Rapid magnetic resonance imaging of displacement wave propagation introduced by a transient high intensity focused ultrasound using a gradient echo sequence

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Introduction: Several groups have demonstrated the feasibility of using magnetic resonance imaging to measure tissue displacement caused by acoustic radiation force (MR-ARFI). MR-ARFI methods encode the tissue displacement caused by a sharp impulse of ultrasound energy imparted in a small focal region using motion-sensitizing gradients. Kaye et al have proposed a reduced FOV, spin-echo based MR-ARFI technique to non-invasively visualize the focus of the high-intensity focused ultrasound (HIFU) without causing concomitant temperature elevation. In this paper, we describe a full field-of-view rapid gradient echo based technique suitable for MR-ARFI with high temporal resolution, and demonstrate the potential to measure the displacement wave speed in phantom experiments.

Methods: All experiments were performed on a 1.5T commercial MR scanner (Philips Healthcare) equipped with a modified table-top embedded with a 256 channel spherical shell HIFU transducer with five degrees of freedom and an integrated 3-element surface coil suitable for receiving MR signals (Sonalleve, Philips Healthcare). *MRI Data acquisition*: A phase contrast based gradient-echo pulse sequence was modified to include motion-sensitizing gradients between the excitation pulse and the spatial encoding gradients (Figure 1 and Figure 2). The pulse-sequence provided control over the duration, amplitude, timing, and the direction of the application of the motion-encoding gradients. Specific acquisition parameters were: acquired voxel size: 2.5 mm x 2.1 mm x 7 mm; field of view: 250 mm x 250 mm; TR/TE/flip angle = 29 ms/13 ms/12°; bandwidth: 110 Hz/pixel; scan time: 6.4 s. The duration of the symmetric bipolar motion encoding gradient was 4 ms, and the displacement encoding gradient was set to encode a maximum displacement of 135 nm. A coronal slice bisecting the plane of the HIFU focus was imaged, and the displacement encoding direction was set perpendicular to the slice-select direction.

HIFU- MRI scanner Interface: A programmable electronic signal from the scanner triggered the HIFU device to emit a 2 ms burst of ultrasound (1.2 MHz) at a power of 250 W at a prescribed focus location of 6.7 cm within a tissue mimicking gel phantom. The time delay (τ) between the application of the HIFU energy and the motion encoding gradient was altered to capture the propagation of the displacement wave.

Data Analysis: A phase difference image from the two sets of raw data (acquired with opposing polarities of displacement encoding gradient) was reconstructed after correcting for the background phase shift caused by system induced errors such as eddy currents. The conversion of the phase map to the displacement map was accomplished using the relationship: $\Delta\phi = 4\pi\gamma G\delta\Delta d$, here Δd is the displacement amplitude, $\Delta\phi$ is the measured phase change, γ is the gyro magnetic ratio, G is the encoding gradient strength, δ is the duration of the lobe of bipolar gradients.

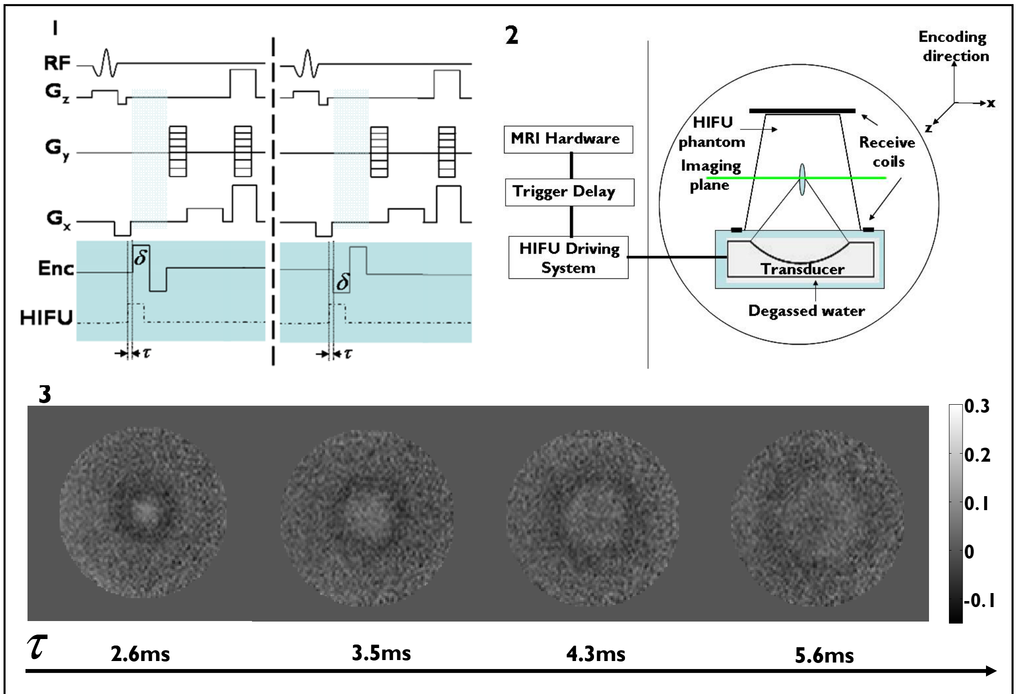

Figure 1: The MRI pulse sequence with displacement encoding gradients is shown on top left; Figure 2: The MR-ARFI system setup; Figure 3: The phase difference images at different τ demonstrate the propagation of the displacement wave in the medium.

Results: Displacement maps acquired in a gel phantom (diameter: 170mm in imaging plane) at progressively increasing delays between the mechanical excitation and displacement encoding gradients capture the spread of the propagating displacement wave (Figure 3). Despite the very low HIFU duty cycle (~ 7%) the HIFU focus can be clearly visualized as a region with a peak displacement of 4.2 nm. By measuring the distance the wave traveled between two delay time points, the wave velocity can be calculated and related to the mechanical properties of the medium.

Conclusions: The results from the current study demonstrate the feasibility to directly encode sub-micron displacements caused by the impulse transfer of HIFU energy using a gradient echo based MR-ARFI method very rapidly (< 7 s). This method might pave way for direct encoding of the displacement wave emanating from the HIFU focus. Our current ongoing work is to further shorten the acquisition time, and to relate the mechanical properties of the medium to the measured displacements.

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References:

1. McDannold N, et . al. Med Phys. 2008; 35: 3748-3758; 2. Huang Y, et al. Med Phys. 2009; 36: 2016-2020; 3. Chen J, et al.MRM. 2010; 63(4): 1050-1058;
4. Kaye E, et al. MRM. 2011; 65:738-743; 5. Wu T, et al. MRM. 2000; 43(1): 111-115; 6. Muthupillai R, et al. Science. 1995; 269(5232): 1854-1857.