Blood Vessel Characterization by MR Elastography

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Background: Hypertension affects over 140 million people in North America, many of which do not know they have it. This condition is one of the most important risk factors in the development of cardiovascular diseases leading to premature death. Hypertension and subsequent arterial stiffness are determined by vascular smooth muscle tone and by the elastin/collagen content of the vessel wall. Magnetic resonance elastography (MRE) is a new technique to image tissue motion in the order of hundreds of nanometers enabling the imaging of the physical properties of tissue such as stress and strain. Our hypothesis is that MRE can be used to image early hypertensive changes enabling targeted therapy and prevention of secondary cardiovascular disease. The purpose of this study is to demonstrate that MRE can be applied to blood vessels and can identify early hypertensive changes.

Methods: Using a vessel phantom model of thin-walled latex tubing, harmonic mechanical pressure waves were applied at frequencies of 100-500 Hz, and imaged using a modified phase contrast MR technique sensitive to cyclic motion. Wall properties and tension were varied by changing the static pressure and wall thickness. The effects of stenosis were tested. Following these preliminary studies, a trial of the technique was performed using *ex vivo* excised aortic segments of hypertensive(N=5) and normal control(N=3) pigs. Hypertensive pigs had a mean arterial pressure significantly higher than control pigs (115 ± 11 vs. 173 ± 12 mmHg, $p=0.05$). Mean duration of hypertension, induced by renal artery stenosis, was 3 months. Wavelength was measured for each frequency applied (100-500 Hz) and normalized to a stimulation frequency of 100 Hz. Initial histologic examination was performed on the ex vivo aortic segments to measure wall thickness. In vivo human experiments utilized harmonic mechanical pressure waves applied over the femoral head with imaging plane on the femoral artery.

Theory: The mechanical model used to predict wave propagation in our system is the thin-walled elastic tube model. Using this model, the Moens-Korteweg equation predicts that: $Et = 2\rho a\lambda^2 f^2$, where E is Young's modulus, t is wall thickness, ρ is filling fluid density, a is the inner radius, λ is wavelength, and f is frequency. From this equation, we can predict that variation in the Young's modulus-wall thickness product will be reflected in changing wavelength if all other variables are constant. Additionally, from the laws of energy conservation, the amplitude of an incident wave should equal the amplitudes of the reflected and transmitted waves through a focal stenosis.

Results: The experimental results demonstrated that propagating mechanical waves with amplitudes as small as 1 micron in the model vessel wall can be readily visualized. The measured wavelength varied with changing wall thickness and tension as expected. Varying the wall thickness and Et product, with constant stimulation frequency, progressively increased the wavelength as demonstrated in Figure 1. Applying varying degrees of occlusion (25%, 50%, and 75%) and directionally filtering the propagating wave allowed for accurate prediction of the applied stenosis by measuring the amplitudes of the incident and transmitted waves (19.7 ± 5.1, 47.9 ± 6.2, and 71.5 ± 5.5 percent stenosis, respectively).

Figure 1

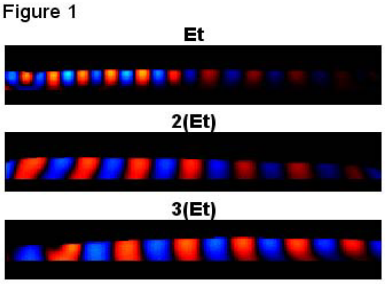


Figure 2

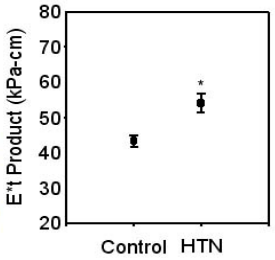
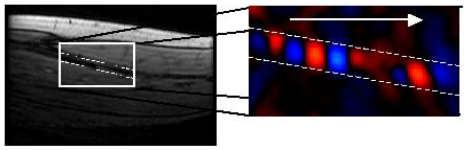


Figure 3



In the ex vivo aorta segments, the (Et) product was greater in the hypertensive vessels (54.1 ± 2.8 kPa-cm) compared to normals (43.2 ± 1.5 kPa-cm) (Figure 2). However, the histologic analysis demonstrates no significant difference between the intima-media wall thickness in the control (0.049 ± 0.012 cm) or hypertensive (0.054 ± 0.031 cm) aortas. Furthermore, experiments to verify that the MR wave propagation analysis could be applied to in vivo human arteries demonstrates a propagating wave within the local musculature with preferential propagation through the arterial wall (Figure 3).

Conclusions: The results indicate that this technique is a sensitive method for evaluating vessel wall mechanical properties. Furthermore, the technique can be applied to ex vivo aorta vessels and can detect early intramural hypertensive changes that alter the elastic properties of blood vessel walls before significant changes in wall thickness. This suggests that hypertension produces changes in the elastic properties of the vessel before the wall thickness changes. Finally, initial experiments suggest the feasibility of applying MR elastography in vivo.