Magnetic Resonance Elastography of the Lung parenchyma: Correlation of Shear Stiffness with airway opening Pressures

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Introduction: The mechanical properties of the lung parenchyma have a profound importance in normal pulmonary function and changes in these properties are key factors in the development of lung diseases. Conventional pulmonary function testing can only provide a global estimate of the mechanical properties of lung parenchyma and this provides motivation for developing imaging-based methods for assessing these properties regionally [1]. Magnetic resonance elastography (MRE, [2]), is a phase contrast MRI based elasticity imaging technique, that may provide this capability. However, its implementation in the lung is challenging due to several factors including low tissue density, poor ^{1}H MR signal properties as well as cardiac and respiratory motion induced artifacts. Previous small animal experiments with an invasive driver in direct contact with the lungs have indicated that it is feasible to quantitate lung shear modulus with ^{1}H MRE [3]. In this work, we hypothesized that it is possible to extend this approach to a larger animal model, using a more practical noninvasive driver. We tested this hypothesis in ten adult pigs, assessing our ability to observe the expected change in stiffness of lung parenchyma as a function of airway opening pressures (P_{ao}).

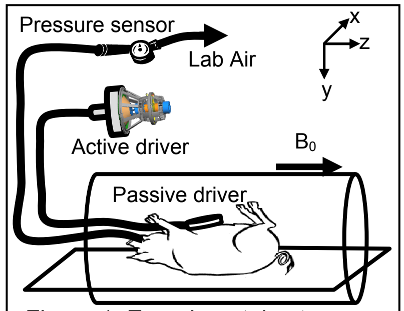

Figure 1: Experimental setup

Methods: All experiments were performed with a 1.5-T whole-body scanner (Signa EXCITE, GE Healthcare, Milwaukee, WI). Ten adult pigs were studied according to IACUC guidelines. The animals were euthanized by means of a fatal dose of anesthesia to remove cardiac and respiratory artifacts. An air line continuous with a pressure sensor and medical air source was introduced into the trachea of the pig to enable controlled inflation (and deflation) of both the lungs to any desired P_{ao}. For this study, the lungs were inflated to four P_{ao} (5, 10, 15 and 20 cm H_2O) and MRE was performed at each pressure. The animal was positioned supine with a pressure-activated passive drum driver placed on the chest anterior to the lungs as shown in Figure 1. A modified spin echo pulse sequence with two 5-ms motion encoding gradient lobes, placed one on each side of the 180° refocusing pulse was used to image the shear wave propagation. Other imaging parameters included: Imaging plane = coronal, frequency of motion = 100 Hz, FOV = 30 cm, acquisition matrix = 128x64, frequency-encoding direction = SI, motion-sensitizing direction = AP, TR/TE = 210/26 ms, slice thickness = 10 mm, and 4 phase offsets. A local frequency estimation algorithm with spatio-temporal directional filters was used for the calculation of shear stiffness maps (elastograms) of the lungs [4]. MRE-derived stiffness estimates in which the tissue density is assumed to be equal to 1000 kg/m^3 (default density estimate) were first calculated and termed as $\mu_{effective}$. To account for density differences between solid organs (i.e. ρ = 1000 kg/m^3) and lungs as well as variations associated with differing degrees of inflation as measured by P_{ao}, lung density values were estimated by measuring the average magnitude signal at the four pressure levels and calibrating them to previously reported values [5]. Stiffness values that incorporate lung density estimates were termed as $\mu_{dens\ corr}$. The change in the mean effective stiffness and density corrected stiffness as a function of P_{ao} was studied using ANOVA with an α value of 0.01.

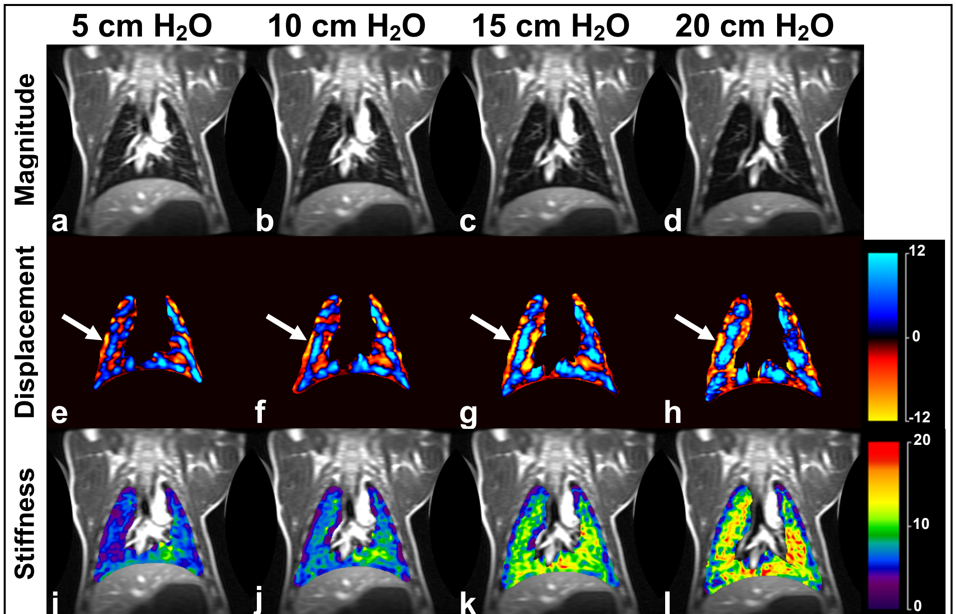

Figure 2: MRE results. (a-d) Magnitude images, (e-h) wave images, and (i-l) shear stiffness maps overlaid on the magnitude images, for the four P_{ao}. The shear wavelength (arrows) and the effective stiffnesses increase with P_{ao}.

Results: Figure 2 shows typical results obtained from the MRE experiments. The top row shows the magnitude images at the four P_{ao} values. The increase in the lung volume and decrease in the lung MR signal with increase in P_{ao} is evident. The middle and bottom rows show the corresponding displacement images and effective stiffness maps. From these data the increase in the shear wavelength and shear stiffness is observable. Effective stiffness and density corrected stiffness values obtained in a region of interest with visually detectable wave amplitude from all the animals are plotted as a function of P_{ao} in figures 3a and 3b respectively. P_{ao} dependent increase in both sets of stiffnesses is visible, is statistically highly significant and is in agreement previously reported values [5].

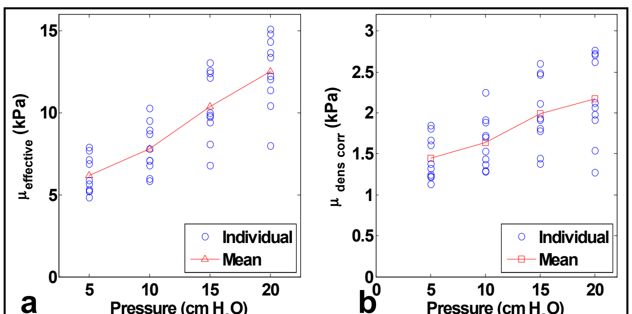

Figure 3: (a) Effective stiffness values and (b) density corrected stiffness values for the four P_{ao}.

Conclusion: These data indicate that the shear stiffness of lung parenchyma can be measured and its change as a function of airway opening pressure can be monitored with MRE using a noninvasive driver.

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References: (1) Suki et al., Respir Physiol Neurobiol 163 : 33-43, 2008. (2) Muthupillai et al., *Science* 269: 1854-1857, 1995. (3) McGee et al., MRM 59 :14-18, 2008. (4) Manduca A et al., *Med Imag Anal*. 5: 237-254, 2001. (5) Jahed M et al., *J Appl Physiol* 76(2):565-571, 1994.