Simultaneous Acquisition of MR Acoustic Radiation Force Imaging and Proton Resonance Shift Thermometry with 3D Multi-Contrast Pulse Sequence

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PURPOSE: The 3D multi-contrast MRI pulse sequence presented here is a novel method for performing Acoustic Radiation Force Imaging (mcMR-ARFI) simultaneously with Proton Resonance Frequency (PRF) thermometry. This would be especially beneficial for MR guided Focused Ultrasound (MRgFUS) as a method for safely localizing the ultrasound focal spot in all three dimensions while simultaneously measuring the induced temperature rise. This 3D sequence builds on other 2D and 3D MR-ARFI techniques [1-5] and provides large volumetric coverage while also providing invaluable temperature monitoring for increased safety.

METHODS: A 3D Gradient Echo segmented EPI pulse sequence was modified to include a Motion Encoding Gradient (MEG), configurable to be either bipolar or tripolar, with multiple contrasts achieved by repeating the EPI readout multiple times during the TR interval. Optionally, the readout uses a 'flyback' scheme (figure 1). An ultrasound burst is synchronized with the second lobe of the MEG via an optical trigger emitted by the MR pulse sequence. The phase change for any given voxel is given by: $\Delta\varphi = \gamma B_0(\Delta T \cdot \alpha TE) + \gamma \int MEG_{amp}(t) \cdot \Delta D(t) \cdot dt$, where γ is the gyromagnetic ratio ($2\pi \cdot 42.577$ MHz/T), α is the constant 0.01 ppm/°C, ΔT is temperature rise in °C, MEG_{amp} is the MEG amplitude in mT/m, and ΔD is tissue placement in µm. To separate the phase change due to temperature versus displacement, the complex phase difference is taken between one image acquired with no ultrasound and a second with ultrasound, and, for each voxel, a linear least-squares fit, weighted by signal magnitude, is made to the measured phase at each contrast's echo time (figure 2). The slope of this line is the phase induced by a change in temperature while the intercept at t = 0 s is the phase induced due to tissue displacement. Experiments were performed in a gelatin phantom with a phased array transducer (256-channel, f = 1MHz, Image Guided Therapy, Pessac, France) and a Siemens Trio 3T MRI scanner (Erlangen, Germany). Simultaneous 3D ARFI and temperature maps were acquired in a 160x120x36 mm volume at 1.25x1.25x2 mm resolution and zero-fill-interpolated to 0.5x0.5x0.5 mm voxel spacing. TR = 160 ms, TE = [39, 72, 105, 139] ms, ETL = 7, BW = 752 Hz/px, FA = 60°, MEG_{amp} = 28 mT/m, MEG_{dur} = 10.2 ms, time/meas = 49 s, US power = 150 W, δ = 10 ms (6.25% duty cycle). The focal spot was electronically steered to (0, -5, 0) mm.

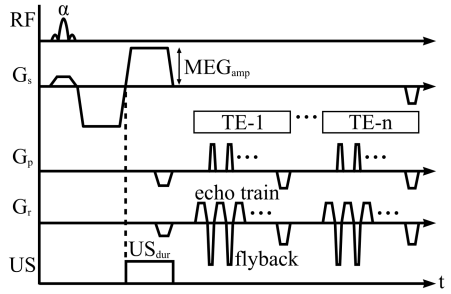

Figure 1: 3D Multi-Contrast ARFI + PRF Thermometry pulse sequence diagram

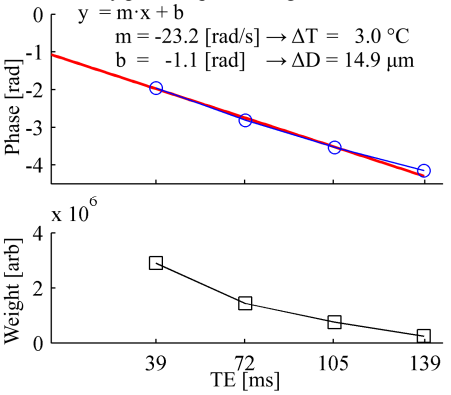

Figure 2: Example of separating phase change due to tissue displacement vs temperature rise, for a single voxel, by a weighted linear fit of the measured phase over each contrast.

RESULTS: The ARFI and temperature maps derived simultaneously from this new sequence are shown in Figure 3a-d. The peak ARFI displacement occurred at (13, -5, -5.5) mm while the peak temperature rise occurred at (13.5, -5, -2.5) mm, demonstrating spatial agreement within 0.5 mm in the plane perpendicular to the beam, and within 3 mm along the direction of beam propagation. Figure 3a and 3b show coronal slices (perpendicular to the beam) through maximum displacement (z = -5.5 mm) and maximum temperature rise (z = -2.5 mm) respectively. Figure 3c and 3d show sagittal slices (along the beam) at x = 13 mm, with the transducer to the left of the figure. Line plots through figure 3a and 3b along y = -5 mm (white arrow in 3a) are shown in figure 3e where we see the expected broader ARFI pattern and peak locations matching closely. Similarly, figure 3f shows the line through the sagittal slices at y = -5 mm (black arrow in 3d) which demonstrates how the displacement profile is shifted closer to the transducer than the temperature profile.

CONCLUSION: mcMR-ARFI measured displacement distribution in a large volume at high spatial resolution and the simultaneous temperature measurements revealed only 3.8 °C temperature rise. These features are beneficial for within-sample beam characterization and focusing, while providing temperature feedback to ensure safety with no time penalty. Temporal resolution could be improved by further sequence optimization and more aggressive choices of imaging parameters. By running the sequence in 2D mode, acquisition times of 1-2 s are possible if very fine temporal resolution is required.

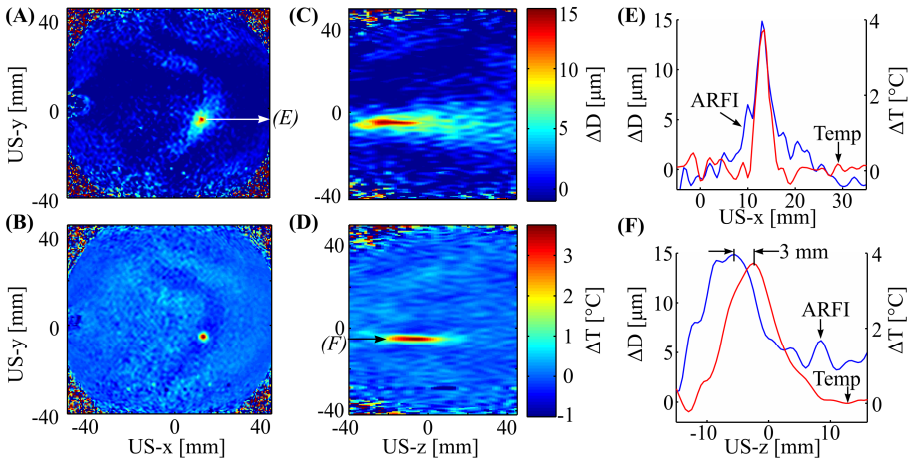

Figure 3: (A-B) Coronal slices (A) at maximum displacement (B) at maximum temperature rise. (C-D) Sagittal slices through the maximum ARFI/Temperature rise. (E) Line through slices shown in (A-B). (F) Line through slice shown in (E-F)

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