Frequency Dependent Mechanical Contrast : An Analytical Perspective of the High Frequency Mode Conversion Magnetic Resonance Elastography

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Introduction: High Frequency Mode Conversion technique is a novel Magnetic Resonance Elastography (MRE) technique that can detect stiff regions present in soft background regions (simulating stiff tumors in normal soft tissues) by using high frequency longitudinal waves to excite the sample of interest and imaging the mode converted shear waves that are present only in the stiff regions(1). The feasibility of applying this technique to real tissues has been demonstrated using an ex-vivo breast specimen (2, Fig 1). Conventional MRE experiments use mechanical wave frequencies in the range of 50 Hz - 300 Hz whereas in the preliminary set of high frequency mode conversion MRE experiments, mechanical waves of frequency 1000 Hz - 1500 Hz were used arbitrarily. The purpose of this work is to develop a theoretical model that can predict a critical frequency which defines the minimum wave frequency to be used to differentiate soft and stiff regions in High Frequency Mode Conversion MR Elastography and to test the model in some phantom materials with known material parameters.

Theory: The basic contrast mechanism of this technique is the differential attenuation of shear waves in stiff and soft materials. The wave attenuation increases and wave penetration decreases with increasing frequencies for all materials, but the attenuation will be lesser in stiff regions in comparison to the attenuation in soft regions. In the conventional MRE frequency range, the difference in attenuation will not suffice to be a contrast, whereas if very high frequency waves are used the attenuation will be too high, in both the regions, to be used to differentiate the two materials and there are some practical imaging limitations too. Thus it is desired to use a frequency just high enough to distinguish the tissues.

The amplitude of a shear wave propagating in an attenuating medium decreases exponentially due to energy dissipation and can be expressed as $e^{-\alpha r}$ where α is the attenuation factor and r is the distance in the direction of propagation. In a homogenous, isotropic visco-elastic medium, this attenuation factor is given by $\alpha^2 = (\rho\omega^2(\mu_0^2+\omega^2\eta^2)^{1/2}-\mu_0)/(2(\mu_0^2+\omega^2\eta^2))$ where ρ is the density of the medium, μ_0 is the true 'shear modulus', η is the viscosity and ω is the angular frequency (3 , 4). Voigt's visco-elastic model has been used in this work since it has been shown to fit better to real values in comparison to the competing models(5). Since the wave decays exponentially, mathematically, the amplitude will reach zero only at infinity. For practical purposes, it was assumed that if the wave amplitude reaches 1/100th of its original amplitude in a distance 5 mm, then the wave has almost completely attenuated and the frequency this occurs is referred to as the "Critical Frequency". This means that if a higher frequency wave is used, then shear waves created at surface would attenuate quickly and only those shear waves created at region boundaries would be present in the stiff regions.

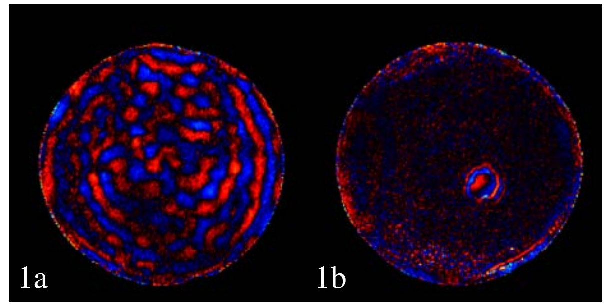
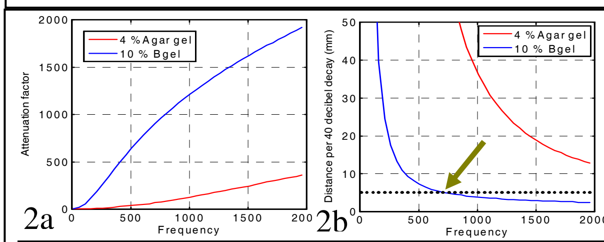


Fig 1. A single shear wave image of the ex-vivo breast specimen with 200 Hz waves induced in it. b. Here a mechanical wave of 1000 Hz was introduced and the presence of the stiff lesion can be easily detected



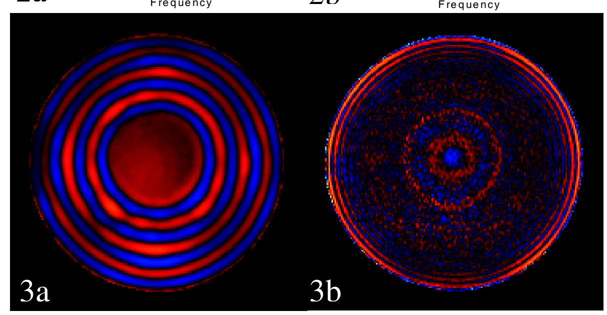


Fig 2. a. Attenuation factor vs. frequency relationship for both the Agar and Bovine gel. b. Graph showing how the distance required for 40 db attenuation changes with frequency for both the materials.

Fig 3. a. A single shear wave image of the phantom with 200 Hz waves. b. A single shear wave image of the phantom with a 750 Hz wave. Shear waves created at the surface has attenuated and the shear waves created at the boundary between the materials can still be seen in the inclusion.

Materials and Methods: A 1.5-T whole body scanner (GE Signa, Milwaukee, WI) was used in all the experiments. An ex vivo breast specimen with a focused ultrasound created stiff lesion was used to demonstrate the feasibility of this technique in real tissues. A cylindrical tissue simulating phantom of diameter 10 cm and height 10 cm was made up with 10 % bovine gel(B-gel – Shear stiffness approximately 3 KPa and shear viscosity approximately 1.35 Pa.s) around a cylindrical inclusion made up of 4 % Agar (Shear stiffness – approximately 120 KPa and shear viscosity 9.6 Pa.s). A tapping electromechanical driver with a resistance of 4 ohms was used to induce longitudinal waves in the sample (1).

Results and Discussion: Fig 1a shows a shear wave image of the ex vivo breast specimen, excited at a frequency 200 Hz. It is hard to detect the presence of the stiff lesion without any processing. But, in fig 1b, where the sample was excited at 1000 Hz , the shear waves are present only in the stiff region and it could be easily detected. Fig 2a shows how the attenuation factor α changes with increasing frequency: the attenuation factor (and hence the attenuation) is very high for the soft B-gel than the stiff agar gel. Fig 2b shows a graph that relates the distance required for a 40 db (corresponding to 1/100th amplitude reduction) decay of the wave to the frequency of excitation. It can be seen that it requires lesser distance for the B-gel to achieve the same attenuation as that of the agar. The graph also shows a black dotted line at 5 mm which meets the B-gel(blue) curve at the critical frequency 720 Hz (shown by the arrow mark). According to the assumptions stated above, if longitudinal waves at a frequency larger than 720 Hz are induced in the sample, the shear waves created at the surface would attenuate quickly and shear waves created at material boundaries would be seen in the stiff regions. Thus using a frequency above this critical frequency, stiff regions could be detected easily. The red curve crosses the 5mm threshold at about 4800 Hz (data not shown), which sets an upper limit for the frequency to be used, however at these very high frequencies one have to be wary of the voxel to wavelength ratio also. Fig 3a and 3b show a single wave image of the phantom with the mechanical waves at a frequency of 200 Hz and 750 Hz (which is above the critical frequency) respectively, and the circular stiff region can be easily detected in fig 3b.

Conclusion: From these results it is concluded that the theoretical model can predict a critical frequency to help choosing a frequency that has to be used in the high frequency mode conversion technique to detect a stiff region in a soft background using MR Elastography.

References:

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