Regional Measurements of Pulmonary Strain Index using a Low Field Portable Device

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Target Audience: Pulmonary researchers and ICU clinicians.

Purpose: The overall purpose is to develop a portable, low field MR device for use in the ICU to assist clinicians treating mechanically ventilated ARDS patients. If positive end expiratory pressure (PEEP) is too low, collapsed lung regions either fail to open or undergo repeated recruitment/derecruitment patterns. If PEEP is too high, the lung can be over-distended with tidal ventilation. Both conditions may contribute to further ventilator induced lung injury. At present, the mortality rate (20-40%) is unacceptably high. Current ventilators provide a measure of the shape of the pressure/volume curve, the "stress index", which is thought to distinguish between PEEPs that are too high or too low. This index is used to titrate PEEP to an optimal level [1]. Because of the highly heterogeneous pressure volume relationship for different regions of a diseased lung, this whole lung index is likely inadequate. Our device, a MR Lung Density Monitor (MR-LDM) is designed to provide regional stress indices. Previously we reported a prototype single-sided NMR magnet that produces a remote homogeneous field region that when placed on the chest surface, it interrogates a region of size ~20cc inside the lung parenchyma [2]. Prior results required long breath holds (~40s) at different lung volumes. For practical use, the proposed device will make measurements while the subject is freely breathing. As a step towards that goal, we implemented a pseudo free breathing protocol [volumetric square wave (Fig. 1)] to demonstrate our ability to measure regional lung density versus lung volume, which is a regional strain index, complementary to the stress index.

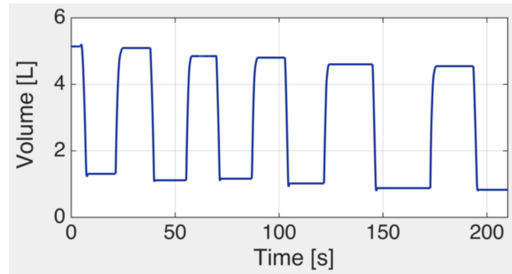

Figure 1. Example of "square-wave" breathing.

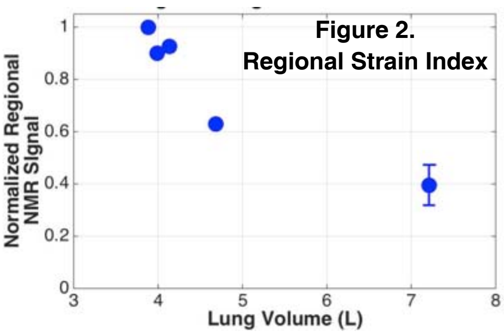

Figure 2. Regional Strain Index

Methods: The MR-LDM (12kG weight, 54x37x4cm) is inlaid in a custom bed that can be positioned horizontally or vertically. The subject lies supine or, to explore gravitational gradients, is seated upright. The square wave breathing protocol lasts 3.5 min during which the subject breathes between two target lung volumes. At the end of inspiration and expiration, the subject holds their breath for ~10 seconds or as long as is comfortable. The subject is asked to inhale to Total Lung Capacity (TLC) and then to exhale close to either Functional Residual Volume (FRC) or Residual Volume (RV). The subject's airflow is monitored with a spirometer (Pneumotrac, Morgan Scientific) and NMR CPMG data is continuously acquired. NMR data coinciding with zero airflow periods is then binned to high and low volumes. The CPMG data is processed as described previously [2] resulting in averaged phased real NMR spectra for each individual zero flow period. We assume the subject reaches TLC during each inhalation. The spirometer records lung volume differences from TLC achieved for each exhalation. TLC is estimated from age, height and gender [3].

Results: An example of the regional strain index in a healthy subject is shown in Figure 2. The 4 data points at the 4 lower lung volumes are the average signal intensity during each of 4 separate exhalation breath-holds during the 3.5 minute data acquisition. The single data point at the high lung volume is the average from the 4 breath-hold measurements obtained at TLC at the end of each inhalation. The data show lower lung volumes close to RV in three cases and near FRC in one case. Additional data were obtained with the subject upright (Figure 3) while breathing between TLC and RV. These data show the signal intensity changes were much smaller at the apex of the lung compared to 20cm below, near the base of the lung.

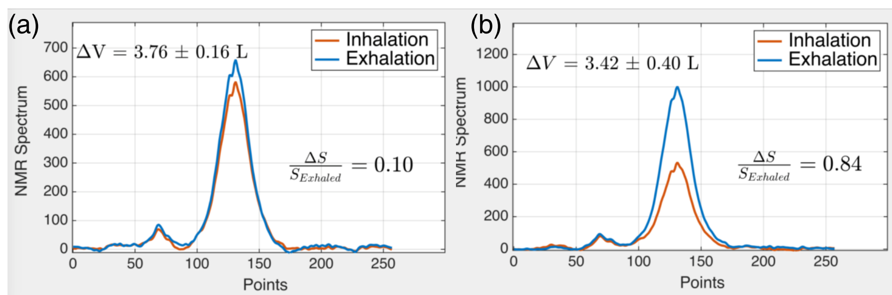

Figure 3. NMR spectra with subject upright at TLC (Red) and RV (Blue). Signal measured at (a) top of lung & (b) 20cm below.

Discussion and Conclusion: We have demonstrated a regional stress curve from a 3.5 min acquisition. Using density changes, we have also demonstrated the ability to detect differences in specific ventilation, due to gravitational height. Note that Figure 2 shows the expected monotonic decay in signal intensity with increasing lung volume. However, it is clear that the sensitive volume of the MR-LDM does not lie completely within the lung parenchyma. The known distribution of the magnetic field in the target region will allow correction for this partial volume effect. We will simultaneously measure P_{ao} to estimate regional pulmonary compliance, i.e. the inverse of regional lung density vs. P_{ao}, and which will also be used to determine a regional stress index.

References: 1. Grasso et al. Am J Respir Crit Care Med 176;761-767(2007). 2. Dabaghyan et al. NMR Biomed 2014, DOI: 10.1002/nbm.3149. 3. Roberts et al. Thorax 1991;46:643-650.