Waveguide Magnetic Resonance Elastography of the Left Ventricle in a Pressure Varying Model

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Targeted Audience: Biomedical and biomechanical engineers, cardiologists, radiologists, researchers.

Purpose: Increased myocardial stiffness (MS), abnormal left ventricular (LV) filling and delayed relaxation has been associated with heart failure with preserved ejection fraction (HFPEF) also known as diastolic heart failure wherein the ejection fraction (EF) of the LV stays normal (>50%). Hence, conventional determinants of heart failure such as LV EF do not indicate the true pathophysiology underlying HFPEF. Therefore, there is a need to develop an alternative diagnostic tool. Since, MS is elevated as a result of HFPEF, quantifying MS may reveal pathophysiological conditions which might assist in diagnosis and prognosis of HFPEF patients. Recently, magnetic resonance elastography (MRE) has emerged as a non-invasive tool to estimate the shear stiffness of myocardium. However, the current established MRE technique assumes the myocardium to be an infinite homogenous isotropic structure; which is not true. Previous studies have shown that the myocardium exhibited anisotropy and passive MS changed nonlinearly. Romano et al. has demonstrated a novel technique known as waveguide MRE to quantify anisotropic stiffness of soft tissues. Therefore, the purpose of this study was to estimate anisotropic myocardial stiffness using waveguide MRE in an ex-vivo porcine model with varying LV pressure.

Methods: Experimental Set-Up: Three juvenile Yorkshire (~80 lbs) pigs were used for this study. After the animals were euthanized, their hearts were extracted, flushed and stored in Ringer’s solution at 4°C till the scanner was available (i.e. ~5 hrs). A balloon was inserted through the aortic opening into the LV chamber via a plastic tube (Figure 1). A syringe was attached to the end of the tube via a T-connection and was used to inflate the balloon with air at two different pressure points (Pressure range for all the three hearts: Lower (50-70mm of Hg) and higher (80-110mm of Hg)). A pressure transducer (PX26-005GV, Omega Engineering, Stamford, CT) was connected to the other end of the T-connection to measure the real-time pressure in the heart using a computer at a sampling rate of 1kHz.

Acquisition: In order to estimate anisotropic stiffness, prior information of the fiber directions is necessary which was achieved using diffusion tensor imaging (DTI). DTI and MRE were performed on ex-vivo pig hearts in a 3T MRI scanner (Tim Trio, Siemens Healthcare, Erlangen, Germany). Short axis views covering the entire myocardium were imaged at an isotropic resolution of 2x2x2mm (imaging matrix: 128x128 mm²; FOV: 256x256mm²). DTI: Imaging parameters included: 30 diffusion encoding directions; 4 averages; TE/TR=90/5000ms; b-values=0,10000s/mm²; MRE: Imaging parameters included: TE/TR=23.3mms/33.33ms; α=22°; mechanical vibration frequency=60Hz; 4 MRE time offsets; and motion encoding gradients of 16.67ms duration (60Hz) was applied in all the three directions (x, y, z) to encode the in-plane and through plane motion.

Analysis: The acquired MRE and DTI images were masked to segment the LV. Custom-built software written in Matlab (Mathworks, Natick, MA) was used to obtain the principal eigenvectors. A spatial spectral filter based on the principal eigenvector was applied on the first harmonic displacement data to identify waves traveling in particular directions defined by a local coordinate system. Simultaneously, a Helmholtz decomposition was performed to separate the total field into its longitudinal and transverse components. Finally an orthotropic inversion was implemented to evaluate the compressional (C11, C22, C33) and shear (C44, C55, C66) complex stiffness values along the fiber (C13), sheet (C13) and sheet normal (C22) directions of the heart. Additionally, isotropic stiffness was measured using MRE Lab (Mayo Clinic, Rochester, MN). A 3D local frequency estimation inversion (LFE) was performed by applying a directional filter in 8 directions (to remove the reflected waves) and a band-pass filter (to remove the longitudinal motion). The mean anisotropic and isotropic stiffness values and their standard deviation (SD) from all the slices were reported. Paired student’s t-test was performed to determine the significant difference in stiffness value between the two pressure points with the two different inversion techniques.

Discussion & Conclusion: We have demonstrated that non-invasive measurement of anisotropic stiffness is feasible using waveguide MRE. As expected, stiffness increased with increasing pressure. Furthermore, we have seen that anisotropic stiffness estimation showed a significant difference between the two pressure points both in the compressional (P = Value = 0.0053) and shear (P = Value = 0.0015) stiffnesses. However, the isotropic stiffness measurements showed only slight increase in stiffness as a function of pressure with no significant difference (P = Value = 0.75).