Volumetric real-time magnetic resonance imaging in breast focused ultrasound treatments

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MAGNETIC RESONANCE IMAGING

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

OUTLINE

• Benefits of volumetric imaging
  – Breast MRgFUS
• Hardware and treatment protocol advancements
  – Integrated RF receive and positioning coils
  – Planning: MR-acoustic radiation force imaging
  – Monitoring: MR temperature imaging
  – Assessment: MR shear wave elastography
• Looking forward – voxel-based correlation to histology
TRADEOFFS OF VOLUMETRIC IMAGING

+ Allows for multi-plane reformatting
+ Interpolation in all directions
+ Complete and accurate planning, monitoring and assessment
  - Increased scan time
+ Higher SNR
  - Increased artifacts

HARDWARE: BREAST MRgFUS SYSTEM


HARDWARE: RADIOFREQUENCY COILS

Mroczka et al., MRM 2013, 69:295-302
Swati et al., MRM 2017, 77:2424-2430

Increased SNR allows for:
- Increased temporal resolution
- Increased spatial resolution
- Increased FOV
- $\sigma_r \sim 1/SNR$
HARDWARE: RADIOFREQUENCY COILS

- Transducer has 5 degrees of mechanical movement
- Positioning algorithm + positioning coils compute transducer targeting

PLANNING: ULTRASOUND BEAM TARGETING

- Beam localization often done with low power interrogation pulses
  - Ineffective in fat
- MR-acoustic radiation force imaging uses low duty cycle to measure tissue displacement
  - Can measure displacement in any tissue type
- 3D acquisition has benefit of contiguous slices improving the accuracy of localization
  - Imaging time similar to an averaged 2D acquisition
PLANNING: MR-Acoustic Radiation Force Imaging

- de Bever et al. MRM 76:803-816, 2016

MONITORING: MR Temperature Imaging (MRTI)

- The proton resonance frequency (PRF) decreases with temperature increase
- \[ \Delta T = \frac{\Delta \phi}{\alpha \gamma B_y \cdot TE} \]

- PRF inaccurate in tissues with high lipid content

MONITORING: BREAST MRTI

- PRF inaccurate in tissues with high lipid content
- Relaxometry methods were first used to demonstrate MR temperature imaging techniques
  - T2-based thermometry
  - T1-based thermometry


MONITORING: T1-BASED THERMOMETRY

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


MONITORING: RAPID, VOLUMETRIC SIMULTANEOUS PRF/T1 THERMOMETRY

- Multi-echo pseudo golden angle stack of stars acquisition
- K-space weighted image contrast (KWIC) reconstruction
- Single reference variable flip angle T1 calculations

Svedin et al., MRM 2019, 81: 3138-3152.
MONITORING: RAPID, VOLUMETRIC, SIMULTANEOUS PRF/T1 THERMOMETRY

Svedin et al., MRM 2019, 81: 3138-3152.

MONITORING: MRTI TECHNICAL SPECS

Spatial Resolution: 1 x 1 x 3 mm
Temporal Resolution: 2 sec/acquisition
Signal-to-Noise:

Todd et al., MRM 2011, 65:515-521

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Temperature Plot

Thermal Dose Plot

\[ TD(t) = \int_{0}^{t} R(\theta) d\theta \]
MONITORING: MRTI TECHNICAL SPECS

Spatial Resolution: \( 1 \times 1 \times 3 \) mm
Temporal Resolution: \( 2 \) sec/acquisition
Signal-to-Noise: \( > 25 \)

Temperature accuracy: \( \sigma_T \approx \frac{1}{\text{SNR}} \)

![Temperature Maps]

ASSESSMENT: ELASTOGRAPHY TECHNIQUES

- Tissue stiffness a known marker of disease
  - Malignant tumors > benign tumors > healthy tissue
- Ultrasound shear wave elastography + B-mode imaging increases diagnostic accuracy
  - Increases prediction of NACT pathological response
- MR elastography + MR imaging increases specificity
- Tissue stiffness changes with thermal treatments


MR IMAGING OF PROPAGATING SHEAR WAVE

- Modified 3D gradient echo EPI sequence
  - 4 motion encoding gradient lobes
- Synchronized, short (3 ms) acoustic radiation force pulses
- Position of initial acoustic radiation force pulse and propagating shear wave encoded in phase image

Hofstetter et al. MRM 2019;82:3153-3167
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ACOUSTIC RADIATION FORCE, TRANSIENT SHEAR WAVE ELASTOGRAPHY

ASSESSMENT: STIFFNESS CHANGE WITH MRgFUS

- 28 cm³ shear wave speed map acquired in 85 seconds
- Detected 10% reduction of speed due to MRgFUS ablation
LOOKING FORWARD: MRI TO HISTOLOGY CORRELATION

• Multi-parametric quantitative data can potentially determine tissue status
• Validation of metrics requires registration of MR images to histology is required

End-to-end processing pipeline

Surface renderings
Excised tissue

In-vivo MR 3D Histopathology
CONCLUSIONS

- Volumetric imaging can be used efficiently in MRgFUS treatments
- Proper hardware and protocols do not increase treatment times
- Multi-plane reformatting allows for more accessible data and treatment assessment
- Advanced, quantitative metrics are allowing for correlation to histological data

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