Magnetic Resonance Elastography of cysts and fluid filled cavities

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Target audience: Physicians and scientists interested in high resolution elastography.

Background: MRE measures viscoelastic constants of soft tissues for an improved diagnosis of hepatic fibrosis , cardiac dysfunction or neurological disorders (1). Recently, MRE was used for the characterization of tumors (2-4) indicating the potential of MRE to provide spatially resolved maps of viscoelastic properties. Today, MRE can differentiate small lesions based on their stiffness or softness compared to surrounding healthy tissue. However, in tissue with fluid filled cavities, the obtained elastograms are biased due to effects of the lesion's geometry on the refracted wave field resulting in an overestimation of stiffness in cysts or other regularly shaped cavities.

Purpose: To demonstrate and analyze the effect of in vivo fluid filled cavities on high resolution MRE.

Methods: To illustrate the effect of cysts in MRE, an agarose phantom was built with an embedded water filled spherical balloon. The phantom was investigated by multifrequency MRE (MMRE) based on 4 harmonic drive frequencies (30, 40, 50 and 60 Hz). To further illustrate the effect of cysts and fluid filled cavities in vivo, the brain of a patient with cystic glioblastoma and the uterus of a volunteer with a uterine cyst were scanned by MMRE at 7 drive frequencies (30, 35 to 60 Hz). The same protocol was applied to the filled bladder of a volunteer. Image resolution was identical in all MMRE experiments (2x2x2 mm^3). Data processing was performed by direct inversion of the magnitude Helmholtz equation based on the solution for the magnitude of the complex shear modulus $|G^*|=\rho\Sigma_i\Sigma_j\ \omega_j^2|C_i|/\ \Sigma_i\Sigma_j|\Delta C_i|$. Here, C_i represents the ith-curl component of the wave field, ω_j is the jth-angular drive frequency and ρ represents the material's density. This solution is similar to the method proposed in (5), however, without the Laplacian (Δ)-weigthed sum originating from the least-squares solution. Simulations of cylindrical cavity waves have been performed in two dimensions ($z = 0$) by solving the scalar wave equation in cylindrical coordinates (r, θ, z) with the boundary condition for the field at cavity radius $r = r_0$: $u_z(r_0, \theta)=J_n(k\cdot r)\exp(I\cdot n\cdot\theta)$ with n = 0,1,2,.. and J_n, the Bessel function of the first kind. The integer variable n ensures that a continuous wave oscillates around the cavity's circumference. The wave number k refers to the intrinsic material's property of the cavity fluid, which is assumed to be viscous according to $G^* = I\cdot\eta\cdot\omega$ with viscosity parameter η.

Results: Fig.1 demonstrates the appearance of ideal cavity waves induced by oscillations of the edge (out the plane) with integer n. Direct inversion produces elastograms dependent on n, i.e. the number of standing waves on the edge of the cavity determines the apparent material property inside the cavity. In all simulated cases, the apparent viscoelasticity |G*| was much higher (> 10 kPa) than expected from the model material properties. This effect was reproduced in a phantom and in vivo (Fig.2). All experimental |G*| images illustrate the severe overestimation of viscoelasticity regarding the balloon, the bladder and cysts that all contained aqueous solutions of low viscosity and no shear elasticity. Unlike in cavities with regularly shaped boundaries, the ventricles in the brain as well as necrotic tumor tissue as seen in Fig.2 (yellow arrow) appear dark in |G*| maps indicating the importance of oscillating boundary conditions with integer n.

Discussion: We have demonstrated that in vivo cysts are source of parameter overestimation in MRE. We attributed this effect to regular geometrical boundary conditions causing interference between matrix properties, cavity size and oscillation frequency. As such the refracted field inside the cavity can be considered as a resonance with wavelengths dependent on cavity diameter rather than material's properties such as fluid viscosity or cavity pressure. This phenomenon has been observed in vivo only in virtually spherical structures like cysts or the bladder allowing us to differentiate e.g. necrotic tissue from cysts by MMRE as illustrated in Fig.2.

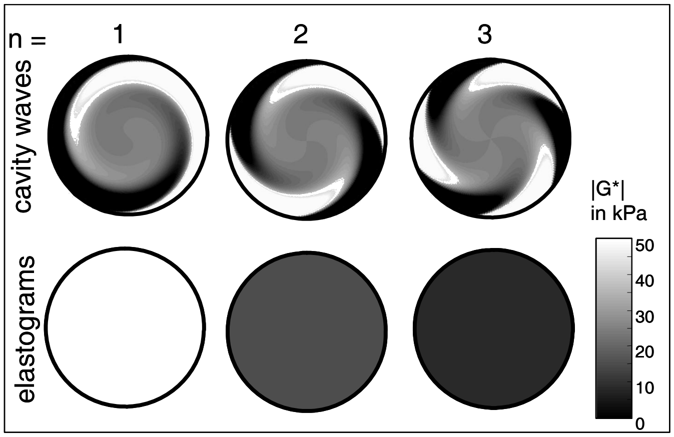

Fig.1: Simulation of waves emanating from a cylindrical boundary at 60 Hz harmonic frequency with integer number of waves (n) along the circumference (cavity diameter 2 cm).

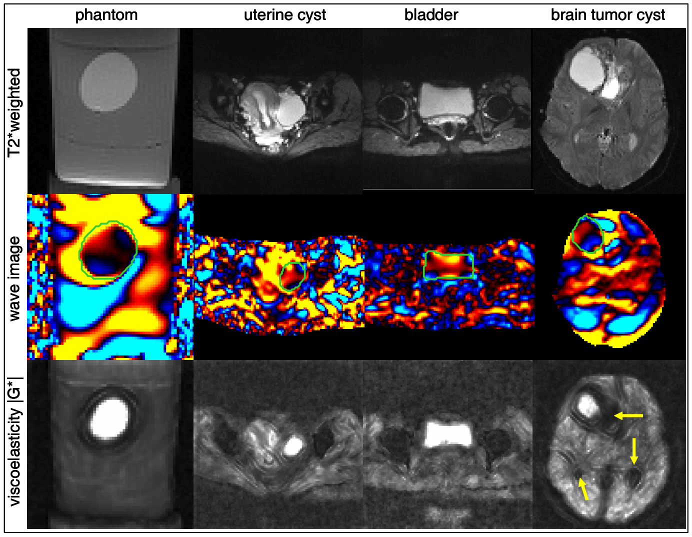

Fig.2: Experimental situations in MMRE where fluid filled cavities appear to be stiffer than surrounding tissue. The arrows in the brain demarcate fluid-filled spaces (necrotic tissue, ventricles) which are not biased by overestimated stiffness values. Scaling of |G*| was from 0 to 8, 4, 4, and 3.5 kPa from left to right.

Conclusion: This study presents the first analysis of high resolution MRE in cysts using numerical simulations, phantom data and in vivo data acquired in the abdomen and the brain. Our results indicate severe overestimation of viscoelasticity in spherically shaped cysts unlike other fluid filled parts of the tissue such as ventricles or necrotic tissue. We attribute this effect to resonances in oscillating cavities with regular interfaces matching the frequency range of MRE.

Literature: (1) Venkatesh et al. J Magn Reson Imaging 2013;37:544-555. (2) Garteiser et al. Eur Radiol 2012;22:2169-2177. (3) Murphy et al. Journal of neurosurgery 2013; 18:643-8. (4) Simon et al. The New Journal of Physics 2013;15:085024. (5) Guo et al. PloS one 2013;8:e71807.