Dynamic 3D MR Acoustic Radiation Force Imaging for Tissue Property Estimation

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PURPOSE: The dynamic response of tissue due to acoustic radiation force can provide valuable information about the state of tissue elastic properties, and assist with phase correction algorithms for beam focusing through aberrating tissue environments such breast and skull. A 3D technique that can measure dynamic tissue properties in a time efficient manner could benefit these algorithms and improve MRgFUS therapies.

METHODS: A 3D spin echo segmented EPI pulse sequence was modified to include an unbalanced bipolar Motion Encoding Gradient (MEG)[1], and an optional unipolar 'flyback' readout (**Fig 1**). The MR pulse sequence emits an optical trigger to activate a 12 ms ultrasound burst. Tissue displaced by the ultrasound during MEG_{A2} will accrue phase according to: $\Delta\varphi = \gamma \int MEGamp(t) \cdot \Delta D(t) \cdot dt$. Here, γ is the gyromagnetic ratio, MEGamp is the MEG amplitude, and ΔD is tissue displacement. Performing a complex subtraction between images without and with US on, the phase change can be measured and the displacement can be calculated by assuming constant displacement over the encoding interval. To measure the dynamic response of the tissue, a short (4 ms) duration was used for MEG_{A2} and multiple displacement measurements were made while varying the ultrasound trigger offset. This scheme is similar to that used by Kaye[2], and offsets ranged from 0 ms (MEG_{A2} and US begin synchronously) to −20 ms (US begins before MEG_{A2}) in 2 ms increments. A 20 ms gap was inserted between MEG_{A1} and MEG_{A2}, and a 12 ms gap was inserted between MEG_{A2} and the 180° pulse to allow sufficient time to vary the trigger offset and to allow the tissue to relax. Experiments were performed in a gelatin phantom with a phased array transducer (256-channel, 1MHz, Image Guided Therapy, Pessac, France) and a Siemens Trio 3T MRI scanner (Erlangen, Germany). Images were acquired in a 240x108x36 mm volume at 1.5x1.5x2 mm resolution and zero-fill-interpolated to 0.5x0.5x0.5 mm voxel spacing. TR/TE = 200/85 ms, ETL = 7, BW = 744 Hz/px, FA = 90°, MEGamp = 30 mT/m, time per displacement map = 147 s, US power = 110 W, δ = 12 ms. The focal spot remained at geometric focus. Tissue displacement was calculated for each trigger-offset, and the dynamic tissue motion was modeled as an exponential overdamped response[2]. The following parameters were estimated in 3D using a least-squared error fit to each voxel's dynamic tissue response: [1] steady-state displacement (Rise-A), [2] delay before rise, (Rise-Delay), [3] Rising time constant (τ-rise), and [4] Relaxing time constant (τ-fall).

RESULTS: At the center of the focus, a steady-state tissue displacement of 27 um, τ-rise of 4 ms and τ-fall of 5.3 ms were obtained (**Fig 2**). These values agree well with other estimates[2,4,5] which found τ-rise = 3-7 ms and τ-fall = 5-8 ms. At a distance of 10 mm from the focus, a Rise-Delay of 3.52 ms was observed which corresponds to an estimated shear wave velocity of 2.8 m/s. This agrees with estimates derived from modeling[6] the gelatin phantom. Parameter estimates are most accurate in the vicinity of the focus and could be improved by reducing the size of the MEG and obtaining more displacement maps. Time could be saved by reducing the field of view, but the time to acquire each 3D displacement measurement is similar to that of 2D techniques, which required extensive averaging.

CONCLUSION: A 3D technique for measuring the dynamic response of tissue due to acoustic radiation force was presented and successfully tested. This technique could provide more information to ultrasound phase aberration correction algorithms, which are used to more efficiently transfer ultrasound energy through the skull or through other inhomogeneous tissues environments such as the breast. It may also be possible to use modeling to estimate the force applied in 3D, which would make it possible to estimate additional elastic tissue properties.

REFERENCES: [1] J. de Bever *et al*, *ISMRM 2013,* **[2]** E. Kaye *et al*, *MRM* 69(3):724-733, 2013, **[3]** R. Souchon *et al, MRM 60(4):871-881.* **[4]** K. Nightingale *et al, J. Acoust. Soc. Am.* 110:625-634, 2001. **[5]** Y. Huang *et al, Med Phys* 36:2016-2020, 2009, **[6]** A. Payne *et al*, *ISMRM 2014*.

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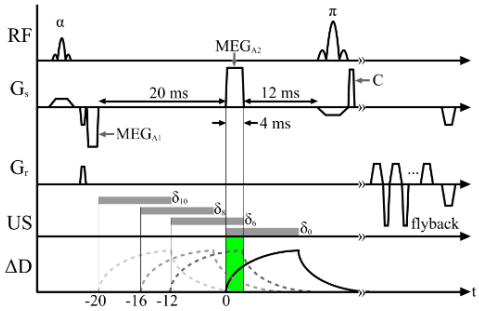

Figure 1: Dynamic 3D SE ARFI pulse sequence. Multiple snapshots of tissue displacement were acquired with varying delays between the US and motion encoding gradient.

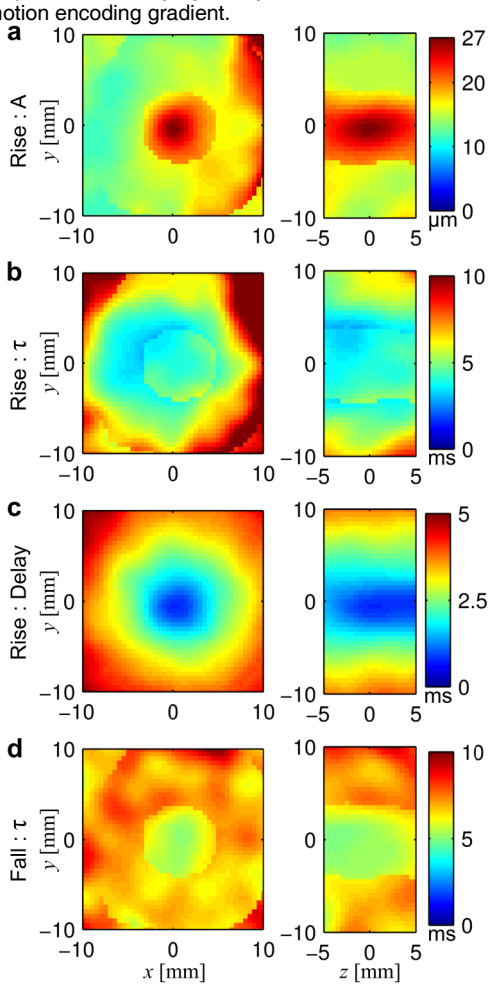

Figure 2: Orthogonal slices through 3D parameter maps derived from dynamic 3D ARFI tissue response measurement. **(a)** Steady-state tissue displacement, **(b)** Time constant of exponential displacement during rise, **(c)** Delay-offset before displacement begins relative to start of pulse, **(d)** Time constant of exponential tissue relaxation.