In vivo MR elastography of liver: Comparison to oscillatory rheometer studies of tissue specimen

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Introduction: Magnetic Resonance Elastography (MRE) is capable to measure the mechanical properties of living tissue by externally introduced shear vibrations and phase contrast MRI [1]. In multifrequency MRE the complex shear modulus $G^*(\omega)$ of biological tissue is measured at various mechanical vibration frequencies simultaneously. Viscoelastic tissue parameters can then be calculated by fitting $G^*(\omega)$ to the dispersion relations of rheological models [2].

Problem: In previous studies various rheological models have been proposed to analyze the viscoelastic behavior of liver tissue [2-9]. However, no comparison of MRE data to standard rheometer tests was performed.

Objective: In this study $G^*(\omega)$ is measured in ex vivo bovine liver in the frequency range 2.5 Hz – 70 Hz using an oscillatory rheometer device. The resulting dispersion relations are compared to those acquired by multifrequency MRE of in vivo human liver.

Methods: Using multifrequency MRE the complex modulus of in vivo human liver was determined for five healthy male volunteers (mean age: 35.6 ± 8.3 a) at mechanical frequencies of 25 Hz, 37.5 Hz, 50 Hz and 62.5 Hz. Each subject was examined four times. The experimental set-up and the data processing have been described in detail elsewhere [2]. In ex vivo tests fresh bovine liver was frozen and cut into six cylindrical geometries with a diameter of 50 mm and uniform thickness. The thickness varied for each specimen between 0.9 and 2.4 mm. The experiments were performed with an oscillatory rheometer device (MCR 301, Anton Paar, Austria) at a temperature of 1°C. Applying a deformation of 0.3% strain $G^*(\omega)$ was determined in the frequency range 2.5 Hz – 70 Hz. In both, the ex vivo and the in vivo measurements a density of 1000 kg/m^3 was assumed and viscoelastic parameters according to the springpot model (η set to 1 Pa s) were calculated by minimizing χ [2, 3].

Results: In general, higher values for the real part G' and for the imaginary part G'' of the complex modulus are obtained in ex vivo bovine liver compared to in vivo human liver (see fig. 1). In the ex vivo measurements G'' shows a powerlaw behavior $\sim\omega^{\alpha}$ over the entire experimental frequency range resulting in an excellent linear fit to G'' with a slope (logarithmic scale) α''=0.40 in figure 1. A similar value is measured for G' with α'=0.41. However, a deviation from powerlaw behavior is found at frequencies above 50 Hz. In the limited frequency range of MRE experiments the dispersion of G^* is well approximated by a powerlaw. The experimental tolerance in follow-up experiments is in the same order for both rheometer and MRE experiments. The modulus dispersion given by the two-parameter springpot model fits to the experimental data with viscoelastic constants μ=6.5 kPa and α=0.28 in bovine liver, and μ=3.7 kPa and α=0.22 in human liver.

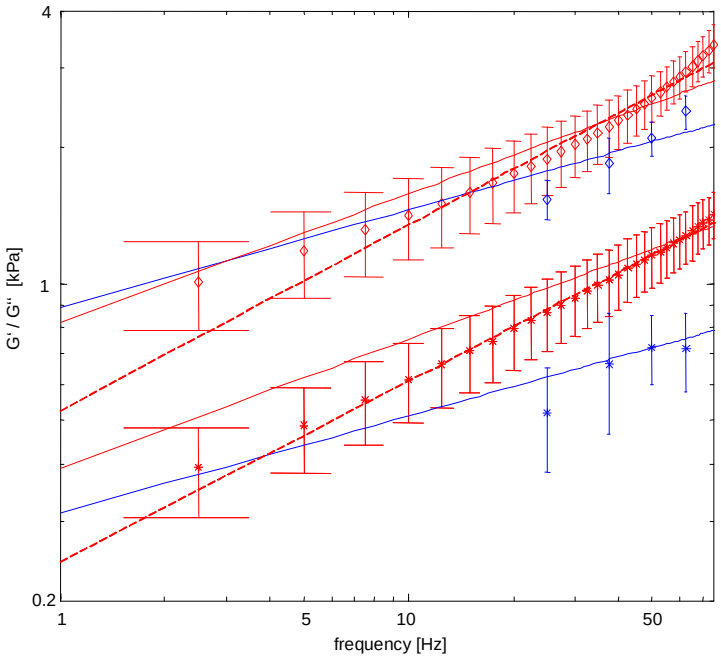

Fig.1: The real part G' (symbol: diamond) and the imaginary part G'' (symbol: asterisk) of the complex moduls in the rheometer measurements (red) and in the MRE experiments (blue) are displayed with the best fit of the dispersion relations according to the springpot model (solid line). The corresponding viscoelastic parameters are denoted in the text. In addition individual linear fits to G' and to G'' of the rheometer data are plotted as dashed lines. The error bars correspond to the standard deviations over all individual experiments.

Discussion and Conclusion: The higher values in the rheometer experiments can be caused by several factors. To avoid clotting effects the ex vivo measurements had to be performed at a temperature of 1°C which altered the mechanical properties compared to the ones at body temperature. Furthermore, obvious structural differences between ex vivo bovine liver tissue and in vivo human liver may impact the comparability of viscoelastic constants. An indication about structural differences between both types of tissue is gained by the dimensionless parameter α [10]. However, in both experiments a powerlaw $G^*\sim\omega^{\alpha}$ was observed. This function indicates multi-scaling properties of tissue structures as it is observed in soft gels over a wide frequency range. This conclusion applies to liver tissue in the limited frequency range below 50 Hz. In summary, multifrequency MRE of in vivo liver is capable to measure similar dispersion relations as observed by oscillatory rheometers.

References: [1] Muthupillai et al., Science 269, 1854-1857 (1995); [2] Klatt et al., Phys Med Biol 52, 7281-7294 (2007); [3] Klatt et al., Roefo (2008), in print; [4] Kruse et al., Phys Med Biol 45, 1579-1590 (2000); [5] Liu et al., Biorheology 37, 191-201 (2000); [6] Valtorta et al., Med Image Anal 9, 481-490 (2005); [7] Robert et al., ISMRM 14, 2560 (2006); [8] Nava et al., Med Image Anal 12, 203-216 (2008); [9] Asbach et al. MRM 60, 373-379 (2008); [10] Schiessel et al., Macromolecules 28, 4013-4019 (1995).