Comparison of MR elastography inversion methods on high-resolution measurements in the human brain

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Target audience: Researchers and clinicians interested in the brain's mechanical properties.

Purpose: To critically evaluate the effect of inversion algorithm on material properties estimated by magnetic resonance elastography (MRE). MRE has recently been applied to detect material changes in the human brain due to aging [1] or disease [2]. Brain material properties are also needed for computer simulations of traumatic brain injury (TBI). Estimates of properties vary among different studies, in part because of the use of different inversion methods, including local frequency estimation (LFE), local direct inversion (LDI), and nonlinear inversion (NLI). While each inversion method has been validated using gel phantoms, the complicated structure of the human head (comprising skull, meninges, CSF, and brain) and the complex material behavior of the brain (anisotropic, heterogeneous, nonlinear, and poroelastic) challenge the underlying assumptions of each method. In this work, LFE, LDI, and NLI were each used to estimate viscoelastic parameters of the human brain from high-resolution MRE data.

Methods: MR images of displacement during shear wave propagation in the brain were acquired on an Avanto 1.5T scanner (Siemens Medical Systems, Erlangen, Germany). The protocol was approved by the Washington University IRB. Shear waves were induced by application of steady 50 Hz sinusoidal loading to the side of the skull [3]. Excitation was provided by an acoustic actuator (Resoundant™, Rochester, MN) connected by flexible tubing to a hollow paddle with a flexible membrane pre-loaded against the head. MRE data were acquired with a multishot, variable-density spiral acquisition sequence (TR=2800/TE=75 ms) with correction for motion-induced phase errors [4] allowing high resolution (2x2x2 mm^3 isotropic voxels) over a 240x240x40 mm field of view in ~10 minutes. Three inversion methods were used to estimate viscoelastic or elastic moduli from these data: (1) LFE was performed on the z-component of the curl field following the procedures outlined in [5], and the shear modulus was obtained from the local wavelength. (2) LDI was performed by locally fitting the measured curl field to the 3D wave equation as in [6]. (3) NLI minimizes the difference between measured and simulated displacements by iteratively updating modeled mechanical properties. NLI is performed on 24mm overlapping subzones [7].

Results and Discussion: Fig. 1 shows sample elastograms (shear moduli) obtained by the three methods; Fig. 2 shows average moduli over the entire imaging volume in each subject (N=8). Average shear moduli estimated by the three methods differ (NLI>LFE>LDI), but remain within a reasonably narrow range from 1.2-2.6 kPa. Relative differences between individuals were consistent among all methods. The results generated by each algorithm reflect the underlying assumptions. LFE estimates are based on isotropic, locally homogeneous, linear elastic behavior. LDI accounts for viscoelastic effects, but still assumes local homogeneity, which does not truly reflect the case of brain tissue in which properties often change significantly within one wavelength. Direct inversion techniques may underestimate material properties in the presence of noise. NLI handles the effects of heterogeneity and is less sensitive to noise, but remains constrained by the specific material model. For each algorithm, choices of smoothing and discretization may affect parameter estimates, both globally and locally. Comparison between estimates from different methods increases confidence in bounds and relative trends.

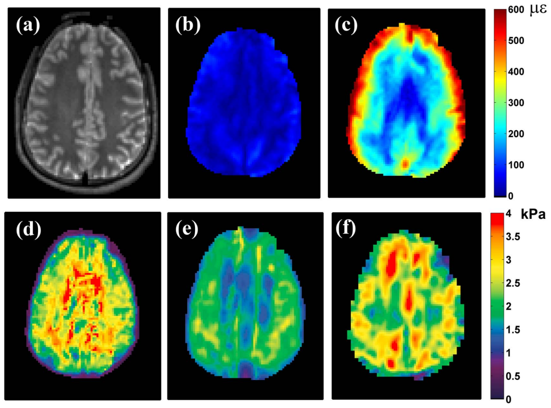

Fig. 1: (a) Anatomical images, (b) volumetric strain, (c) octahedral shear strain, and shear (storage) modulus maps from (d) LFE (edge effects masked), (e) LDI and (f) NLI.

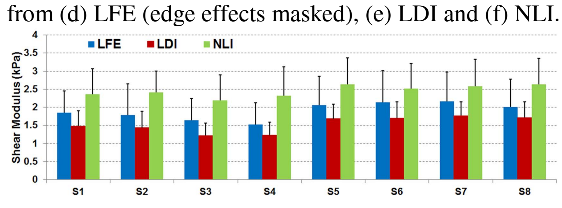

Fig. 2: Volume-averaged storage modulus estimates obtained by LFE, LDI, and NLI, in individual subjects.

Conclusions: This is the first comparative study of the major inversion techniques used in brain MRE. As the number of brain MRE studies grows, it is important to be able to compare results across inversion methods. We observed differences in mean properties estimated by LFE, LDI, and NLI. Future work will investigate the sensitivity of local properties to inversion technique and parameter choices.

References

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