MODES OF SHEAR WAVES IN BRAIN MR ELASTOGRAPHY

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Target Audience: Researchers studying MR elastography.

Purpose: The purpose of this study is to analyze modes of shear waves that may occur during MR elastography (MRE) of the brain. Results of this study may provide insight on the excitation frequency and direction to be used for brain MRE for higher shear wave displacement. It is shown that the shear wave eigenfrequencies in the brain are directly related to the stiffness of the brain which in return may be used in diagnosing conditions related to brain stiffness.

Methods: MRE technique consists of inducing shear waves in the tissue, obtaining phase-contrast MR images demonstrating shear wave propagation and processing phase-contrast MR images to obtain tissue stiffness maps indicating shear modulus values quantitatively. Tissue stiffness maps are obtained by measuring the wavelength of shear waves. In addition to wavelength, frequency response of the shear wave displacement can provide important information about mechanical properties of the brain. Although various actuator systems have been implemented for inducing shear waves into brain such as head cradle[1], bite actuator[2] and pneumatic pillow actuators[3], displacement response of the brain has not been studied in relation to the direction and frequency of mechanical excitation. In this study, a 3D model of brain is developed from segmented brain images of a healthy human. Eigenfrequency analysis of the brain is performed, using COMSOL Multiphysics (COMSOL, Sweden) finite element method (FEM) software. The imported 3D model of the brain is segmented into scalp, skull, CSF, gray matter (GM) and white matter (WM). Young's modulus, Poisson's ratio and density of the segmented parts are obtained from previous studies[4,5,6]. Young's modulus map of the brain used in simulations is given in Figure 1. Stiffness damping parameter of Rayleigh damping is used for damping in WM and GM, similar to a previous study[7]. Modes of rotatory shear waves are observed which have different eigenfrequencies around different axes of the head and can be excited by conventional actuator systems. Eigenfrequency results for rotation of head about three different axes, corresponding to naying, nodding and Indian head bobble, are compared to total displacement amplitudes in frequency domain analysis of exciting these three motions of head. In frequency domain analysis, excitation frequency is swept from 1 Hz to 100 Hz with frequency step of 1 Hz. Motion induced into the head at the excitation location is 20 µm. Simulations are repeated for a 10% lower Young's modulus of WM and GM in order to simulate a neurodegenerative disease state[8,9]. Displacement is measured at the same point on 3D model of brain for all simulations. Furthermore, experiments are performed to analyze possible modes of shear waves on a healthy volunteer, with permission from local board of ethics. Experiments are conducted in a 3 Tesla Siemens Tim Trio scanner. A conventional bite actuator[3] is used for inducing shear waves into brain by forming a similar motion to Indian head bobble. The motion is induced continuously and frequency of excitation was swept from 20 Hz to 40 Hz, with frequency steps of 2 Hz. A gradient echo pulse with motion encoding gradient (MEG) is used for acquisition. Two acquisitions are made in each scan by switching polarity of the zeroth and first moment nulled MEG, having same frequency with excitation frequency, in an interleaved fashion. Two scans are performed for each frequency, by adjusting the phase of the actuator signal, in order to obtain two phase difference images at steady state of shear waves having $\pi/2$ phase difference to each other. From these two phase images the rms value of the displacement is obtained. Amount of displacement of shear waves were measured on the same line, shown in figure 3(c), for all frequencies. In order to eliminate the effect of different amount of induced motion into head caused by the bite actuator, measured displacements are normalized to displacement of the actuator measured for each excitation frequency by an optical method, while volunteer is biting the actuator in MR scanner.

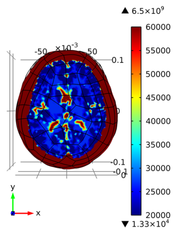

Figure 1: Young's modulus (Pa) map of 3D brain model

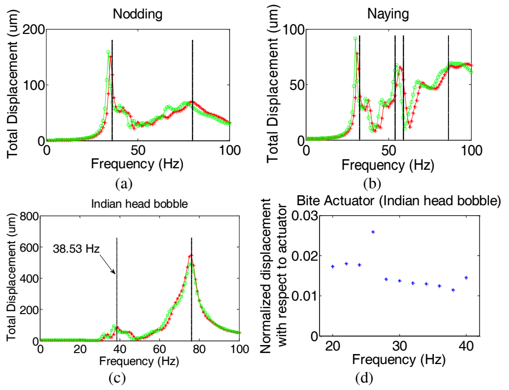

Figure 2: Simulation results for displacement versus frequency swept and eigenfrequencies for different motions (a) nodding, (b) naying, (c) Indian head bobble, (d) human experiment results with bite actuator for normalized displacement versus frequency swept. Frequency domain analysis in normal brain (red), 10% reduced Young's modulus (green), eigenfrequency (black), human experiment (blue).

Results: Results of eigenfrequency analysis demonstrates that brain has modes at certain frequencies for different motions corresponding to nodding, naying, and Indian head bobble. Frequency domain analysis indicates that displacement of shear waves formed in the brain can increase significantly when brain is excited at its eigenfrequencies with correct excitation at that frequency, since peak displacements match with eigenfrequencies as seen in Figure 2(a-c). For instance, first mode for Indian head bobble is found at 38.53+1.09i Hz, where complex part is related to the damping of the eigenmode, and a peak in the displacement is observed in frequency sweeping simulation at 39 Hz. In Figure 3(a,b,d,e), similar shear waves patterns are observed with eigenfrequency and frequency domain analyses. In the case of reduced stiffness, frequencies of peak displacements shift but displacement response patterns do not change, as seen from Figure 2(a-c). Considering the experiment results, at 26 Hz a displacement peak is observed as shown in Figure 2(d). In addition, the human shear wave pattern observed at 26 Hz is similar to the mode at 38.53 Hz of eigenfrequency analysis and 39 Hz of frequency sweeping simulation, as in Figure 3(c,f).

Conclusion and Discussion: It is demonstrated by three different analysis techniques that there are resonant modes of shear waves in MRE of the brain that can be excited by conventional actuator systems at correct frequencies. Furthermore, difference in patterns of shear waves observed between simulations and experiment can be caused by waves reflected from falx cerebri, which is not present in the 3D model of brain used in simulations. Another conclusion of this study is that safety limits of vibration[9] in MRE should be more carefully considered when exciting such resonant modes. This method can be used in diagnosing neurodegenerative disease by detecting shift in frequency of peak displacement and be beneficial for patient follow-up.

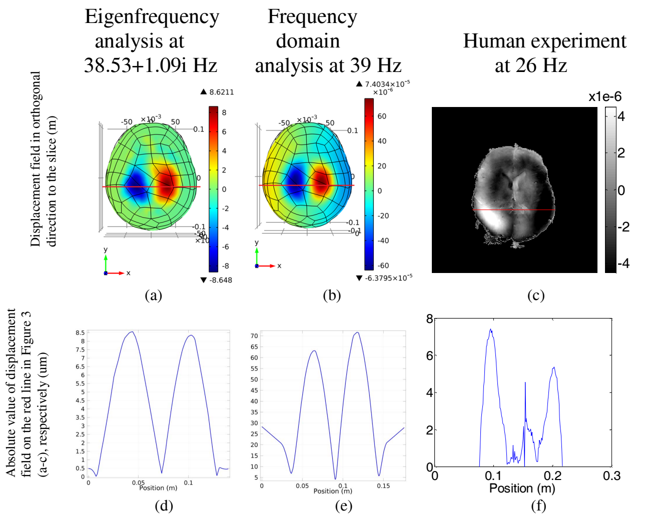

Figure 3: Displacement fields for orthogonal to slice direction in simulations (a)eigenfrequency (b)frequency domain, (c)human experiment. Absolute value of displacement on red line for (a-c) is shown in (d-f), respectively. Numerical values in (a), (d) are in arbitrary units.

References:[1]Sack et al, NMR Biomed. 2008, 21:265-271 [2]Hamhaber et al, Acta Biomaterialia 2007, 3:127-152 [3]Latta et al, MRI 2011, 29:147-152 [4]McCracken et al, MRM 2005, 53:628-639 [5]Ruan et al, Journal of Biomechanical Engineering 1991, 113:276-283 [6]Kleiven et al, Journal of Biomechanics 2002, 35:153-160 [7]Hamhaber et al, Proc ISMRM 2009, 4349 [8]Murphy et al, JMRI 2011, 34:494-498 [9]Wuerfel et al, NeuroImage 2010, 49:2520-2525 [9]Ehman et al, Phys Med Biol. 2008, 53(4):925-935