Acquisition of Spatially-registered Helium-3 and Proton 3D Image Sets of the Lung in less than 10 seconds using Compressed Sensing

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Introduction: Acquisition of hyperpolarized helium-3 (3He) and proton (1H) MR lung images during the same breath hold provides complementary functional and anatomical information [1]. The availability of such spatially-registered images greatly facilitates quantitative analysis of ventilation defects in 3He images. Ideally, an isotropic 3D acquisition (e.g., [2]) would be used for both the 3He and 1H images. However, this requires a breath-hold duration of roughly 20 seconds, which may be too long for subjects with compromised respiratory function. Compressed sensing (CS) makes use of the sparsity implicit in MR images to accelerate the acquisition without the need for a multi-channel RF coil [3]. In this study, we implemented accelerated 3D acquisition of 3He and 1H images within one breathhold by randomly undersampling the 3D *k*-space data, followed with reconstruction by minimizing the L-1 norm of the transformed images [3], and compared the accelerated acquisitions to their fully-sampled counterparts.

Methods: *Experimental setup*: Helium and proton studies were performed using a 1.5-T whole-body scanner (Avanto, Siemens Medical Solutions) equipped with the multi-nuclear option and a chest 3He RF coil (Rapid Biomedical). 3He gas was polarized by collisional spin exchange with an optically-pumped rubidium vapor using a prototype commercial system (Magnetic Imaging Technologies, Inc.). All experiments were performed under a Physician's IND (#57866) for imaging with hyperpolarized 3He using a protocol approved by our institutional review board. Informed consent was obtained in call cases. *Pulse sequences*: A 3D balanced steady-state free precession (TrueFISP) sequence [2] was used for both 3He and 1H. Parameter settings included: 3He: TR/TE = 1.86/0.79 ms, matrix = 128x88x52; and 1H: TR/TE = 1.79/0.74 ms, matrix = 128x110x64. Common parameters for both scans included: flip angle = 9°, spatial resolution = 3.9x3.9x3.9 mm, bandwidth/pixel = 1085 Hz. Total acquisition time was reduced to 4.3 s for 3He and 6.6 s for 1H at a random-undersampling acceleration factor (R) of 2, and to 2.8 s for 3He and 4.1 s for 1H at R=3, compared with 6.7 s for 3He and 9.7 s for 1H for the fully-sampled scans. (To keep the total acquisition time below 20 s, the fully sampled scans used elliptical sampling of the phase-encoding steps [i.e., the "corners" were not sampled]. The accelerated scans did not use elliptical sampling.) *Compressed-sensing setup*: Undersampling patterns were generated using a MonteCarlo algorithm, as described by Lustig et al [3]. The Cohen-Daubechies-Feauveau 9/7 (CDF 9/7) wavelet was used as the sparsifying transform. All CS reconstructions were implemented in MATLAB (The Mathworks, Natick, MA). Performance of the CS reconstruction was evaluated using mean absolute error (MAE) and the structural similarity (SSIM) index. *Human studies*: Two healthy subjects were scanned using only the 3He pulse sequence to test the performance of the undersampled acquisition and CS reconstruction. The first was scanned using R=2 and R=3 during a single breath hold, and the second was scanned using fully-sampled, R=2, and R=3 acquisitions, each during a separate breath hold. Three healthy subjects were scanned using the combined 3He and 1H acquisition. The first two were scanned using fully-sampled and R=3 acquisitions; each during a separate breath hold, while the third was scanned using fully-sampled and R=2 acquisitions.

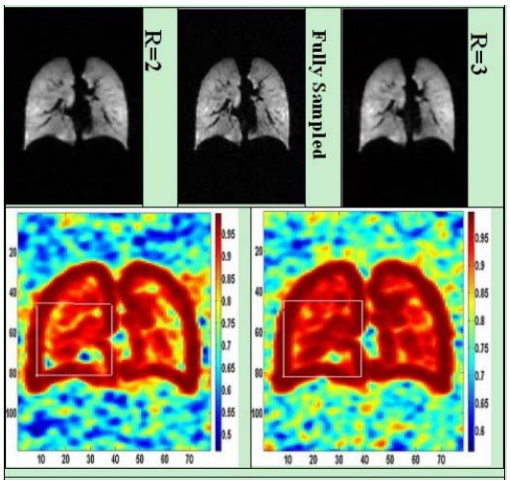

Fig. 1. Comparison of fully-sampled image with CS-reconstructed versions (R=2 and R=3) of the fully-sampled dataset. SSIM index maps, calculated from the 3 images in the upper row, are shown in the lower row, with fully-sampled vs. R=2 on the left and fully-sampled vs. R=3 on the right.

Results & Discussion: Performance of the CS reconstruction was evaluated by randomly undersampling a fully sampled 3He dataset, applying the same undersampling patterns used in the undersampled acquisitions, and reconstructing the images with the same algorithm and parameter settings. The SNR of the fully sampled 3He data was ~25, while the MAE values calculated from the reconstructed and original images were 5.1% for R=2 and 7.5% for R=3 (SNR and MAE values are averaged over all slices). **Fig. 1** illustrates use of the SSIM index to evaluate performance of the CS reconstruction at R=2 and R=3. The upper row shows three images used for comparison, and the lower row shows the SSIM index map calculated between the fully-sampled image and the corresponding reconstructed undersampled image. Mean SSIM index values for the lung region demonstrating the lowest values (lower part of right lung, region within the white rectangle) were 0.95 for fully-sampled vs. R=2, and 0.90 for fully-sampled vs. R=3 (maximum possible value is 1.0), which suggests reasonably good agreement between the reconstructed and original images.

Fig. 2 shows images reconstructed in 3 planes from the second subject scanned using the combined 3He and 1H 3D acquisition. The upper row shows the fully-sampled images, acquired during one breath hold, while the lower row shows the undersampled images, acquired with R=3 during a second breath hold. The accelerated images appear very similar to their fully-sampled counterparts even though the acquisition time was reduced by a factor a 2.4.

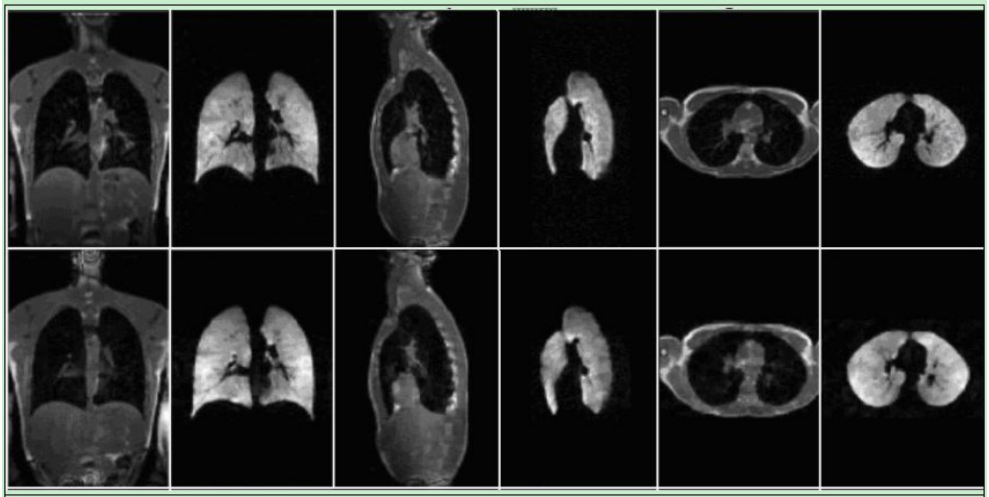

Fig. 2. Comparison of fully-sampled images (upper row) and CS-reconstructed undersampled images at R=3 (lower row) for a combined helium-3 and proton 3D acquisition in one breath hold. Orientation: coronal (left), sagittal (center) and axial (right).

Conclusions: Random undersampling combined with compressed-sensing reconstruction permits acquisition of 3D helium-3 and proton data sets, with isotropic 3.9-mm spatial resolution, during a 7-second breath hold. The resulting image quality is very similar to that obtained using a fully-sampled acquisition that requires almost 20 seconds. This capability should be valuable for quantitative assessment of ventilation defects in obstructive lung diseases such as asthma, CF or COPD.

References:

[1] Wild JM et al. NMR Biomed 2010. [2] Mugler JP et al. Proc ISMRM 16 (2008); 2644. [3] Michael Lustig et al. Magn Reson Med 2007; 58:1182. **Acknowledgements:** This work was supported by NIH R01 HL079077 and Siemens Medical Solutions.