

MR Elastography as a method for the assessment of myocardial stiffness throughout the cardiac cycle

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Introduction:

Within the heart, pressure-volume (P-V) relationships have been used to diagnose disease states such as diastolic dysfunction, hypertension and myocardial infarction [1-3]. However, these P-V methods are invasive and do not assess the true intrinsic properties of the myocardium. Recently, a novel imaging technique known as magnetic resonance elastography (MRE) has been used to spatially the shear stiffness [4]. The purpose of this study was to determine if MRE can resolve the shear modulus of myocardium in vivo throughout the cardiac cycle.

Methods:

Experimental Setup: In vivo cardiac MRE was performed on six porcine animals. The animals were anesthetized by intramuscular injections of a combination of Telazol (5mg/kg), Xylazine (2mg/kg) and Glycopyrrolate (0.06mg/kg) and were also maintained using an isoflurane inhalation anesthesia (1-3%). The animals were also externally ventilated. A percutaneous femoral arterial puncture was made and an 8 French introducer set was placed into the femoral artery. A 7 French pig tail catheter containing a fiber optic pressure sensor (DL-PM-250, FOP-MIV, FISO Technologies Inc. Quebec, Canada) was advanced through the introducer sheath through the aorta and into the left ventricle (LV). Left ventricular (LV) pressure waveforms were sampled at rates of 250 Hz and 1 kHz and were recorded using a computer.

MRE Image Acquisition and Analysis: All imaging was performed in a 1.5-Tesla MRI scanner (Signa Excite, GE Health Care, Milwaukee, WI). The animals were positioned in the supine position and placed feet first into the scanner. A cine gradient echo MRE sequence [5,6] was used to acquire a short-axis slice at the midventricular level avoiding the papillary muscles. Mechanical waves were introduced into the heart by a pneumatic driver system as shown in figure 1. Imaging parameters included TE/TR= 11.7/25 ms; FOV= 27 cm; α = 30°; slice thickness= 5 mm; acquisition matrix= 256x64; receiver bandwidth= \pm 16 kHz; excitation frequency= 80 Hz; heart rate= 80-143 bpm; VPS= 4; cardiac phases= 20; 4 MRE time offsets; and 6.25-ms duration (160 Hz) motion encoding gradients were applied separately in the x and y directions to measure the in-plane motion. Due to technical limitations, pressure measurements in 3 animals were acquired using a fiber optic pressure sensor and in the remaining 3 using a fluid-filled catheter. The short-axis images in all the animals were masked with epicardial and endocardial contours to obtain only the left ventricular (LV) myocardium as shown in figure 2. The x and y components of motion were analyzed using a spherical shell analysis [6] to obtain mean stiffness measurements during each cardiac phase for each animal. Spherical shell analysis is only valid when the inner radius is greater than the thickness of the shell. However, during the systolic phase of the cardiac cycle in this in vivo model, the inner radius was almost equal to or even less than the thickness of the myocardium. Therefore, finite element modeling (FEM) was performed in a spherical shell model to determine the ratio of radius to thickness at which the analysis in [6] failed and also to obtain correction factors to adjust the results when the ratio falls into the thick-shell regime. For the in vivo analysis, the inner radius and thickness of the myocardium were determined from MRE magnitude images.

Volume Measurements: 2D multislice, short-axis, balanced steady-state free precession images were acquired covering the entire ventricle. The imaging parameters included TE/TR= 1.8/4 ms; FOV= 27 cm; α = 55°; slice thickness= 8 mm; receiver bandwidth= \pm 125 KHz; acquisition matrix= 256x224; VPS= 10; and cardiac phases= 20. Volumetric analysis was performed by two experienced observers using Mass Analysis software (6.0v, MEDIS, Netherlands). Volume measurements were matched to the pressures to obtain pressure-volume loops.

Results:

Figure 2 (a) shows an example of a short-axis magnitude image during diastole with the contours used for delineating the LV myocardium. The arrow in the LV blood pool indicates the location of the pressure sensor. Figure 2 (b-d) shows the radial and circumferential components of displacement and the corresponding stiffness map obtained from the spherical shell analysis during the diastolic phase (pressure = 8.61 mmHg). The mean shear stiffness in the region of interest (ROI) was 6.4 ± 1.1 kPa. Figure 3 (a) shows a plot of stiffness and pressure variations during the cardiac cycle in one of the animals. The corresponding pressure-volume loop and stiffness-volume loop is shown in figure 3 (b). Figure 3 (c) shows the linear correlation ($R^2 = 0.84$) between stiffness and pressure obtained from all animals during the cardiac cycle. The LV pressure in all pigs ranged from 2 to 85 mmHg and shear stiffness ranged from 5.1 to 9.89 kPa during the cardiac cycle.

Discussion:

The results show variation in shear stiffness during the cardiac cycle, indicating that the myocardium is stiffer in systole than in diastole. A strong linear correlation was observed between stiffness and pressure. Excellent agreement between the stiffness-volume loops and the P-V loops in these animals was observed, implying stiffness-volume loops can possibly be used as noninvasive identifiers of cardiac disease states. This study indicates the in vivo feasibility of cardiac MRE and its ability to spatially resolve the stiffness of the myocardium throughout the cardiac cycle.

References:

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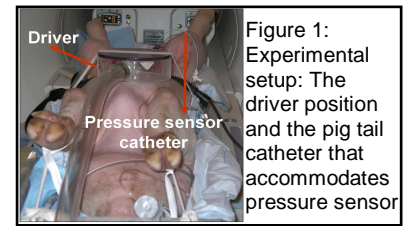


Figure 1: Experimental setup: The driver position and the pig tail catheter that accommodates pressure sensor

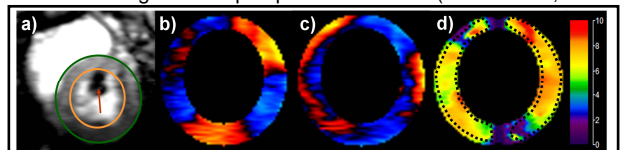


Figure 2: (a) A short-axis magnitude image during diastole with contours delineating the LV myocardium and an arrow in the blood pool indicating the pressure sensor. (b, c) MRE wave images of the LV myocardium showing one offset of the radial and circumferential components of displacement, respectively. (d) The corresponding stiffness map obtained from the spherical shell analysis at a pressure of 8.61 mmHg with a mean stiffness in the ROI of 6.4 ± 1.1 kPa.

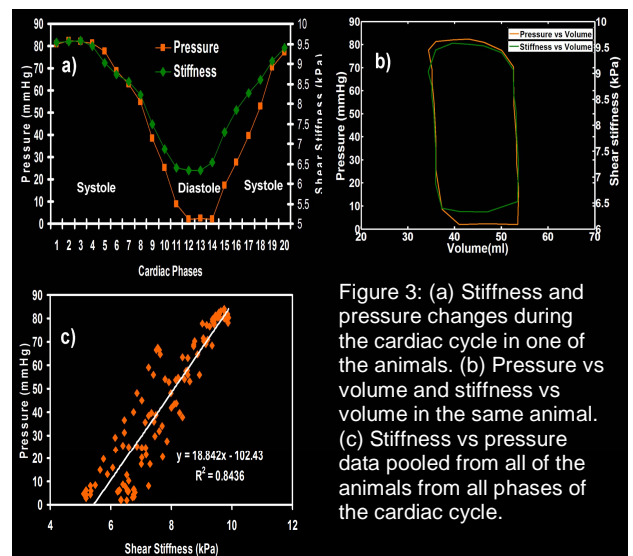


Figure 3: (a) Stiffness and pressure changes during the cardiac cycle in one of the animals. (b) Pressure vs volume and stiffness vs volume in the same animal. (c) Stiffness vs pressure data pooled from all of the animals from all phases of the cardiac cycle.