Shear wave scattering in MR elastography: Detection of elasticity interfaces

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Introduction: MR elastography (MRE) is a MRI-based method to quantitatively estimate in vivo elasticities. The elastic information is typically acquired in terms of phase images, which display the shear wave propagation through the examined tissue [1]. Such wave patterns can be inverted to obtain spatially resolve elastograms.
Problem: Elastograms in MRE often suffer from limited spatial resolution, which can be due to the damping of the shear wave amplitudes, the low phase-to-noise-ratio, large shear wavelengths, and/or artifacts at amplitude nulls.
Objective: A method is introduced to analyze scattering of shear waves at interfaces between tissues of different elasticities. This new approach in MRE allows the localization of tissue boundaries without inversion of wave images. The method is applied to transient MR elastography [2] on agarose and in vivo human brain.

Theory: An incident shear wave $u_i(x,t)$ shall be scattered at an elastic interface at $x = 0$ between compartment A and B with shear wave speeds c_A and c_B, respectively and equal densities. At this position, $u_i(x,t)$ can be written as $u_i(t) = a_i \exp(-I\omega t)$ assuming harmonic excitation with frequency ω and amplitude a_i. The reflected and transmitted waves $u_r(t)$ and $u_t(t)$ (at $x = 0$) are correspondingly given to $u_i(t)$ but with the unknown amplitudes a_r and a_t. These amplitudes can be derived using the conservation principles of momentum ($a_i + a_r = a_t$) and energy ($c_A a_i^2 = c_A a_r^2 + c_B a_t^2$):

$$a_r = \frac{c_B - c_A}{c_B + c_A};\quad a_t = \frac{2c_A}{c_B + c_A}, \qquad (1)$$

with $a_i = 1$ for simplicity. From (eq.1) follows that the wave amplitude decreases with transition to stiffer material and increases when the wave is entering softer tissue. Additionally, the conservation of momentum requires a continuous wave function, which yields distinct amplitude changes dependent on the phase ωt. This results differently scaled real and imaginary parts of $u_t(t)$.

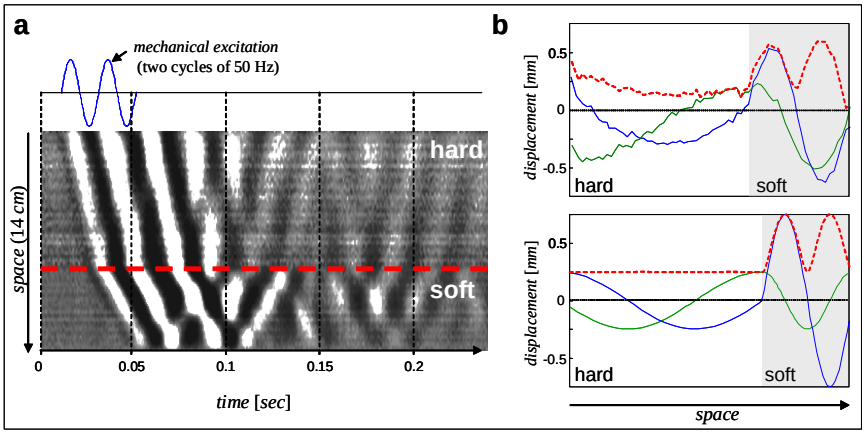

Fig.1a: Experimental shear wave scattering of a wave profile $u(x,t)$ at an elastic interface (at $x = 8.4$ cm) in Agarose. The hard and soft compartments display elasticities of 70 and 7.7 kPa, respectively. **b, first row:** $\hat{u}(x)$, i.e. 50 Hz component of the t-FT of $u(x,t)$. green, blue and red (dashed) display the imaginary part, real part and magnitudes of $\hat{u}(x)$. **b, second row:** analytical wave function that fits to the experimental observation ($c_A / c_B = 3$).

Methods: A transient MRE experiment was designed for observing the propagation of finite shear wave pulses through soft material. The examined tissue was mechanically excited by 2 cycles of 50Hz shear vibration. The traveling waves were repeatedly captured with incremented trigger delay between wave generator and MR sequence. For MRE image acquisition a modified EPI sequence [3] was used incorporating two cycles of 100 Hz motion encoding gradients (1.5 T Siemens Sonata). Two experiments were performed on i) a phantom material consisting of 2 compartments of 1.5% (upper part) and 0.5% (lower part) agarose and ii) a volunteer's brain using bite-bar actuation. The resulting time resolved series of wave images have been analyzed by extraction of 1D-wave profiles ($u(x,t)$) at different spatial locations. To estimate signal amplitudes these profiles were temporally Fourier transformed and chopped at the 50 Hz spectral component ($\hat{u}(x)$).

Results: Fig. 1 demonstrates the agreement between theoretical model and experiment. Two findings are visible: i) the shear wave amplitude is increased about the factor of 3 at the hard / soft boundary in agarose and ii) the amplitude elevation is shared between real and imaginary part of the wave, i.e. the magnitude of the wave image is no longer constant. The peak amplitude of the wave magnitudes equals $2a_t$ (eq.1). a_t was derived from $c_A = 8.3$ m/s and $c_B = 2.8$ m/s with $1.5a_i$. Fig. 2 shows shear wave scattering in the brain. 1D wave profiles in vertical and horizontal directions show incident waves that penetrate the brain from the outer boundaries. At specific positions these waves become scattered. The drop of their amplitudes indicates the transition from soft to stiffer material. From this decrease the ratio of wave speeds c_{soft} / c_{hard} of 0.7 was derived. This value agrees to the wave speeds, which were derived from phase gradients: $c_{soft} = 4 \pm 0.5$m/s and $c_{hard} = 5.5 \pm 0.5$ m/s. Fig. 2c demonstrates that the positions of wave scattering coincide well with the approximate tissue interfaces between gray and white matter.
Discussion and Conclusion: Transient MRE experiments on agarose and living brain tissue demonstrated the feasibility of the new scatter analysis for detecting elastic interfaces. It was shown that scattering of shear waves sensitively indicates elasticity changes in tissue. A difference of shear wave speeds of only 1.5 m/s yields clear wave scattering in the brain. Thus, the boundaries of gray and white matter could be detected on a biomechanical scale. In future experiments the tolerances of the determined interface positions could be further refined towards a biomechanical detection of pathological lesions.

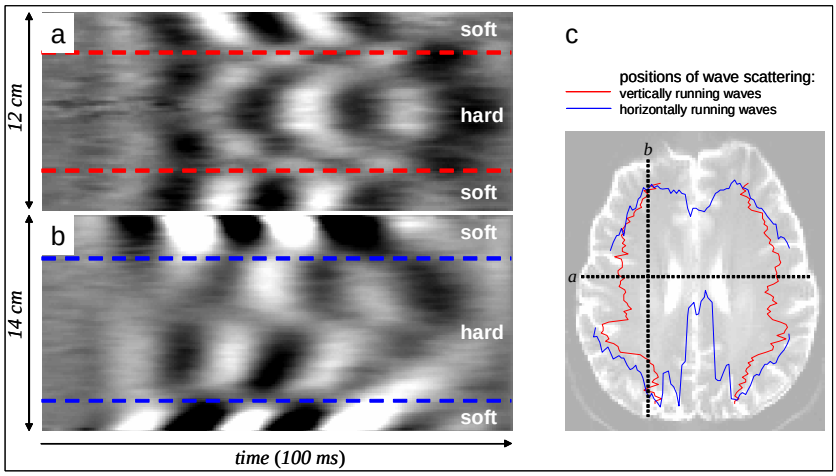

Fig. 2: in vivo MRE experiments on the brain. The volunteer's head was mechanically driven by a bit-bar actuator with 2 cycles of 50 Hz. **a, b:** exemplary wave propagation of horizontal and vertical wave profiles at positions shown in c. It is visible that the shear waves are scattered at interfaces of different elasticities (demarcated as dashed lines). **c:** positions of shear wave scattering derived from single wave profiles along vertical and horizontal directions. At the positions where the profiles cross only one type of tissue, no shear wave scattering was observed.

References: [1] Muthupillai R et al, Science 1995; 269: 1854-1857; [2] McCracken PJ et al, ISMRM 2002: 34; [3] Braun J et al, ISMRM 2002: 2597