Measurement of Shear Stiffness in the Heart Using Magnetic Resonance Elastography: Initial Feasibility

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Introduction:

Heart disease is the leading cause of premature death in the United States [1]. Current methods for performing cardiac MR imaging provide a variety of useful information including: function, viability, perfusion, infarct status and size. However, these techniques do not assess the mechanical properties of myocardium, a parameter which is of great interest in the assessment of numerous cardiac disease processes.

A novel MR imaging technique, known as MR elastography (MRE) [2] has been shown to accurately measure the shear stiffness of a variety of organs including the prostate [3], and breast [4]. The technique applies cyclic motion encoding gradients synchronized with mechanical shear waves and a phase contrast imaging sequence to estimate mechanical stiffness. The aim of this work was to assess the feasibility of phase contrast MR imaging techniques for the assessment of shear stiffness in a simple heart model.

Materials and Methods:

A spherical phantom with internal radius and wall thickness of 36.5 mm and 8.75 mm, respectively was constructed from a silicone rubber composite [Wirosil, BEGO, Germany] which can be easily formed into a variety of shapes and provides adequate signal when imaged in MR. Figure 1(a) shows the experimental setup used to perform MRE on the phantom and consists of a mechanical oscillator, internal bladder, and t-piece connector. The t-piece provided a direct contact between the mechanical driver and phantom while allowing the internal air pressure of the sphere to be monitored and varied remotely during imaging. The phantom was placed inside a transmit/receive head coil and all imaging was performed on a 1.5T MR scanner (GE Health Care, Waukesha, WI). MRE data were acquired using the following parameters: TR/TE 150/22.5 msec, 256x64 acquisition matrix, and a 14 cm axial field-of-view. The frequency of the mechanical shear waves was 300 Hz and four separate phase offsets were applied to obtain an image of the propagation of the shear wave in the wall of the phantom. MRE data were then acquired at five separate internal air pressures covering the range of zero to 60 kPa above atmospheric. For each internal pressure, the wavelength of the shear wave was measured and the shear stiffness was calculated using the relationship $\mu=\rho f^2 \lambda^2$, where, μ, ρ, f and λ are the shear stiffness, density, driving frequency and wavelength of propagating waves. A theoretical estimate of the shear stiffness was calculated using the Timoshenko model [5] which estimates stiffness using the equation: $\mu = \frac{p r_i (4 r_i + r_o^2 + r_i r_o)}{4(r_o^3 - r_i^3)}$ where p is the applied pressure, r_i the inner, and r_o the outer radius of the sphere.

Results:

Figure 1(b) shows the phase difference image of an axial slice through the center of the phantom at an internal pressure of 0 kPa above atmospheric. The phase is linearly related to the amplitude of the propagating shear wave. Figure 1(c) is a volume rendered image of the propagating shear wave in the spherical phantom in which the displacement has been amplified significantly. The actual displacement caused by the shear wave was 145 microns. Figure 1(d) is a plot of the internal air pressure versus the shear stiffness of the phantom wall. The black curve represents the MRE based measurements while the red curve shows the theoretical values calculated using Timoshenko model. The figure also demonstrates that the MRE derived stiffness measurements are in good agreement with the theoretical model and that shear stiffness is linear over the pressure range studied. A least squares linear regression model was applied to both data sets providing slope and intercept values of 3.9 and 123.6 kPa for the experimental and 4.7 and 115.4 kPa for the mathematical model.

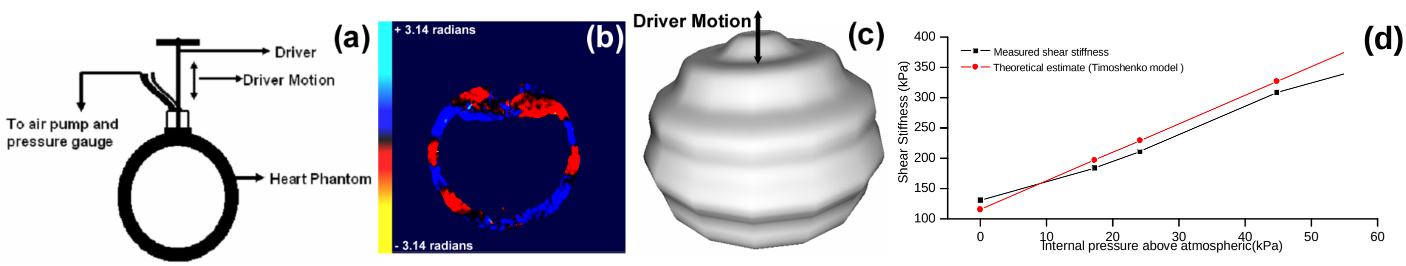

Figure 1: **(a)** Experimental setup showing the mechanical driver directly coupled to the top of the spherical phantom as well as the connection to the air pump**. (b)** Phase difference image showing propagating shear waves in the wall of the phantom. **(c)** Volume rendering of propagating shear waves on the surface of the phantom. The arrow indicates the direction of motion of the mechanical driver. **(d)** Measured and theoretical shear stiffness values in the wall of the phantom as a function of applied pressure.

Discussion:

We have demonstrated a non-invasive method for evaluating the mechanical properties of the wall of a spherical phantom of the heart. These results indicate that phase contrast based imaging techniques are sensitive measures of change in stiffness with increased pressure within this phantom. MRE based stiffness measures promise to provide a method for monitoring the change of transmural filling pressure, which is responsible for the change of left ventricular end-diastolic pressure, stroke volume and thus cardiac output through the Starling mechanism, by observing the regressive changes of wall stiffness and internal pressure. In-vivo measurement of shear stiffness cannot be applied using direct physical contact of the mechanical driver to the heart. However, previous work has shown that the application of an acoustic driver coupled to the abdomen of volunteers can be used to generate shear waves in the liver [6]. We expect that a similar device can be applied to measure in-vivo myocardial stiffness for a variety of cardiac diseases.

References:

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