Advancing the role of MRI in high intensity focused ultrasound treatments

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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

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

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

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

Ghamoni et al., Am J Roentgenol 2015, 205:150-159

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)

THERMAL TISSUE PROPERTIES

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

ACOUSTIC TISSUE PROPERTIES

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

MRI treatment monitoring techniques

MRI treatment monitoring techniques

Wijlemans et al., Inv Radiol, 2013

TYPICAL ABLATION REGIONS

Wijlemans et al., Inv Radiol, 2013
MR THERMOMETRY: PROTON RESONANCE FREQUENCY

- Linear with the temperature range of interest
  \[ \alpha = \frac{d\omega}{dT} \]
- Calculated from the phase image

MR THERMOMETRY: PROTON RESONANCE FREQUENCY

MU(C)R

\[ \omega_{\text{low}}(T+\Delta T) = \gamma B_0 (1-\sigma (T+\Delta T)) \]

\[ \omega_{\text{high}}(T) = \gamma B_0 (1-\sigma T) \]

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: SNR = 47
*Specific for brain treatments

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: \( \sigma_T \approx 1/\text{SNR} \)

\[ \Delta T = \frac{\Delta \phi}{\alpha \gamma B_0 TE} \]

Not absolute temperature

\( T+\Delta T \)
\( T \)
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 multi-echo stack-of-stars sequence
- Simultaneous acquisition of multiple parameters
  - \(\Delta T\), \(M(0)\), \(T^2\), fat/water separation

VOLUMETRIC MR THERMOMETRY
- 3D reduced field of view
- 2D spatially selective RF excitation
- Parallel imaging + UNFOLD\(^6\)

Model predictive filtering

VOLUMETRIC MR THERMOMETRY
- Simultaneous acquisition of multiple parameters
  - \(\Delta T\), \(M(0)\), \(T^2\), fat/water separation

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.

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

*References:*
1. Marx et al., JET Trans Med Imag, 2014 34:248-255
6. Davatzikos et al., J Ther Ultrasound 3(18) 2015

*Images:*
- Payne et al., Advancing MRI in HIFU Treatments 2017 AAPM Meeting, Denver CO
- Svedin et al., Magn Reson Med, 2017 early view
Incomplete spoiling of the transverse magnetization, and

FIG. 3. Simulation results showing the effects of noise as a function of TR and TE.

The slope was found to be 4.5 ms/

Temperature dependence values reported by others

Due to heat perfused fat/water voxels.

Hybrid PRF/T1 thermometry measurements

Calibration done on excised human breast fat samples

Room temperature (21 °C). The temperature dependence calibration. The

T1-based thermometry

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

T1-based Thermometry

TREATMENT ASSESSMENT

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

VOLUMETRIC MR THERMOMETRY

• Treatment endpoint evaluation by interrogating changes in tissue mechanical properties

MULTI-POINT MR-ARFI

92 second acquisition time

MULTI-PARAMETRIC ASSESSMENT

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

THOMAS ET AL., MAG RECON MED. 2013, 49:62-70

BIBER ET AL., JMRI 2016, 43:282-289

PAYS ET AL., MED PHYS 2015, 42:302-317

PAYNE ET AL., MAG RECON MED. 2013, 49:62-70
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

SUMMARY

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

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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