Quantification of Pulmonary Edema in Heart Failure Patients and Controls with B1-Field Corrected Free-Breathing MRI

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Introduction: In cardiogenic pulmonary edema, increased hydrostatic pressure results in extravasation of fluid into the interstitial and alveolar spaces of the lungs. Clinical diagnosis is made primarily from physical symptoms and confirmed with chest x-rays, where significant edema can be seen as increased density of the flooded lungs. Magnetic resonance has been proposed as an alternative imaging modality for edema[1,2], but existing techniques have not accounted for B_1 (radiofrequency) field heterogeneity, which varies greatly between the left and right lung[3]. Additionally, traditional breath-hold imaging is onerous for many patients with pulmonary edema and often subject to mis-alignment between breath-holds even in healthy subjects. We describe a new free-breathing MRI technique for the measurement of pulmonary edema that incorporates B_1 field heterogeneity correction and its application to a population of healthy volunteers and heart failure patients with suspected pulmonary edema. Invasively measured pressures in heart failure subjects are used to provide validation of non-invasive MRI estimations of pulmonary edema.

Methods: *Image Acquisition*: 7 healthy male volunteers (31±9 yrs) and 10 heart failure patients (53±14 yrs; 8 male) were imaged on a Siemens Sonata 1.5T MRI scanner with informed consent and IRB approval. A half-Fourier single-shot turbo spin-echo (HASTE) pulse sequence was used with typical acquisition parameters: body coil excitation and reception, 1.4×1.4×8.0 mm^3 resolution, ECG (end-diastolic) gating, 12ms effective TE, >5s effective TR, 5min total acquisition time. 10-12 sagittal slices of the chest provided complete lung coverage.

Water Quantification: Each image acquisition was repeated 7 times during normal free-breathing. An automated morphing algorithm[4] non-rigidly transformed each image to a reference respiratory phase (end-expiration) and lung signal intensity was corrected for normal variations due to changes in the partial volume of air during respiration[5]. Images were acquired with two excitation flip angles (θ=60°, 120°) and the Double Angle Method[3,6] was adapted to measure B_1 field distribution over the entire lung. The lung was manually traced once per sagittal slice and automatically segmented into square regions of interest (ROIs) approximately 3.5cm^2 in area. A regional signal intensity thresholding algorithm removed contributions from bright blood vessels and lung signal intensity was referenced against a large region of the liver (mid-sagittal) with known water density (~70%).

Validation: In heart failure patients, the root cause of pulmonary edema can be directly (invasively) measured via the left ventricular end-diastolic pressure (LVEDP), providing gold-standard validation for MRI-derived pulmonary edema. B-type natriuretic peptide (BNP) concentration in blood serum has been highly correlated with increased heart pressures during heart failure, providing secondary validation. As part of a standard clinical workup of heart failure subjects, LVEDP was measured via catheter immediately prior to MRI examination and serum BNP immediately afterward.

Results: Average lung water density for healthy subjects was found to be 23±2% (percentage water per unit volume), consistent with previously reported MR measurements[2,7,8,9]. In heart failure subjects, water content was significantly more varied, ranging from 16% to 37%, with good correlation to LVEDP (R^2=0.77, Fig. 1) and BNP (R^2=0.75). LVEDP and BNP also correlated well with each other (R^2=0.57). Representative lung water density maps for a mid-sagittal slice of the right lung in both a healthy subject and a heart failure patient (Fig. 2) show an anterior-posterior gradient, previously seen and attributed to gravity effects[2,7,8]. For a prescribed excitation flip angle of 90°, the average flip angle experienced was 77±2° in the left lung and only 61±2° in the right lung. Correcting for B_1 field heterogeneity resulted in an absolute increase of lung water density by 10±2% in the right lung, with negligible effect in the left lung.

Conclusion: A free-breathing MRI approach to pulmonary edema measurement was implemented using a single-shot HASTE sequence on healthy subjects and heart failure patients, providing comprehensive lung water density. B_1 field heterogeneity correction significantly altered absolute water density, particularly in the right lung. Lung water correlated well with gold-standard measurements (LVEDP, BNP) in heart failure subjects.

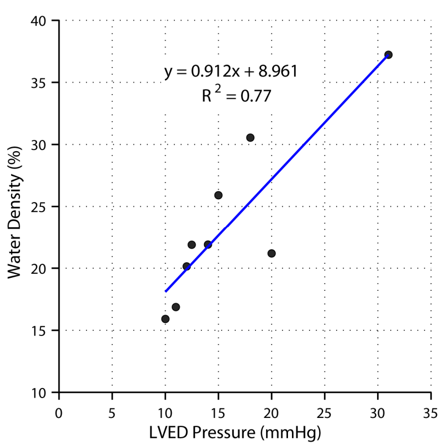

Fig. 1 (left) Left ventricular end-diastolic pressure correlates well with MRI-derived water density in heart failure subjects.

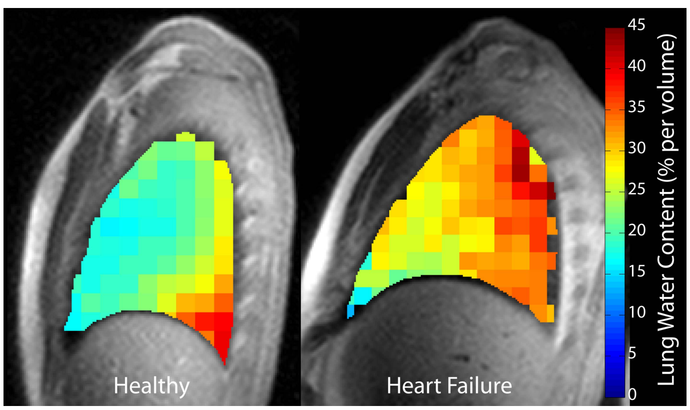

Fig. 2 (right) Lung water density maps of the right lung (mid-sagittal) show increased edema in a heart failure subject (average lung water 37%) vs. a healthy subject (22%).

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