Multi-Direction Excitation for Magnetic Resonance Elastography to Increase the Fidelity of Mechanical Properties

Aaron T Anderson[1], Curtis L Johnson[2], Joseph L Holtrop[2,3], Elijah EW Van Houten[4,5], Matthew DJ McGarry[5], Keith D Paulsen[5,6], Bradley P Sutton[2,3], and John G Georgiadis[1,2]

[1]Mechanical Science & Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, United States, [2]Beckman Institute for Advanced Science, University of Illinois at Urbana-Champaign, Urbana, IL, United States, [3]Bioengineering, University of Illinois at Urbana-Champaign, Urbana, IL, United States, [4]Département de Génie Mécanique, Université de Sherbrooke, Sherbrooke, QC, Canada, [5]Thayer School of Engineering, Dartmouth College, Hanover, NH, United States, [6]Dartmouth-Hitchcock Medical Center, Lebanon, NH, United States

INTRODUCTION: Diseases affecting the microstructure of the brain have a significant effect on the tissue mechanical properties, and in vivo techniques, like magnetic resonance elastography (MRE), have shown promise as a contrast technique for disease detection. Commercially available shear wave drivers, improved MR sequences [1], and non-linear finite element-based inversion (NLI) [2] have all resulted in improved property estimates. However, brain tissue is known to be mechanically anisotropic, and the accuracy of MRE methods are limited by the propagation of waves relative to oriented fiber bundles. Analysis by Romano et al. [3] showed how specific features in the brain's microstructure caused waves to travel along fiber tracks, and leveraging this known wave behavior based on microstructure can result in improved local property estimation of anisotropic brain tissue. The work presented here recognizes the potential increase in fidelity of mechanical properties images by forcing the human head in two different directions within the existing framework of MR displacement imaging and nonlinear inversion.

METHODS: A Resoundant pneumatic forcing system, with two passive drivers, was used to generate shear displacements at 50 Hz within the human brain in two distinct forcing directions. The forcing was applied during two separate acquisitions in a single experiment, one at the back of the head with anterior-posterior shaking (A-P), and the other on the right temple with lateral left-right shaking (L-R). The subject's head positioning did not move between experiments. Displacement fields were acquired using a multishot, variable-density spiral sequence on a Siemens 3T Trio scanner with 12-channel head coil [1]. Imaging parameters included: TR/TE = 2000/55 ms; FOV = 240mm; matrix = 120x120; slices = 20 (2mm thick). The mechanical properties were reconstructed for each individual displacement field (A-P and L-R) using an isotropic finite-element based nonlinear inversion of the storage modulus (G') and loss modulus (G''). The two fields were then used together in a joint property estimation, where the minimization for NLI is governed by the sum of error between the two measured displacement fields, $u_1^m$and u_2^m, and the two computed displacement field, u_1^c and u_2^c, via the objective function $\phi = \sum_\Omega [\|u_1^c(\theta) - u_1^m\|^2 + \|u_2^c(\theta) - u_2^m\|^2]$. In this case, θ is the mechanical property distribution and Ω represents the domain, which are the same for both displacement fields.

RESULTS and DISCUSSION: Figure 1 presents the computed storage modulus, G', for the subject and the combined cases, each property map highlighting, potentially, important areas of microstructural differences. Individual shaking directions cause distinct displacement fields (Figure 2), though very similar maps of the brain mechanical properties are reconstructed. The property maps have distinctly different local property variations, which depend on how the microstructural features were oriented compared to the forcing. For example, the A-P forcing distinctly reconstructs the ventricles $G' \sim 0$, which is due to the para-medial vibration along the long structures being more likely to shear the fluid compared with the lateral shaking. Conversely, A-P forcing is unable to cause a shear stress on the laterally oriented corpus callosum splenium because it lies directly on the medial plane along the forcing direction. When the forcing is normal to the direction of the splenium fiber orientation, the apparent shear modulus looks stiffer because the microstructural feature will move together rather than shearing in place. For the L-R forcing, microstructural features along the medial section are more distinct and overall have a smaller range for the shear modulus throughout the imaging slice. As one might expect, the prominent features from both forcing directions are captured in the combined reconstruction. The joint reconstruction, from two displacement fields, helps overcome bias in property estimates due to wave propagation relative to microstructural features and improves the resulting property maps.

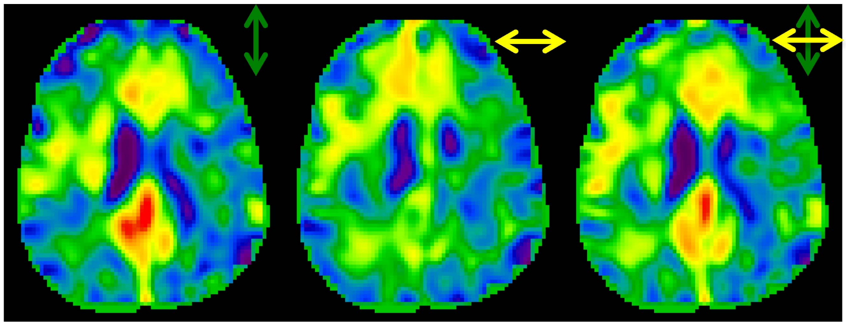

Figure 1: Computed shear modulus, G', scaled from 0 kPa (purple) to 5 kPa (red) at the axial slice inferior to the corpus collosum, showing the genu (anteriorly) and the splenium (posteriorly), for the three different cases: *(left)* anterior-posterior shaking, *(middle)* lateral shaking, and *(right)* combined (anterior-posterior and lateral); property features more prominent in one shaking direction show-up in the combined property map.

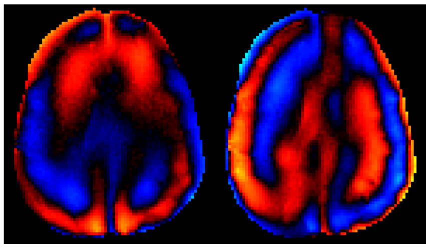

Figure 2: Through-plane displacement field of the anterior-posterior shaking *(left)* and lateral shaking *(right)*, scaled from -5 µm (blue) to 5 µm (red).

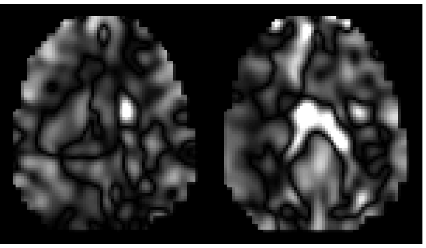

Figure 3: The normalized difference in shear modulus, G', between the combined reconstruction and the individual reconstructions: anterior-posterior *(left)* and lateral *(right)*.

CONCLUSION: By increasing the amount of displacement data available to the inversion routines, we were able to increase the sharpness of features and thus showed potential areas of directionality in the shear waves causing a change in the apparent mechanical properties of the human brain. Large, orderly white matter (WM) structures, like the corpus callosum, are expected to have different mechanical responses depending on the direction of applied shear, i.e. longitudinal compared to transverse, and this was observed in the reconstructed material properties. By employing both displacement fields in NLI, we demonstrated how to leverage the redundant information from the two directions in order to increase the fidelity of the mechanical properties. We anticipate that this strategy will also be effective in anisotropic inversion routines that require wave propagation in multiple directions to resolve parallel and perpendicular shear moduli.

REFERENCES: [1] CL Johnson, *et al.*, *Magn Reson Med*, 2013, 70(2):404-412; [2] EEW Van Houten, *et al.*, *Med Phys*, 2011, 38(4):1993-2004. [3] A Romano, *et al.*, *Magn Reson Med*, 2012, 68(5):1410-1422