

Modulated Radiation Force of US as Shear Wave Source in Microscopic MRE

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INTRODUCTION

Microscopic magnetic resonance elastography (μ MRE) is a high resolution imaging technique for measuring the viscoelastic properties of small synthetic and biological samples. Taking MRE to the microscopic scale requires stronger static fields, stronger magnetic field gradients, higher performance RF coils, and more compact, higher frequency shear wave actuators. Prior work by our group [1] has been conducted at 11.74 T. A needle attached to a vibrating cantilever beam was placed in contact with the surface of the sample to generate shear waves up to 800 Hz. At higher frequencies, the excited shear waves attenuate within an extremely short distance such that only a very small region in the vicinity of the actuator can be studied due to inherent dynamic range limitations. In principle, modulated radiation force of ultrasound (MRFU) should be able to create a localized shear wave source within the test sample at a distance from the US transducer, thereby enabling μ MRE probing of the sample at very high frequencies (up to 5 kHz). Use of confocal and amplitude-modulated US transducers to create such a source within the working constraints of the μ MRE system is investigated. Figure 1 illustrates the geometry of MRFU prototypes (#1 and #2 dimensions given in caption) and the envisioned application of MRFU as a shear wave source within the constraints imposed by the small bore magnet (imaging diameter of ~ 1 cm). Figure 1 also includes a photograph of prototype #1.

THEORY

The predicted axisymmetric radiation force field in a dissipative medium created by a sinusoidally driven (at f_0) spherically-focused transducer with a curvature radius of R and disk radius of “ a ” can be found in Rudenko et al. (96) [2]. Taking the linear approximation and incorporating amplitude modulation at frequency $\Delta f/2 \ll f_0$ results in the following expression for the modulated (slowly time varying) component of the radiation force, where positions x and r are indicated in Figure 1:

$$F[x, r] = \alpha c_0^2 \left(\frac{p_0}{c_0 \rho_0} \right)^2 \frac{1}{f^2 |x|} \exp \left[-2\alpha x - \frac{2r^2}{a^2 f^2 |x|} \right] \frac{1}{2} \cos[2\pi \Delta f t] \quad f[x] = \sqrt{\left(1 - \frac{x}{R} \right)^2 + \frac{x^2}{x_{\text{diff}}^2}}, \quad x_{\text{diff}} = \frac{\pi f_0 a^2}{c_0}$$

Here, α , c_0 , and ρ_0 refer to the absorption coefficient, compression wave phase speed and density of the medium. The absorption coefficient and phase speed are taken at f_0 and can be related to viscoelastic constants, thermal conductivity and the ratio of specific heats. The term p_0 is the acoustic pressure generated within the medium right at the transducer surface and can be related to its normal velocity, which in turn can be related to the voltage applied to the transducer if it's piezoelectric material properties and resonant behavior are known. A similar expression for the axisymmetric modulated radiation force field can be developed for the confocal excitation configuration where the independent electrodes of the disk are driven at $f_1 = f_0 + \Delta f/2$ and $f_2 = f_0 - \Delta f/2$. For the case of homogenous mediums of agarose gels with $\Delta f = 0.5$ to 5 kHz and the geometry of prototypes #1 and #2, the stress field is calculated using the above equation for amplitude modulation, with a resulting form that is similar to those given in the reference [2]. The precise stress field amplitude for a given voltage input to the transducer cannot be predicted without knowing the effective quality “ Q ” factor of the transducer's resonant response, as well as its piezoelectric material properties. Taking typical property values and assuming a “ Q ” factor of 100 with 10 volt peak excitation, the predicted shear wave field is computationally predicted using finite element analysis (ANSYS 9.0). An example is shown in Fig. 2. This level of motion is above the signal-to-noise floor of the μ MRE system.

METHODS

At the time of submission of this summary, initial experimental tests on prototype #1 only with limited instrumentation have been performed. A simple experiment confirmed the transducer could generate a modulated radiation force. The transducer was placed on the surface of $\sim 0.5\%$ w agarose gel using US coupling gel, driven sinusoidally in the confocal arrangement at frequencies $f_1 = 10 \text{ MHz} + \Delta f/2$ and $f_2 = 10 \text{ MHz} - \Delta f/2$ at 10 volts pk-pk, where Δf ranged from 500 to 5000 Hz. A 26.5 milligram nominally flat drop of solder with a small piece of retroreflective tape facing away from the transducer was placed at the focal point, which was a free surface of the gel (opposite side from where the transducer was placed). A laser Doppler vibrometer (LDV, Polytec CLV-800, threshold sensitivity 0.5 $\mu\text{m/s}$, Tustin, CA) measured the motion of the solder droplet. Spectral analysis confirmed that a significant vibratory response was measurable at Δf throughout the frequency band of interest. This response ranged from peak displacement values of ~ 0.04 microns at 500 Hz down to ~ 1 angstrom at 5000 Hz. Elastography experiments are conducted using the transducers in the 11.74 T (500 MHz for protons) vertical bore magnet (Oxford Instruments, Oxford, UK) using a Bruker DRX 500 MHz Avance spectrometer (Bruker Instruments, Billerica, MA). Acoustic signals are applied with synchrony with the NMR pulse sequence. The RF saddle coil has a diameter of 10 mm and is used to acquire phase difference maps [1].

RESULTS

Shear wave images obtained for agarose gel phantoms of different concentrations using the confocal and amplitude-modulated configurations will be presented. Figure 3 shows a shear wave image through agarose gel phantom of a concentration 0.25% wt, with $\Delta f = 100$ Hz synchronized with 4 bipolar gradients in the phase encoding direction. Positive and negative wave fronts are evident.

DISCUSSION and CONCLUSION

Use of MRFU as a shear wave excitation source in μ MRE is feasible and enables higher shear wave frequencies with consequently, improved resolution in identifying material viscoelastic properties. This feasibility will be translated into practical capability as we continue to push the resolution limits of μ MRE to identify material properties relevant to pathology in biological tissues as well as for other applications, such as noninvasively monitoring the progress of tissue-engineered constructs.

REFERENCES: [1] Othman et al., Mag. Res. Med., 54:605-615;05. [2] Rudenko et al., J. Acous. Soc. Am. 99:2791-2798;96.

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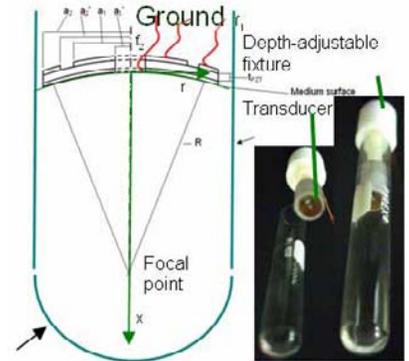


Fig. 1. Schematic of confocal arrangement. Prototype #1: $R = 9$ mm, $a_1 = 1.89$ mm, $a_1' = 0.5$, $a_2 = 3$ mm, $a_2' = 2.39$ mm. Prototype #2: $R = 15$ mm, $a_1 = 2.6$ mm, $a_1' = 0$, $a_2 = 4$ mm, $a_2' = 3.1$ mm. Both designed to resonate at 10 M, air-backed. For amplitude-modulated configuration, $f_0 = f_1 = f_2$ (back electrodes shorted together).

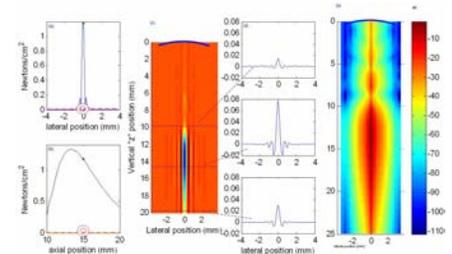


Fig. 2. Simulations of stress and wave field created by confocal MRFU transducer 2 with $\Delta f = 2$ kHz. (a,b) Radiation stress prediction on focal axis and plane for 10 v. pk-pk input to transducer. (c) Planar (coronal) view and (d) indicated line profiles within the plane of vertical vibratory motion in mm predicted by ANSYS 9.0 (axisymmetric analysis, plane42 elements, ~ 0.2 mm dimension). (e) Magnitude of motion in dB normalized to maximum value within planar coronal FOV.

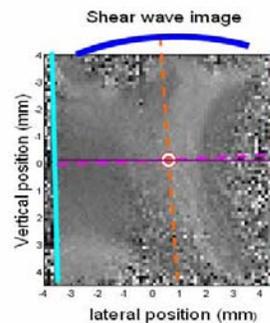


Fig. 3. Shear wave image produced by the prototype #1 with $\Delta f = 100$ Hz, confocal excitation. A modified spin-echo phase contrast pulse sequence was used to acquire the shear wave image. TR = 800 ms, in plane resolution = $133 \mu\text{m} \times 133 \mu\text{m}$, slice thickness = 0.5 mm, TE = 46 ms, NEX = 1, number of bipolar gradients = 4.