Wide dynamic range MR elastography of liver

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Introduction: The dynamics of the complex shear modulus of biological tissue is determined by rigidity and connectivity of cells. Thus, measuring the frequency dispersion of G^* of an organ can provide a macroscopic parameter which is related to the mechanical microstructure and therewith to the state of health of tissue. Magnetic Resonance Elastography (MRE) is capable of determining G^* in vivo [1]. Therefore shear waves are excited and measured by motion-sensitive sequences. Multifrequency MRE has been proposed for measuring the dynamics of G^* in liver, muscle and brain in vivo [2,3].
Problem: Structure information about the mechanical network of tissue is accessible by fitting the dispersion relation of G^* in a wide dynamic range. The dynamic range of MRE is intrinsically limited e.g. due to constraints in spatial resolution, in encoding-gradient power and wave inversion artifacts. For these reasons MRE investigations of biological samples have been limited to a frequency range below 2.5 octaves [4,5].
Objective: Wide-dynamic range MRE is performed on tissue samples of bovine liver using a 1.5T human MRI system and a 7T animal scanner. The dynamics of G^* is measured over more than 4.5 octaves (25 Hz–600 Hz) and analyzed employing the springpot model [3].

Methods: Two cylindrical plastic containers (diameter/length [mm]: 28/100 and 140/200) were filled with bovine liver chopped from the same tissue specimen. Gradient-echo based MRE techniques were implemented on a 1.5T Sonata scanner (Siemens, Germany) and on a 7T Pharmascan 70/16 scanner (Bruker Biospin, Germany) for investigations of the larger and smaller samples, respectively. In the following, the two set-ups are referred to as low and high mechanical excitation frequency MRE. In both set-ups the container was placed inside the scanner with its symmetry axis being parallel to the scanner axis. Shear waves were introduced into the liver tissue by vibrating the container around an axis parallel to the left-right direction. Vibrations of 25 Hz - 150 Hz were applied in 12.5 Hz-increments in low mechanical excitation frequency MRE and of 100 Hz, 125 Hz, 150 Hz, 175 Hz, 200 Hz, 300 Hz, 400 Hz, 500 Hz and 600 Hz in high mechanical excitation frequency MRE. Steady-state conditions were achieved by 400 ms pre-oscillations prior to the start of the motion encoding gradient (MEG). A central, transversal image slice was chosen with a direction of motion encoding through the image plane. The frequency of the MEG was matched to the mechanical excitation. In all examinations 16 time-resolved phase-difference images $\phi(x,y,t)$ with a 128x128 matrix size were acquired at room temperature (17°C–19°C). Further acquisition parameters in the low (high) mechanical excitation frequency MRE experiments were: FoV = 192 (40) mm; MEG cycles = 1-3 (1-6); MEG amplitude = 15-30 (285) mT/m; flip angle = 25° (30°); TR = 200-250 (135) ms; TE = 17-45 (16) ms. Fourier-transforming and scaling of $\phi(x,y,t)$ resulted in complex shear wave images $U(x,y,f)$. $G^*(x,y,f)$ was calculated from $U(x,y,f)$ by 2D-inversion of the Helmholtz equation followed by spatially averaging within the region of interest. Finally, the independent parameters α and μ of the springpot model were deduced by fitting the combined experimental data of both MRI systems with $G_S^* = \mu^{1-\alpha}(i2\pi f\eta)^{\alpha}$ assuming a viscosity of $\eta = 7.4$ Pa s according to [6].

Results: Examples of $U(x,y,f)$ in low and high mechanical excitation frequency MRE are displayed in figure 1. It is well visible that the wavelengths are shorter at higher frequencies and that the amplitudes decrease towards the center of the samples. Wave inversion yielded the experimental data shown in figure 2. The excellent agreement of both storage modulus (G') and loss modulus (G'') measured in both systems is particularly perceptible within the common frequency range between 100 and 150 Hz. The fit of the springpot model reveals a power low behavior of G^* with $\mu = 2.94$ kPa and $\alpha = 0.32$.

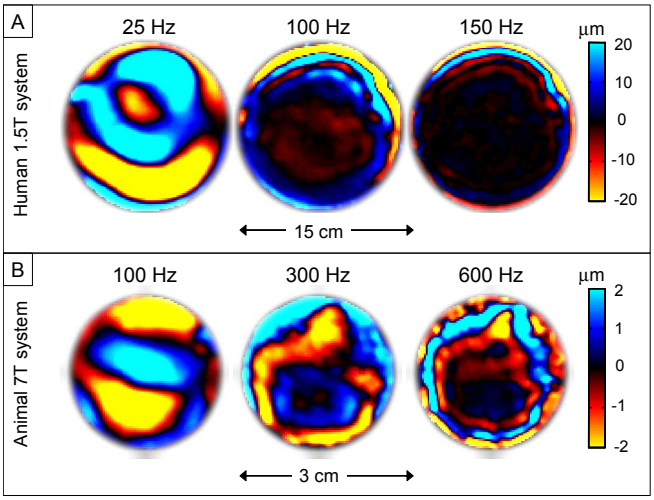

Figure 1: MRE examinations on ex vivo bovine liver using a 1.5T human scanner (A) and a 7T animal scanner (B). Complex wave images (real part) are illustrated for the lowest frequency (left), a central frequency (middle) and highest excitation frequency (right). Please note, the color values have to be scaled by factors of 1/2 and 1/5 in order to match the 100-Hz and 150-Hz images to the color bars.

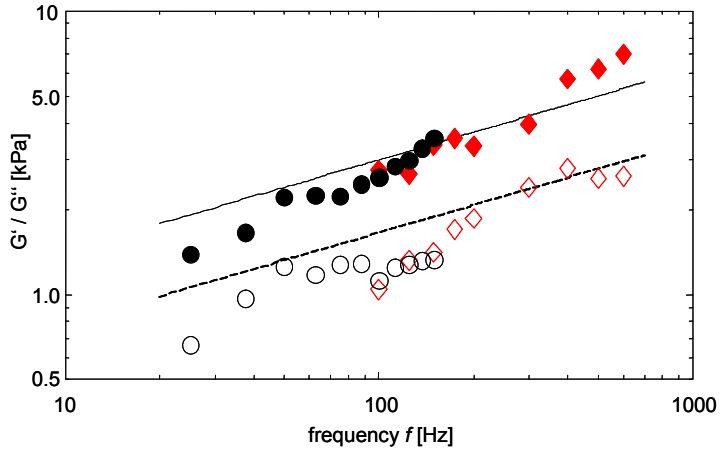

Figure 2: The storage modulus G' (full symbols) and the loss modulus G'' (open symbols) are displayed with the dispersion relations according to the springpot model as a solid line (G') and as a dashed line (G''). The lines were fitted using the viscoelastic parameters $\mu = 2.94$ kPa and $\alpha = 0.32$. Circles and diamonds correspond to values which were derived in low and high mechanical excitation frequency MRE respectively. Note, both fit lines are not independent but represent a combination of the two-parameter fit to G' and G''.

Discussion and Conclusion: Our study presents for the first time viscoelastic parameters of liver based on 4.5 octaves of shear-wave frequencies. We found an excellent agreement of the viscoelastic behavior of ex vivo bovine liver tissue determined in a low field human MRI scanner and in a high field animal scanner. Our results demonstrate that the springpot model is very well suited to characterize the mechanical behavior of liver tissue. The observed power-law behavior of liver indicates that the mechanical microstructure of the tissue is hierarchical scaled towards the macroscopic extension of the investigated specimen. Thus, further in vivo studies of human liver may be based on the springpot model [7]. In summary, we have shown that wide dynamic range MRE can provide valuable data of the mechanical constitution of biological tissue which supports current effort of in vivo MRE of liver.

References: [1] Muthupillai et al., Science 269, 1854-1857 (1995); [2] Klatt et al., Phys Med Biol 52, 7281-7294 (2007); [3] Sack et al., Neuroimage 46, 652-657 (2009); [4] Kruse et al., Phys Med Biol 45, 1579-1590 (2000); [5] Larrat et al., ISMRM 15, 1255 (2007); [6] Asbach et al., MRM 60, 373-379 (2008); [7] Klatt et al., Roefo 180, 1104-1109 (2008).