Simulation of wave fields observed in brain MR elastography by 3D finite element analysis

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Introduction: Image contrast in magnetic resonance elastography (MRE) is based on mechanical properties of tissues [1]. Recently, there has been an increasing interest in the area of MRE of the brain. So far, MRE has shown to be the only suitable noninvasive method for determining elastic [2-4] and even viscoelastic [5-7] properties of the human brain parenchyma in vivo. However, data reported in several studies varies substantially, e.g. the shear modulus varies between about 1 and 15 kPa. Among other reasons these variations are most likely caused by (i) the use of different elasticity reconstruction techniques and (ii) various experimental settings used for the challenging problem of mechanical wave generation in the brain and motion encoding in the phase of the MR signal. The latter is influenced by the type of mechanical excitation devices and the driving frequencies. Two different excitation modes are commonly used to induce mechanical shear waves in the brain tissue by generating either a vibrating nod [6,7] or nay [4,5,8] motion of the head. The objective of this study was to investigate whether it is possible to simulate the wave field characteristics of these different excitation modes with a 3D finite element analysis to get a better understanding of the transfer mechanisms of mechanical head vibrations into shear wave propagation inside the brain.

Methods: All MRE experiments were performed on a healthy volunteer according to the local board of ethics. Two different excitation modes were achieved with (i) a head rocker unit resulting in a nod motion of the head [7] and (ii) an acousto-mechanical actuator achieving a nay motion [8]. The wave fields in the brain were measured with a motion sensitive echo planar imaging based MRE acquisition technique on a Magnetom Sonata (Siemens, Erlangen, Germany) and on a GE scanner (GE, USA), respectively. In both measurements a 62.5 Hz vibration was excited and single axial slice acquisitions were made using the motion encoding normal to the image plane for nod motion and in anterior-posterior direction for nay motion.

The simulation process of the finite element analysis included brain segmentation (brain surface, grey/white matter interface and ventricles) and mesh generation (200000 tetrahedral elements, 115000 for gray matter, 85000 for white matter) from T1-weighted slice images covering the whole brain of a healthy volunteer. The mesh was imported to the finite element program COMSOL Multiphysics (COMSOL, Sweden). Two different load cases corresponding to the nod and nay motion were simulated. Constraints were set to rotate the brain surface nodes with a frequency of 62.5 Hz about the y-axis in the first case and about the z-axis in the second case (fig. 1). In this first approach a homogeneous elasticity and viscosity was assumed for grey and white matter. Elasticity parameters were set according to previous findings at 62.5 Hz [7]. Damping was included by using Rayleigh damping parameters ($\alpha = 0$ and $\beta = (G''/G')/\omega$ with storage modulus G' and loss modulus G''). The ventricle elements were set to inactive. Transient analyses were performed until the wave motion has reached a steady state.

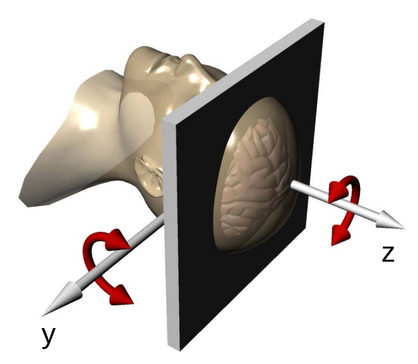

Fig.1: Schematic diagram of axes of rotation typically used in brain MRE (gray arrows). Region of axial slice position used in this brain MRE study.

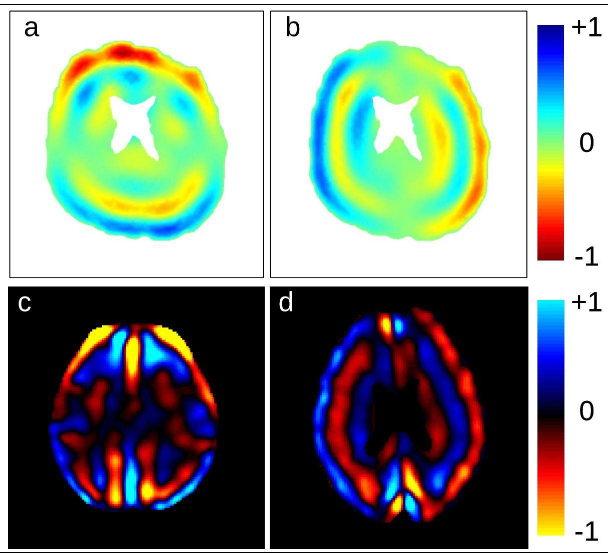

Fig.2: Simulated (a,b) and measured (c,d) axial displacement wave images.
a) out-of-plane displacement component resulting from rotation about y-axis
b) displacement component in x-direction resulting from rotation about z-axis
c) out-of-plane displacement resulting from nodding vibration of the head
d) displacement component in x-direction resulting from nay vibration of the head.

Results: Fig. 2 shows a comparison of simulated and measured wave images of the two excitation modes used in brain MRE for a representative axial slice. The overall wave pattern could be reproduced by the simulation. Wave propagation mainly from the front and back into the center of the brain can be seen in the measured wave image for the nod motion (fig. 2c) and the simulated wave image for the rotation about the y-axis (fig. 2a). In contrast both, the measured wave image for nay motion (fig. 2d) and the simulated wave image for rotation about the z-axis (fig. 2b), show mainly waves propagating from the left and right side into the center of the brain. Noteworthy, in all wave images (fig. 2a-d) amplitude modulations can be seen which are related to the curvature of the brain surface.

Discussion: By modeling the human brain of an individual volunteer with a 3D mesh and performing a 3D finite element analysis it was feasible to investigate different modes which are typical for mechanical excitation applied in brain MRE. The simulations allowed to calculate the displacement wave vector fields in the entire brain. Although the simulation results do not match the measured wave patterns in detail, there is a good agreement with the overall wave patterns. Similar wave amplitude modulations which relate to the surface geometry of the brain could be seen in measured and simulated wave fields.

Further work is necessary to get a better agreement between measurement and simulation. Especially the influence of the meninges in the falx cerebri which probably transfer motion into the brain has to be considered in future finite element models. But even though this study is only a first step in understanding the mechanisms of the generation of mechanical waves inside the brain, 3D finite element analysis opens up the possibility to account for the real 3D structure of the human brain and shear modulus inhomogeneity between grey and white matter. Also properties like nonlinear and anisotropic elasticity which so far are neglected in the reconstruction of elastic parameters with MRE can be modeled and investigated within finite element simulations.

References: [1] Muthupillai et al, Science, 1995, 269: 1854-57; [2] McCracken et al, Magn Reson Med, 2005, 53(3): 628–639; [3] Hamhaber et al, Acta Biomater, 2007, 3(1): 127–137; [4] Kruse et al, Neuroimage, 2007, 39: 231-237; [5] Green et al, NRM Biomed, 21: 755-764; [6] Sack et al, NMR Biomed, 2008, 21:265-271; [7] Klatt et al, 2007, PhyMedBiol, 52:7281-94; [8] Murphy et al, Proc ISMRM, 2008, 3506.