MRI assessment of myocardial diastolic elastic modulus and viscosity: validation and preliminary results in an animal model and normal volunteers

H. Wen[1], E. Bennett[1], N. Epstein[1], J. Plehn[1]
[1]NHLBI, National Institutes of Health, Bethesda, MD, United States

Background

Approximately half of patients experiencing congestive heart failure present with a normal left ventricular ejection fraction. Perturbations in material properties affecting ventricular pressure/volume relationships likely play an important role in the “stiff heart syndrome” yet noninvasive tools permitting the accurate assessment of myocardial elasticity are extremely limited.

Methods

We developed a MRI technique to assess the elastic modulus (EM) and the viscosity of local myocardial wall segments in diastole based on ventricular pressure data and myocardial displacement data. Using phase-contrast (PC) velocity mapping of blood flow and the Navier Stokes relationship, we mapped the dynamic pressure distribution in the ventricles during diastole, and also measured the concurrent myocardial wall displacement using displacement-encoding with stimulated-echoes (DENSE). These data showed a pulse-wave phenomenon, where ventricular pressure waves bounce within the elastic walls, causing the strain pattern in the walls to conform to the pressure gradients in the ventricles. We quantified this phenomenon in terms of the longitudinal gradients of strain in a wall segment and the pressure gradients in the surrounding blood flow:

mean pressure gradient + inertial force = E(1+*$\tau\partial/\partial t$*) (strain gradient),

where E is the elastic modulus of the myocardium, τ the viscous delay time constant (VDTC) is the ratio of viscosity over E, and the inertial force came from the acceleration of the wall segment. The MRI data of pressure and strain gradients were fitted to this relationship to give estimates of the viscoelastic constants.

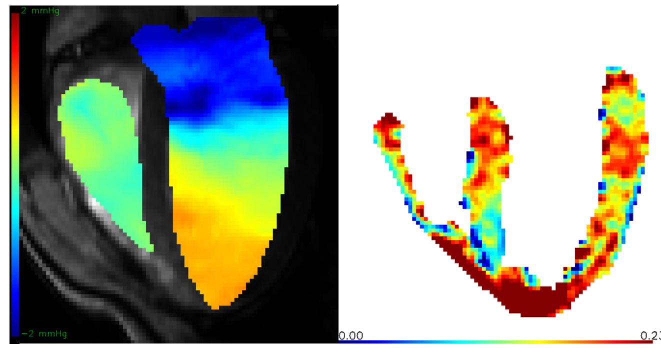

Fig.1 Relative pressure map (-2 to 2 mmHg scale) and longitudinal strain map in a long-axis cross section of a human heart.

In a group of 10 beagles we compared the MRI results with direct strain gauge measurements of muscle elasticity immediately post-mortem. We also compared the MRI estimates with global chamber compliance based on intraventricular pressure transducers. In a group of 6 normal volunteers we obtained the viscoelastic parameters for the lateral wall and the septum. The DENSE and PC velocity sequences were gated to the respiration of the volunteer, and the entire data set took 20 minutes to acquire. The spatial and temporal resolutions were $1.5\times3\times8$ mm^3 and 20 ms.

Results

Figure 1 shows an example of wall strain and ventricular pressure maps of a volunteer. The comparison of EM and VDTC by MRI and strain gauge is shown in Figure 2. In the papillary muscle where muscle fibers are aligned, the mean EM was 7.6 kPa, in agreement with the range of 5.5 kPa to 10 kPa from Usyk, Mazhari and McCulluch, using global chamber compliance data from intra-ventricular pressure transducers (Usyk et. al., J. Elast. 2000; 61:143-164). The EM values of the volunteers are summarized in Fig.2.

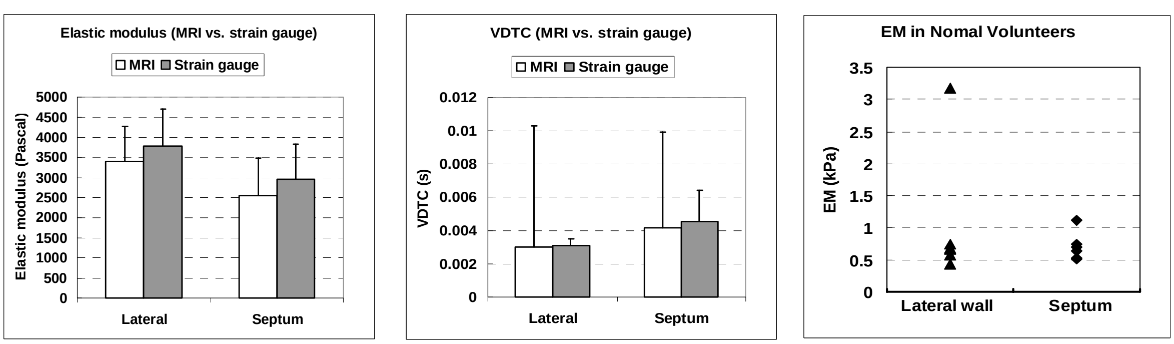

Fig.2 Left and Mid: EM and VDTC comparisons in dogs between MRI and strain gauge measurements. Right: EM values in 6 normal volunteers. The out-lying point was from a 58 yr male with high resting heart rate.

Conclusions

Noninvasive, regional assessment of myocardial stiffness using DENSE and PC velocity mapping is accurate in a canine model and feasible in humans. Further validation in animal models with stiffened left ventricle is underway and parallel imaging and processing is being tested to shorten the scan time in humans.