Estimation of shear modulus in heart phantom using FE-simulated and MRE-measured displacements

Samad Javid[1], David Lake[1], Shivaram Poigai[1], Arvin Arani[1], Armando Manduca[1], Kiaran McGee[1], Richard Ehman[1], Dan Dragomir-Daescu[1], and Philip Araoz[1]
[1]*Mayo Clinic, Rochester, MN, United States*

Target audience: Physicians and scientists in cardiac Magnetic Resonance Elastography (MRE).

PURPOSE: Abnormal myocardial stiffness is the key pathologic cause of heart failure with preserved ejection fraction (HFPEF)[1]. However because myocardial stiffness cannot be measured non-invasively, there is no single, accepted diagnostic technique for diagnosing HFPEF. This has hampered HFPEF research such that no treatment for HFPEF exists, contributing to HFPEF's dismal five year mortality of 50%[2, 3]. Recent animal experiments suggest that cardiac MRE may be able to measure the regional myocardial shear stiffness, which could revolutionize the diagnosis and treatment of HFPEF. Direct inversion (DI) and Local Frequency Estimate **(**LFE) algorithms [4] assume the tissue imaged is larger than an MRE-generated wavelength, an assumption that holds true in large organs such as the liver[5] but not for a thin-walled structure such as the left ventricle where waveguide effects dominate. The purpose of this study was to use DI and LFE to estimate the shear modulus in the myocardial wall of a silicone heart phantom (Fig. 1) using dynamic material analysis (DMA) as a reference standard. Displacements were both generated using a finite element (FE) technique, to simulate a noise free displacement field, and measured with MRE at 100 Hz and 200 Hz.

Fig. 1: The silicone heart phantom.

METHODS: A static silicone heart phantom was constructed (Chamberlain Group, Maryland) based on CT images of a human heart. A 3D model of the heart phantom was created by segmenting CT images of the phantom using Mimics (Materialise, Ann Arbor, MI). The model was exported to ABAQUS (Dassault System, RI, USA), and was meshed using quadratic tetrahedral elements. Using silicone created from the same batch as the phantom, the shear modulus values were measured using DMA at two frequencies (G=10.7 *kPa* at 100 *Hz* and G=14 *kPa* at 200 *Hz*). These DMA shear modulus values were considered the reference standard and were input into the FE simulations. The spatial displacement amplitude and phase angle were captured for all mesh nodes at both 100 Hz and 200 Hz. DI and LFE inversion methods were used on the generated FE displacements to estimate the shear modulus of the phantom's myocardial wall. MRE displacement fields were obtained using a 1.5 T MR scanner (Signa EXCITE, GE Healthcare, Milwaukee, WI) with a 3D GRE technique. The phantom's MRE-measured shear modulus values were also estimated with DI and LFE.

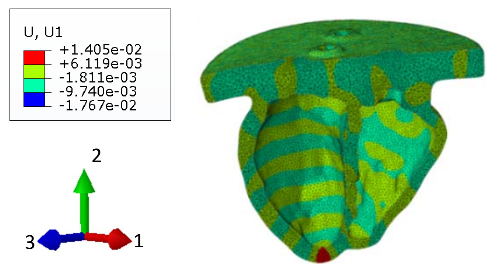

Fig. 2: FE model displacement map in direction 1.

RESULTS: Figure 2 shows the shear displacement contours on a section of the heart model excited harmonically at 100 *Hz* obtained from FE. Figure 3 shows a DI shear modulus map in a coronal slice obtained from FE calculated displacements at both frequencies. The average shear modulus magnitude estimates were 5.1 *kPa* at 100 *Hz* and 11 *kPa* at 200 *HZ*, respectively. Figure 4 shows shear modulus maps in an axial slice of the phantom obtained from a 3D LFE inversion algorithm using the MRE measured displacements. The average magnitudes of the MRE shear modulus were 4.5 *kPa* and 11.5 *kPa* at 100 *HZ* and 200 *HZ*, respectively.

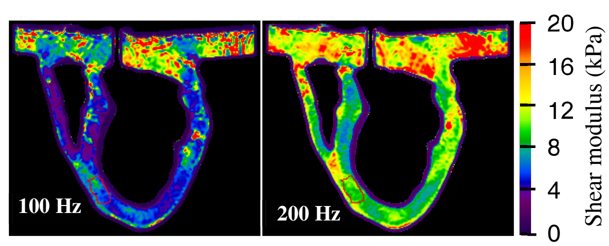

Fig. 3: 3D stiffness maps obtained from FE displacements.

DISCUSSION: Both DI and LFE inversion methods underestimated the shear modulus in the phantom's myocardial wall. At 100 *Hz* the error between the estimated and the actual shear modulus was about ε=53%, while the error at 200 *Hz* was about ε=23%. This suggests that the higher the frequency, the better the estimation of myocardial shear modulus.

CONCLUSION: The DI and LFE inversion methods are more suitable for estimating the stiffness of the myocardial wall at higher frequencies, where waveguide effects are less dominant, as shown for both FE generated and MR measured displacement data, using DMA as a reference standard. The relative thinness of the myocardial wall compared with the shear wavelength biases the standard MRE inversion algorithms due to waveguide effects.

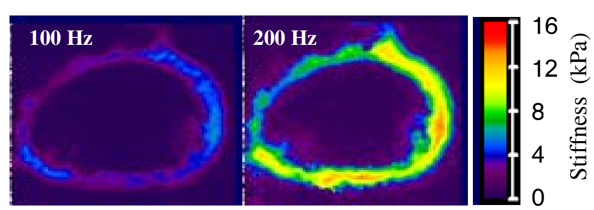

Fig. 4: 3D LFE stiffness maps obtained from MRE images

References: **1.** Zile MR, et al., NEJM, 2004.350(19): p. 1953-59. **2.** Levy D., et al., N Engl J Med, 2002. 347(18): p. 1397-402. **3.** Senni M. and M.M. Redfield, J Am Coll Cardiol, 2001. 38(5): p. 1277-82. **4.** Manduca A., et al., MIA, 2001. 5: p. 237-254. **5.** Yin M., et al., Clin Gastroenterol Hepatol, 2007. 5(10): p. 1207-1213.