Non Invasive Estimation of Tissue Viscoelasticity from Broad-band Mechanical Excitation Using High Intensity Focused Ultrasound

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Introduction: MR elastography (MRE) is a non-invasive method to measure changes in tissue stiffness. A complete assessment of tissue visco-elastic properties is feasible with multi-frequency MRE. The scan time required for evaluating visoco-elastic property dispersion via multiple, temporally resolved, single frequency MRE is clinically prohibitive. Here we measure the displacement wave emanating from an impulse discharge (intrinsically broad band excitation) of acoustic radiation force (ARF) using High-Intensity Focused Ultrasound (HIFU). We propose a frequency domain based analysis to extract multi-frequency motion components to obtain tissue visco-elastic constants.

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 receive coils (Sonalleve™, Philips Healthcare).

MRI Data acquisition: A phase contrast based gradient-echo pulse sequence was modified to include motion encoding gradient (MEG) between the excitation pulse and the spatial encoding gradients. The pulse-sequence provided control over the duration, amplitude, timing, and the direction of the application of the MEG (Fig.1). Specific acquisition parameters were: acquired matrix: 256×64; field of view: 200×200mm^2; TR/TE/flip angle = 65ms/13ms/30°; bandwidth: 170 Hz/pixel; scan time: 8.3 s. The duration of the symmetric bipolar MEG was 4ms, and the MEG strength was set to 27mT/m. A coronal slice (5mm in thickness) bisecting the plane of the HIFU focus was imaged, and the MEG direction was set perpendicular to the slice-select direction (Fig.2).

HIFU- MRI scanner Interface: The scanner triggers the HIFU device to emit an impulse of 2ms (corresponding to duty cycle of 3%), 250W of ultrasound (1.2 MHz) focusing at 6.7 cm within a tissue mimicking gel phantom. A phase shift (τ) at 0.4ms intervals between the application of the HIFU impulse and MEG was used to capture the transient shear wave propagation (Figure 2).

Data Analysis: 1) A phase difference image from the two sets of raw data acquired with opposing polarities of MEG was reconstructed; 2) Fourier transformation of time-domain data and subsequent band-pass filtering of signal resulted in multiple single frequency images from the same data-set; 3) An inverse FT was performed on filtered frequency spectrum to capture displacement wave propagation at specific frequencies; 4) Radon Transform (RT) based method was used to estimate the velocity at specific frequency component (submitted as an separate abstract with this one) and yielded velocity dispersion; 5) Displacement wave attenuation at each filtered frequency (from step 2) was calculated to estimate frequency dependent tissue attenuation; 6) Viscoelasticity was estimated based on Rheological model of soft-tissue (Zener).

$\mu^* = \frac{\mu_1\mu_2+\omega\eta(\mu_1+\mu_2)\mathrm{i}}{\mu_2+\omega\eta\mathrm{i}}$, where μ_1 and μ_2 are shear modulus and η is shear viscosity. ω is the extracted mechanical motion frequency.

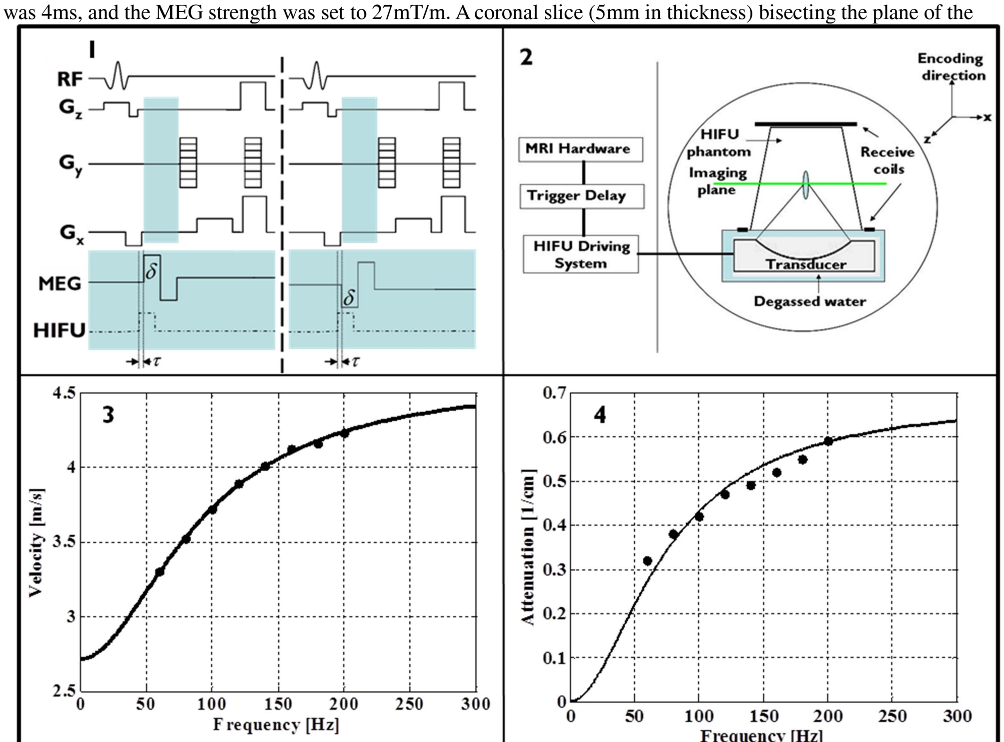

Fig.1: The MR-ARFI pulse sequence with MEG. Fig. 2. The MR-ARFI system set-up; Fig.3: Experimentally determined shear wave velocities at various frequencies (dots) were used to estimate the visco-elastic property of the medium by fitting the measured data to a Zener model (solid line); Fig 4. Experimentally determined shear wave attenuation at various frequencies (closed dots) is shown above. The solid line depicts the theoretically predicted attenuation dispersion based on the visco-elastic properties determined by velocity dispersion measurements (Fig. 3).

Results: The estimated shear modulus (μ_1 and μ_2) and shear viscosity (η) are: μ_1=7.37±0.47kPa, μ_2 = 13.68± 0.6kPa and η = 14.2±1.9Pa·s by fitting the measured frequency-dependent velocity values to a Zener model (r^2=0.99, Fig. 3). Using the estimated values of μ_1, μ_2 and η, from velocity dispersion measurements, attenuation dispersion curve was generated (solid line in Fig. 4).

Discussion and Conclusions: Displacements caused by broad-band motion generated by an impulse excitation can be encoded by a MEG with broad band frequency response. This opens up the possibility to estimate viscoelasticitic properties using a frequency domain analysis. The preliminary results from the tissue mimicking phantom demonstrate that: 1) Frequency domain analysis can be used to measure shear velocity dispersion; 2) Measured shear velocity dispersion can be used to understand and select suitable rheological models that can represent the viscoelastic behavior of the medium under consideration.

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