High Resolution MR-Elastography of In-Vivo Rat Brain – Understanding the Scaling Behaviour of the Structures –

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Introduction

MR Elastography (MRE) represents a unique tool to non-invasively assess the viscoelastic properties of soft tissues. It has shown to be of relevant use for several clinical applications [1-3]. In this study, a 7T animal scanner has been used to record the steady state patterns of mechanical waves inside the brain of rats. Such kind of MR-system allows pushing the frontier of MRE to much higher spatial resolution (due to the higher field strength) and to higher motion sensitivity (due to very strong gradients). 3D maps have been reconstructed for the complex shear modulus $G^*=G_d+iG_l$. G* is the link between stress and strain in the linear regime in the case of shear waves. Often, this parameter is interpreted via a rheological model with one spring and one dashpot in parallel, i.e. the so-called Voigt model. Here, we demonstrate that this model is not applicable to brain tissue within the measured frequency range of 200 to 1000Hz. We show that the dispersion properties of the data can be described by a full propagation model [4] which is based on the causality principle. This removes the need for any rheological interpretation and leaves us with the minimum amount of parameters necessary to describe the data. G* - as a macroscopic parameter – is a result of many microscopic contributions which originate from several different scales due to the hierarchical organization of tissue. This enforces mathematically a frequency power-law behaviour.

Materials & methods

A 7T MRI-system (PharmaScan, Bruker, Ettlingen, Germany) with horizontal bore was utilized. Two piezoelectric plates (PiezoSystems, Inc.) were used for mechanical excitation. The plates were mounted underneath the head of the animal leading to a compressional mode of excitation. A motion sensitive spin-echo sequence [5] was designed in order to visualize wave-amplitudes as small as 100nm. Imaging parameters were: TE=15-20ms, TR=400ms, isotropic voxel size of 500µm (!), matrix size 64*64, 2 NSA. The MRE data of the whole brain were acquired in 3D within the frequency range of 200 to 1000Hz. The rats were previously anaesthetised with pentobarbital (5.5mg/100g). Additionally to the elastography, a high resolution T2-weighted scan was acquired with in-plane resolution of 100µm and the same slice positions as for MRE.

Results

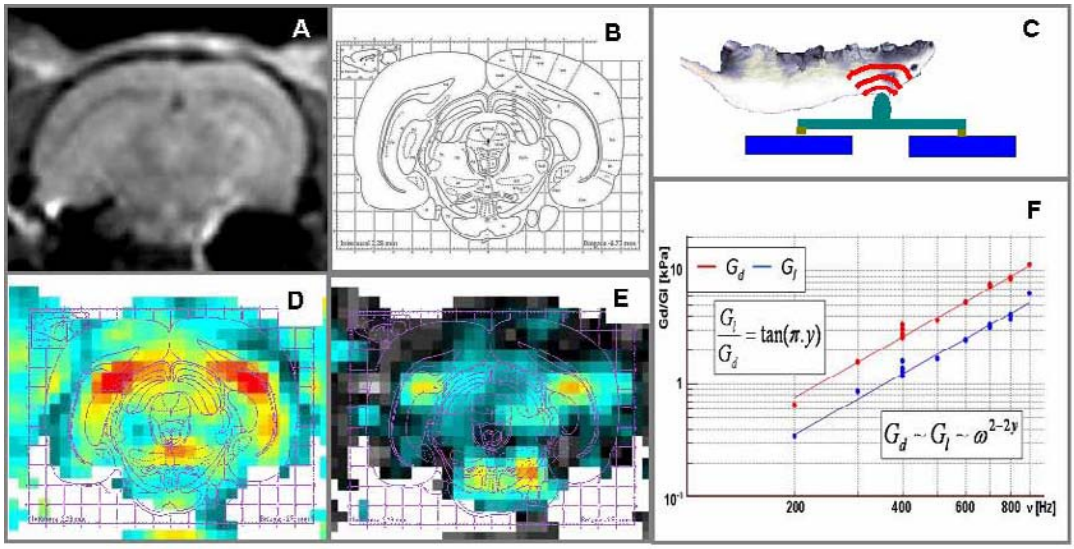

Figure A shows one coronal slice from a high resolution anatomy scan around 6.7mm backwards the Bregma . The anatomy of this slice position (Figure B) can be mapped onto the real (Gd) and the imaginary part (η=Gl/ω) of the complex shear modulus as shown on Figure D and E. These maps were obtained at 400Hz. The main structures of the brain can clearly be seen, some of which showing noticeably high values for either viscosity or elasticity.

Figure C shows the sketch of the experimental setup used to generate vibrations inside the rat brain. Both piezo benders (blue) vibrate in-phase and excite the piston (green), which is placed underneath the head of the rat. The rat lies supine in order to maximize the coupling between the piston and the head. The obtained dispersion curves for Gd and Gl are plotted on a log-log scale between 200 and 1000Hz (Figure F). Those values correspond to the mean values evaluated in a region of interest covering the whole brain. Clear power law behaviour (i.e. $\sim\omega^{\alpha}$) is seen for both Gd and Gl with α=1.8 clearly invalidating the applicability of the classical Voigt model.

Discussion & Conclusions

MRE at high spatial resolution using strong gradients for motion encoding allows mapping both the elasticity and the viscosity of soft tissues. Here we demonstrate the feasibility of in-vivo rat brain experiments. We show a very good match between the map of the mechanical properties and the anatomical structures inside the brain. The exact morphological origin for those viscoelastic variations is still under investigation. Moreover, the multi-frequency data show a very good agreement with the relations predicted by a full propagation model [4]. The only assumption used in that model is the experimental observation that Gd and Gl follow a frequency power-law. Together with the causality principle it is now possible to reveal the underlying relationship between Gd and Gl. This link shows that the exponent of the frequency rise (α) can be calculated from single frequency data via the equation Gl/Gd=tan(πy) with α=2-2y (see Fig. F). Classical viscoelastic materials have α=2. There is evidence that malignant tumors have fractal dimensions less than two due to their specific architecture of the vascularisation. The potential link between the fractal dimension of a material and its corresponding exponent α is currently under investigation. Two more physical parameters are necessary to fully describe the dispersion properties: the speed of sound at infinite frequency and a scaling factor α_0 for the attenuation of the wave.

The potential diagnostic gain of those parameters for disease detection and lesion characterization needs to be studied.

References

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