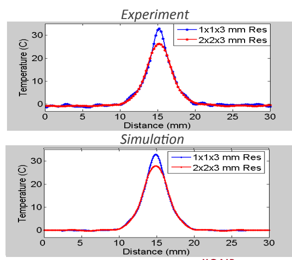
MRI THERMOMETRY: TECHNICAL SPECS

Spatial Resolution: **1 x 1 x 3 mm**
Temporal Resolution:
Volume Coverage:
Signal-to-Noise:





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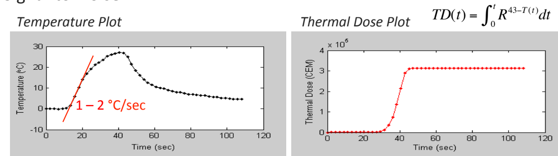
MRI THERMOMETRY: TECHNICAL SPECS

Spatial Resolution: 1 x 1 x 3 mm
Temporal Resolution: **2 sec/image***
Volume Coverage:
Signal-to-Noise:

Temperature Plot *Thermal Dose Plot* $TD(t) = \int_0^t R^{43-T(t)} dt$



*Specific for brain treatments

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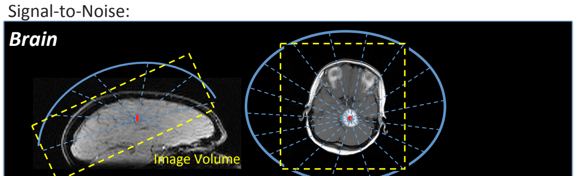
MRI THERMOMETRY: TECHNICAL SPECS

Spatial Resolution: 1 x 1 x 3 mm
Temporal Resolution: 2 seconds per image*
Volume Coverage: **256 x 162 x 72 mm***
Signal-to-Noise:



*Specific for brain treatments

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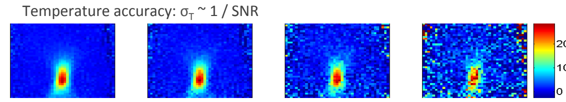
MRI THERMOMETRY: TECHNICAL SPECS

Spatial Resolution: 1 x 1 x 3 mm
Temporal Resolution: 2 seconds per image
Volume Coverage: 256 x 162 x 72 mm
Signal-to-Noise: **> 25***

Temperature accuracy: $\sigma_T \sim 1 / SNR$



SNR = 47 σ_T = 0.5°C
SNR = 26 σ_T = 0.7°C
SNR = 10 σ_T = 1.4°C
SNR = 5 σ_T = 2.5°C

*Specific for brain treatments

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VOLUMETRIC MR THERMOMETRY

- Interleaved 2D
  - MASTER (multiple adjacent slice thermometry with excitation refocusing) [1]
- 3D undersampled
  - Temporally constrained reconstruction[2]
  - Model predictive filtering[3]
  - Direct temperature estimation[4]
  - Hybrid radial-Cartesian[5]
- 3D reduced field of view
  - 2D spatially selective RF excitation
  - Parallel imaging + UNFOLD[6]

[1]Marx et al., IEEE Trans Med Imag, 2014 34:148-155
[2]Todd et al., Mag Reson Med, 2009 62:406-419
[3]Todd et al., Mag Reson Med, 2010 63:1269-1279
[4]Gaur et al., Mag Reson Med, 2015 73:1914-1925
[5]Svedin et al., Mag Reson Med, 2017 early view
[6]Mei et al., Mag Reson Med, 2011 66:112-122

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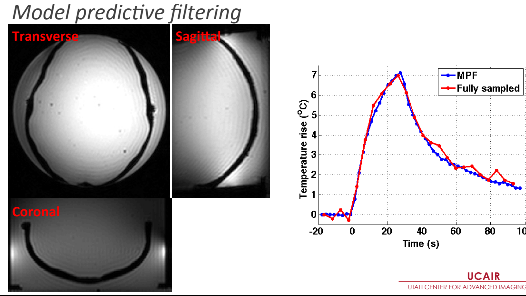
VOLUMETRIC MR THERMOMETRY

Model predictive filtering



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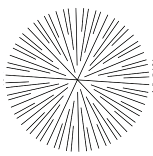
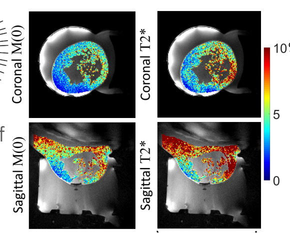
VOLUMETRIC MR THERMOMETRY

3D multi-echo stack-of-stars sequence





- Simultaneous acquisition of multiple parameters
  - ΔT, M(0), T2*, fat/water separation

Svedin et al., Mag Reson Med, 2017 early view

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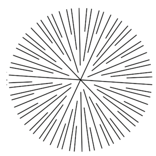
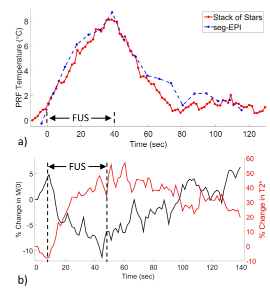
VOLUMETRIC MR THERMOMETRY

3D multi-echo stack-of-stars sequence



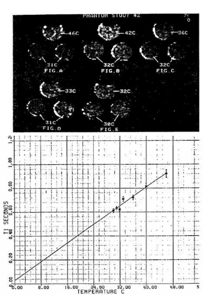


- Simultaneous acquisition of multiple parameters
  - ΔT, M(0), T2*, fat/water separation

Svedin et al., Mag Reson Med, 2017 early view

TEMPERATURE MONITORING IN FAT

- PRF inaccurate in tissues with high lipid content
  - Bone marrow, adipose tissues
  - Subcutaneous fat layers, near-field heating
- Relaxometry methods were first used to demonstrate MR temperature imaging techniques.



Parker D. et al., Med. Phys. 10(3):321-325, 1983

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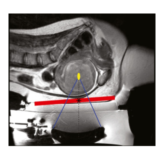
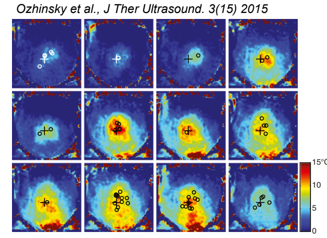
T2-BASED THERMOMETRY



Ozhinsky et al., J Ther Ultrasound. 3(15) 2015



- 3T, dual-echo TSE, 15 second acquisition
- Calibrated T2 changes to ex vivo tissue, normal subjects

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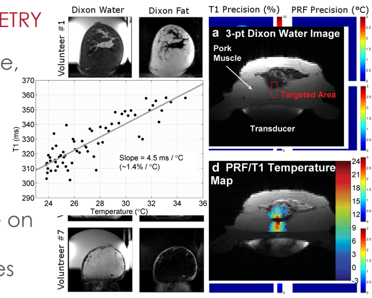
T1-BASED THERMOMETRY

- Variable flip-angle, spoiled GRE sequence
- Hybrid PRF/T1 thermometry measurements
- Calibration done on excised human breast fat samples



Todd et al., Mag Reson Med, 2013, 69:62-70

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MRI treatment assessment

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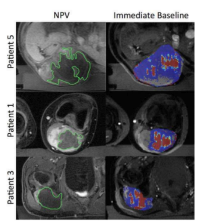
TREATMENT ASSESSMENT

- Thermal dose and non-perfused volume comparison
- 7-42% of the disagreement due to heat accrual errors



Bitton et al., JMRI 2016; 43:181-189

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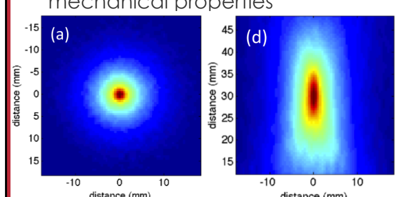
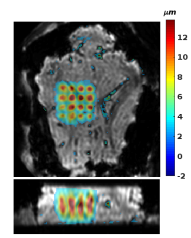
VOLUMETRIC MR THERMOMETRY

- Treatment endpoint evaluation by interrogating changes in tissue mechanical properties



Payne et al., Med Phys 2015, 42(2)



Odeen et al., ISMRM 2017, 1172

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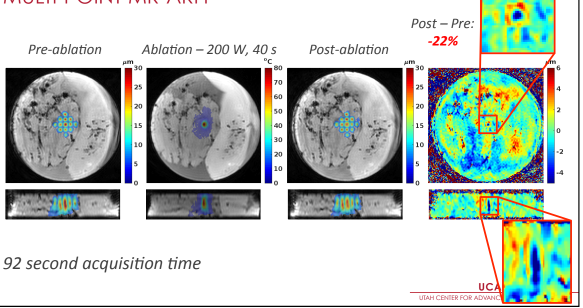
MULTI-POINT MR-ARFI



92 second acquisition time

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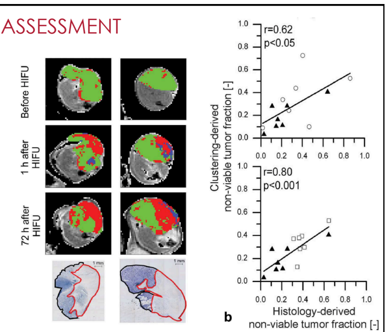
MULTI-PARAMETRIC ASSESSMENT

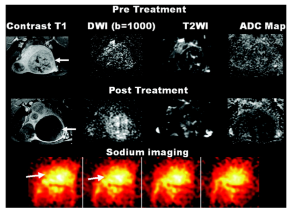
- Cluster analysis of T1, T2, ADC
- Determine tumor viability at multiple time points
- Most sensitive for delayed effects



Hectors et al., Mag Reson Med 2015, 75:302-317

ACUTE TREATMENT ASSESSMENT

- Often conflicting results that are tissue type dependent
- Acute MRI methods should be sensitive to ischemic effects
  - BOLD MRI, amide protein imaging, ^{23}Na



Hectors et al., Mag Reson Med 2015, 75:302-317
Jacobs et al., JMRI 2009 29:649-656

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SUMMARY

- MRI currently used extensively in HIFU treatments
- Planning
  - Visualization and evaluation
  - Patient-specific property estimation and implementation
- Monitoring
  - MR temperature imaing
  - Volumetric multiple parameter, quantitative monitoring measurements

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SUMMARY

- Assessment
  - Thermal dose, non-perfused volumes
  - Mechanical properties
  - Direct measurement of tissue pathology
- Adequate SNR critical for all areas
  - HIFU specific RF coil development

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