Free Breathing Ultra Echo Time Lung Imaging with Variable Density 3D Radial Sampling

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INTRODUCTION: Emerging cardiopulmonary MR techniques promise to provide non-invasive assessment of pulmonary artery hemodynamics[1], lung perfusion[2], and lung ventilation[3]. Detailed lung structure is poorly visualized with conventional MRI due to low tissue density and rapid signal decay. Ultra-short echo time (UTE) imaging holds promise to dramatically enhance signal from short T2/T2* species. Despite a variety of attempts[4] and success in animals[5], UTE lung imaging has remained challenging in human subjects. Even with UTE methods, however, lung signal is still an order of magnitude lower than that of fat due to long T1 and low tissue density. Consequently, 3D UTE imaging is extraordinarily sensitive to artifacts. In this work, we develop a robust technique for free -breathing, high resolution 3D UTE lung imaging that aims to mitigate sources of diagnostically obscuring artifacts.

METHODS: Radial sequences utilized for 3D UTE have low SNR efficiency and are highly sensitive to eddy currents and to aliasing from objects outside the prescribed field of view (FOV). Our 3D UTE approach utilizes a minimum-phase slab-select pulse that reduces TE to the minimum time (~80μs) required for our commercial, unmodified hardware to switch from excite to receive (Figure 1). In addition, the data acquisition (DAQ) sampling rate is set to double the bandwidth required for the prescribed FOV. These improvements limit the superior/inferior (S/I) excitation FOV and effectively double the imaging FOV without penalty. To improve the SNR efficiency, we utilize variable bandwidth readouts designed with an arc-length based optimization. These gradients sample the oversampled center of k-space faster than the singularly sampled edge of k-space, leading to a theoretical ~35-40% increase in SNR. The increased slewing with this readout has the potential to increase eddy currents; however, we compensate for eddy currents retrospectively utilizing per subject thin slice calibrations[5].

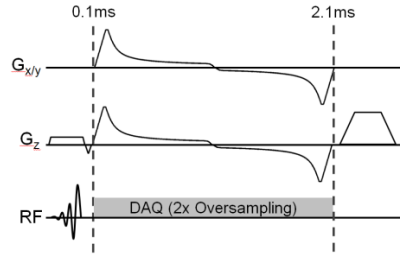

Figure 1. *Pulse sequence diagram for dual-echo variable density 3D UTE.*

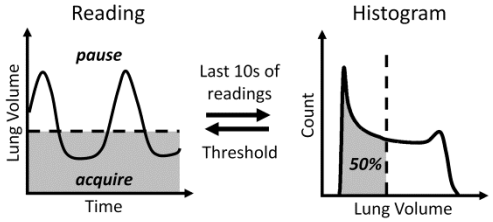

Figure 2. *Respiratory motion was minimized with real-time gating to end-expiration through adaptive feedback from the respiratory bellows signal with a 50% acceptance window.*

To mitigate respiratory motion without interrupting steady state conditions, we utilize bellows gating with adaptive feedback from the respiratory bellows to define an acceptance window as portrayed in Figure 2. An adaptive threshold is set based on the last 10s of bellows data. When above this threshold, the system continues to collect the same projections to maintain steady-state. When below the threshold, projections are acquired in a pseudo-random order to mitigate artifacts for incomplete respiratory compensation and cardiac motion. Images are reconstructed with non-Cartesian iterative SENSE[6] utilizing low-resolution images as estimates of coil sensitivities.

All experiments were performed on a 1.5T clinical scanner (MR450w, GE Healthcare, Waukesha, WI) with an 8ch cardiac coil (HD Cardiac, GE Healthcare, Waukesha, WI). Common imaging parameters include: dual-echo ($TE_{1/2}$=80μs/2ms), TR=4.1ms, Flip=5°, 1ms readout / echo, 1.25mm isotropic image resolution, 32x32x32cm^3 prescribed FOV, 38,000 projections, 50% respiratory gating efficiency for a total scan time of 5min 30sec during free breathing. Quantitative SNR improvements and qualitative image quality were first accessed in phantoms with repeated measurements. Subsequently images were acquired in human volunteers during free breathing with full 3D chest coverage and reconstructed with and without proposed improvements.

RESULTS: In phantom experiments, using variable density imaging gradients led to a better than expected 48% increase in SNR in the first echo compared to ramp-sampled trapezoid gradients. We attribute this gain to reduced sensitivity to T2 decay due to shorter sampling times for all but the center of k-space. Variable density gradients were also found to be more robust to off-resonance artifacts. Representative first echo images demonstrating improvements are shown in Figure 3. DAQ oversampling (2x) reduces artifacts from the arms positioned outside the prescribed FOV. Gradient calibrations improve data consistency for central k-space samples, greatly improving image sharpness. Finally, SENSE reconstruction reduces noise-like sampling artifacts due to aliasing.

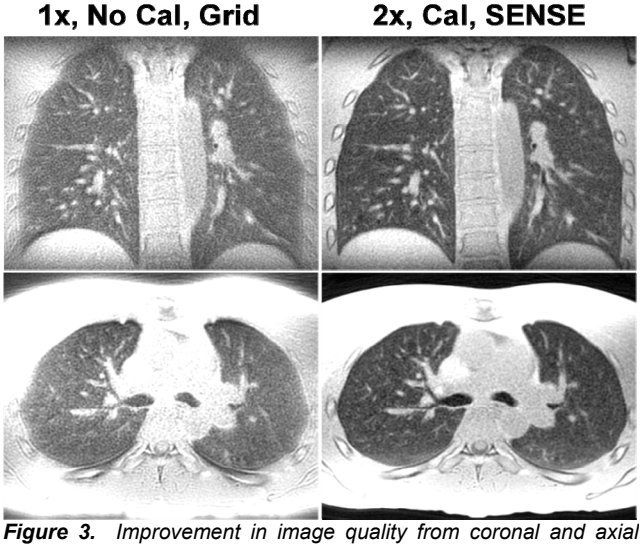

Figure 3. *Improvement in image quality from coronal and axial slices representing the 3D UTE volume. 2X≡ two times oversampling of readout, Cal ≡ gradient trajectory calibration*

DISCUSSION AND CONCLUSION: Progressive improvements to 3D UTE sampling in combination with robust, adaptive respiratory gating improves visualization of lung structural using MRI. Of note is the 3D isotropic high (1.25mm) resolution, enabling direct comparison of structures on pulmonary MRI with volumetric CT. Comparison studies of our pulmonary MRI method in cystic fibrosis, sarcoidosis, and scleroderma with CT are ongoing.

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REFERENCES:[1] Sanz *et al*. Radiology 243:70 [2] Hopkins *et al*. JMRI 32:1287 [3] Fain *et al*. MRI 32:1398 [4] Bergin *et al*. Radiology,179:777 [5] Togao *et al*. MRM 64:1491 [6] Gurney *et al*. ISMRM 05' p866 [7] Pruessmann et al. MRM 46:638