Validation of MR Elastography Derived Stiffness Maps Using Established Pressure-Volume Model in a Simulated Heart Model

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Introduction:

Previous studies have indicated that myocardial stiffness is a clinically important variable in a range of cardiac related illnesses including diastolic dysfunction [1], hypertension [2] and myocardial ischemia [3]. However, the ability to non-invasively quantify this parameter is limited. Our group has developed a MR based technique known as magnetic resonance elastography (MRE) that is capable of spatially resolving the viscoelastic properties of tissue in vivo by imaging shear wave propagation using phase-contrast MR techniques [4]. The objective of this work is to determine if MRE based techniques can be adapted to measure the shear modulus of a cardiac simulating thin shelled spherical phantom under static and cyclic pressure conditions. The hypothesis of this work is that MRE based measures of shear stiffness agree with those obtained from a well known and clinically validated pressure-volume based method (P-V model) [5] of calculating shear stiffness in the heart.

Methods:

Setup and Acquisition: All imaging was performed using a MR 1.5T Signa Excite scanner (GE Health Care, Waukesha, WI). A spherical phantom was constructed using a silicone rubber composite (Wirosil, BEGO, Germany) designed to mimic the left ventricle of the heart (diameter = 96 mm, thickness = 8.5 mm). Figure 1 shows the experimental set up and includes the phantom with a flexible inner bladder filled with water connected to a computer-controlled flow pump (Illinois Pneumatics, Inc). The flow pump system allowed either static or programmable periodic pressure variations within the phantom cavity. A pressure transducer allowed real-time acquisition of line pressure which was considered equal to the pressure within the phantom. An attached pulse plythesmograph provided a waveform of the volumetric changes across a flexible diaphragm which was then used as a trigger for the gated MRE pulse sequence. Mechanical stress waves at 200 Hz were generated in the phantom by an electromechanical driver placed in contact with the top surface of the phantom. MRE imaging parameters included TR/TE =150/16 ms, FOV = 140 mm, 30° flip angle, 10-mm slice thickness, and a 256x64 acquisition matrix. All imaging was performed in the axial plane of the scanner using a transmit-receive birdcage RF coil while motion encoding was performed in-plane along the physical x and y-axes. A series of MRE acquisitions under static and dynamic pressure conditions were then performed. For the static case, pressures equal to 55, 66, 70, 75, 80, 87 mm Hg were used. Dynamic pressure conditions consisted of maximum amplitude periodic pressure waveforms over a pressure range of 55 to 90 mm Hg at a frequency of 1 Hz. MRE imaging of the dynamic pressure experiment was performed at fixed trigger delays during the pressure cycle, providing samples of the pressure waveform at equivalent pressures to those obtained under static conditions.

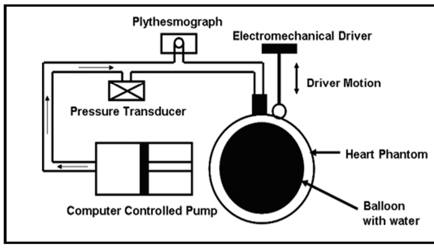
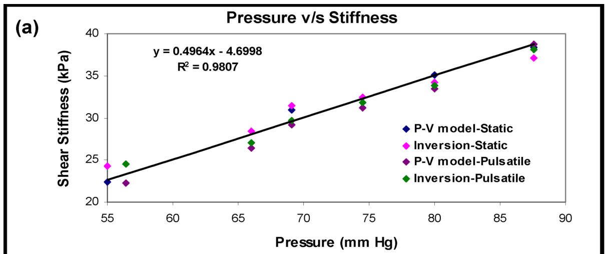


Figure 1: Experimental setup showing connection system of driver, flow pump, pressure transducer and plythesmogrpah.

Image analysis: MRE based stiffness maps of the spherical phantom were obtained by direct inversion of a spherical shell wave equation [6] which provides an estimate of the wave speed allowing calculation of Young's modulus, E . The P-V based method involved calculating E according to the relationship:

$$E = (9/4)*V*[(1+V/V_w)*(dP_t/dV) + P_t/V_w]$$

where V =volume of chamber, V_w = volume of wall, P_t = transmural pressure, and dP_t/dV = chamber stiffness [5]. dP_t/dV was calculated from the slope of the least-squares straight line fit to P_t versus V where P_t is assumed to be the difference between the line and atmospheric pressure and V the inner volume of the sphere derived from the MRE measured inner radius. The Young's modulus calculated from each method was converted to the shear stiffness μ using μ = E/2(1+v), assuming a Poisson's ratio (v) of 0.5.



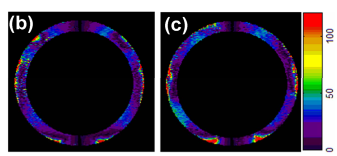


Figure 2: (a) Plot of stiffness v/s pressure during pulsatile and static infusion pressures. (b) Shear Stiffness map (kPa) at pulsatile pressure (c) Stiffness map (kPa) at static pressure

Results:

Figure 2a shows the linear correlation between the shear modulus and pressure measurements during static and pulsatile pressures in the phantom using both the P-V and MRE based methods. For both the P-V and MRE based estimates of shear stiffness, the values ranged from 22 kPa – 40 kPa. And r^2 value greater than 0.98 was obtained in each case. Figures 2b and c shows the stiffness map obtained in the phantom at a pressure of 66 mm of Hg during pulsatile flow and static flow showing an average stiffness values of 27.1± 9.0 kPa and 28.4± 9.4 kPa, respectively.

Discussion:

These results support the hypothesis that MRE derived estimates of shear stiffness under both pulsatile and static pressure conditions agree with those obtained using the PV-based model. These data also suggest that P-V measurements could be used as a reference standard in studies of in-vivo cardiac MRE and that, if shear waves can be transmitted into the myocardium, in vivo cardiac MRE is technically feasible. Future work will extend this methodology to in vitro and in vivo cardiac tissue.

References:

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