# Regional Quantification of Myocardial Stiffness Using MR Elastography

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**Introduction:** The mechanical properties of the myocardium are known to be essential for normal cardiac function [1-4]. Myocardial stiffness is known to be a highly significant diagnostic and prognostic metric in myocardial infarction. *Ex vivo* stretching techniques are performed without *in vivo* loading conditions, and without *in vivo* myocardial geometry, hence they are not applicable clinically. Pressure/volume-based techniques give information primarily about the ventricular cavity (not the myocardium), are global (not regional), are invasive, and require technical precision [5]. It has been recently demonstrated that magnetic resonance elastography (MRE) [6] can be adapted to measure the shear modulus of myocardium. However, to date, no studies have attempted to measure *in vivo* myocardial stiffness in myocardial infarction. Therefore, the purpose of this study was to regionally quantitate effective stiffness in infarcted and remote, non-infarcted myocardium using MRE.

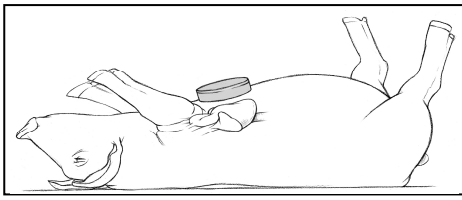

**Figure 1. Acoustic Driver.** A drum driver is placed on the chest wall of the pig to induce 80Hz cyclic motion in the heart. These waves are imaged by MRE and used to calculate stiffness.

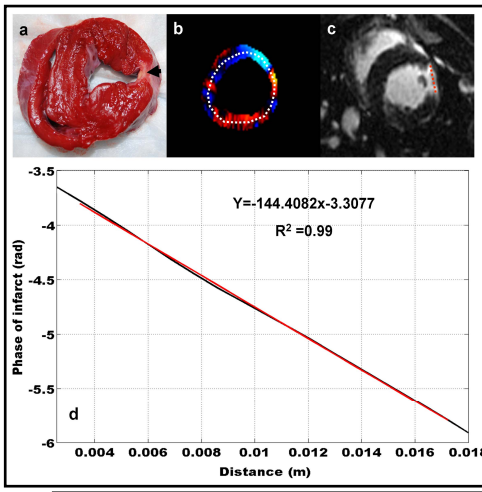


**Figure 2: a)** *Ex vivo TTC* staining image with an arrow identifying the infarct region. **b)** Radial component of displacement image showing a white dotted contour to extract the propagating waves along the contour. **c)** DE image showing the infarct region hyper-enhanced and a red dotted line on the hyper-enhanced region shows the region where the phase data is extracted to obtain the infarcted stiffness (i.e. intersection of infarcted region and 1D wave data is used for stiffness calculation). **d)** Plot of infarcted unwrapped phase of first harmonic (black) versus distance and the corresponding straight line fit (red) used to estimate stiffness. Slope of the line is substituted in the equation $\lambda=2\pi/\text{slope}$ to determine wavelength ($\lambda$). Once the wavelength is known, stiffness ($\mu$) is calculated using the equation $\mu = \rho(\lambda * f)^2$, where $\rho$ is the density of the myocardium (1000kg/m$^3$) and $f$ is the excitation frequency. Similarly, this analysis was repeated for remote, non-infarcted myocardium.

**Methods:** Myocardial infarction was induced in thirteen male pigs (mean weight 43.3 ± 3.6 kg) by embolizing the circumflex artery in compliance with our institutional animal care and use committee recommendations. After an interval of three weeks in which the infarcts were allowed to fibrose [4] MRI was performed on all 13 animals. *In vivo* cardiac MRI was performed under inhalation anesthesia and mechanical ventilation. All imaging was performed in a 1.5 Tesla MRI scanner (Signa Excite, GE Health Care, Milwaukee, WI). The pigs were positioned in the supine position and placed feet first into the scanner. A standard cine steady state free precession sequence (SSFP) with 20 cardiac phases was used to acquire short-axis slices covering the entire left ventricle. Delayed enhancement (DE) imaging was performed following infusion of a commercially available gadolinium-based contrast agent with 0.2 mmol/kg of gadodiamide (Omniscan, GE Healthcare Inc., Princeton, NJ) in the same short-axis plane prescribed by the SSFP sequence so as to locate the infarct on DE short-axis slices (figure 2c). MRE was performed on the infarcted region of the LV indicated by the DE images. For MRE, mechanical waves were introduced into the heart by a pneumatic driver system as shown in figure 1. A cine gradient echo MRE sequence [6] was used to obtain wave displacement images at multiple cardiac phases. Imaging parameters included TE/TR= 9.3/12.5 ms; FOV= 35 cm; α= 30°; slice thickness= 8 mm; acquisition matrix= 220x64; receiver bandwidth= ±62.5 kHz; SENSE acceleration factor= 2; excitation frequency= 80 Hz; heart rate= 86-146 bpm; Views per segment= 4; cardiac phases= 10; 4 MRE time offsets were acquired; 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. Each motion-encoding direction was acquired within a heart rate dependent breath hold of ~14 sec. The short-axis images for each pig were masked with epicardial and endocardial contours to obtain only the left ventricular (LV) myocardium. A 1D phase gradient [7] analysis was performed on the radial component of motion (figure 2b) to obtain stiffness estimates in the remote, non-infarcted (region 180$^0$ opposite to the infarcted region) and infarcted myocardium as shown in figure 2. After MRE, the pigs were sacrificed using euthanasia solution and short axis slices that approximates MRI/MRE images were TTC stained to demonstrate the myocardial infarction (figure 2a). Uni-axial mechanical tensile testing was performed on remote and non-infarcted myocardium from one of these slices. The signed rank test was performed to determine the significant difference ($p<0.05$) between infarcted and remote, non-infarcted myocardium both from MRE and mechanical testing.

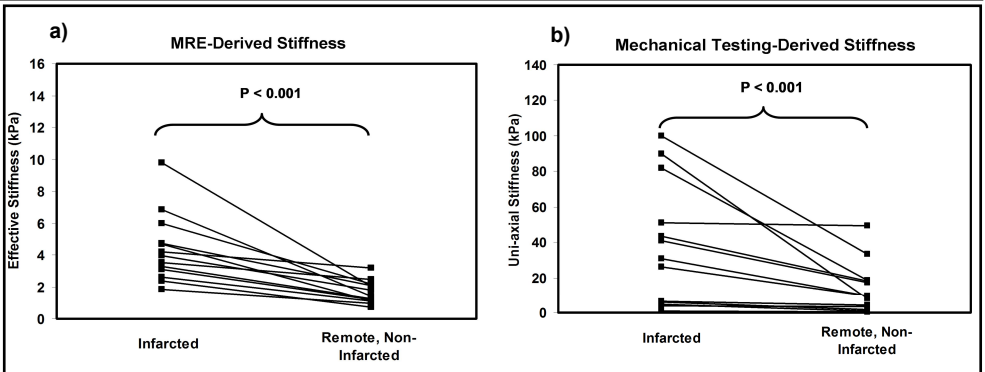


**Figure 3: a)** Plot of MRE-derived stiffness measurements at end-diastole for infarcted and remote, non-infarcted region in each pig **b)** Similarly, plot for mechanical testing-derived stiffness estimates.

**Results:** MRE-derived stiffness of infarcted myocardium was significantly ($p < 0.001$) greater than that of remote, non-infarcted myocardium within the same pig (Figure 3a). The mean infarct stiffness value from all pigs for MRE was 4.4 ± 2.2 kPa while the remote, non-infarcted myocardium mean stiffness value was 1.7 ± 0.7 kPa. Mechanical testing also showed that the stiffness of infarcted myocardium was significantly greater than that of remote, non-infarcted myocardium within the same pig (Figure 3b). The mean infarct stiffness value for the mechanical tensile tests was 37.4 ± 34.8 kPa while the remote, non-infarcted myocardium mean stiffness value was 13.5 ± 14.3 kPa.

**Discussion:** This study demonstrated that MRE can assess regional differences in stiffness between infarcted and remote, non-infarcted myocardium. The results showed a highly significant difference between infarcted and remote, non-infarcted myocardium using both MRE and mechanical tensile testing. However, MRE and mechanical testing stiffness cannot be compared against each other because of many limitations.

**References:1.** Litwin SE, et al, Circulation. 1991;83(3):1028-1037. **2.** Boluyt MO, et al, Eur Heart J. 1995;16 Suppl N:19-30. **3.** Zile MR, et al, NEJM 2004;350(19):1953-59. **4.** Holmes JW, Ann Rev Biomed Engg 2005;7:223-253. **5.** Mirsky I, et al, Circ Res. 1973;33(2):233-243. **6.** Kolipaka A, et al, Magn Reson Med. 2010;64:862-870. **7.** Manduca A, et al, Med Image Anal. 2001;5(4):237-254.