Circular-Trajectory RARE Imaging for Increased SNR in ^{3}He Lung MRI

J. P. Mugler, III[1], K. Ruppert[2], W. A. Tobias[1], G. D. Cates, Jr. [1], E. E. de Lange[1], J. R. Brookeman[1]

[1]University of Virginia, Charlottesville, VA, United States, [2]Advanced MRI Technologies, Sebastopol, CA, United States

Introduction: If it were possible to use a single-shot, high-flip-angle, echo-train pulse sequence, such as RARE or echo-planar imaging, for hyperpolarized-gas MRI of the lung, the signal level would be approximately 10 times higher than that for the commonly-used gradient-echo (GRE) methods, yielding a substantial increase in the signal-to-noise ratio (SNR). The problem with echo-train imaging is that the diffusivity of ^{3}He is so high that even the standard spatial-encoding gradients result in considerable diffusion-induced signal attenuation [1,2]. As a result the signal level decreases throughout the echo train, yielding significant image blurring due to attenuation of high spatial-frequency components if the total diffusion-induced signal decrease is large. Thus, techniques such as RARE can only be used without significant image blurring if the spatial resolution is relatively low. For example, a recently published study by Durand et al [2] states that the diffusion-dependent resolution limit in the human lung for RARE-type ^{3}He techniques is 6 mm, based on an attenuation limit of 37% for the signal remaining at the end of a 36-echo train. The goal of this work was to investigate a circular-trajectory RARE pulse sequence that is designed to yield much lower diffusion-induced signal attenuation than that for a standard RARE sequence, thus potentially allowing resolution similar to that used with GRE techniques (~3 mm in humans) but with much higher SNR.

Theory: The *b* value associated with a gradient waveform can be calculated as the integral of the squared magnitude of the *k*-space trajectory. This relationship is extremely useful as an intuitive guide for the design of pulse sequences that yield a low level of diffusion-induced attenuation for the signals collected during the sequence and that, for our purposes, can be considered to be "diffusion-optimized." For example, a circular *k*-space trajectory provides two distinct advantages compared to a standard rectilinear trajectory with respect to diffusion-induced attenuation [3]. First, the zeroth moment for both in-plane encoding gradients is zero over the time period between refocusing RF pulses. This means that the *k*-space trajectory starts and ends at $k = 0$ between each pair of refocusing RF pulses, whereas the standard rectilinear *k*-space trajectory starts at a high negative spatial frequency and ends at a high positive spatial frequency between each pair of refocusing RF pulses and thus the *b* value (integral of the squared magnitude of the *k*-space trajectory) for the rectilinear trajectory is significantly higher than that for the circular trajectory. Second, only the last few segments of a circular *k*-space trajectory visit the highest spatial-frequency values, whereas every line of the rectilinear trajectory visits the maximum negative and maximum positive spatial-frequency values along the readout direction. Again, this difference results in a higher *b* value for the rectilinear trajectory.

Figure 1 shows the theoretically predicted effect of diffusion-induced signal attenuation in the healthy human lung for a standard rectilinear-trajectory half-Fourier RARE-type (HASTE) implementation compared to that for a centrically-ordered, circular trajectory. Based on the 37% attenuation limit of reference 2, the spatial resolution limit for a 36-echo train is reduced from 6 mm for the standard HASTE implementation to less than 3 mm for the centrically-ordered, circular trajectory. Thus, these results predict that spatial resolution comparable to that currently used for ^{3}He MRI of the human lung can be achieved in conjunction with a several-fold increase in SNR compared to GRE imaging. (The signal level for GRE would be ~0.1 in Fig. 1.)

Methods: To obtain experimental validation of the theoretically-predicted SNR gains, a prototype, non-optimized, low-resolution version of the circular-trajectory spin-echo-train (SE-train) sequence was implemented and used to acquire images of a ^{3}He phantom and of the lungs of 4 human volunteers. Studies were performed on a commercial 1.5-T scanner (Sonata, Siemens Medical Solutions). ^{3}He gas was polarized by collisional spin exchange with an optically-pumped rubidium vapor by using a commercial system (Model 9600 Helium Polarizer, Magnetic Imaging Technologies, Inc.). All experiments were performed under a Physician's IND (# 57866) for imaging with hyperpolarized ^{3}He following a protocol approved by our institutional review board.

Results: Representative circular-trajectory images are shown in Fig. 2a (phantom, projection) and 2c (lung, 15-mm thick). Correcting for voxel-volume and ^{3}He-dose differences between the circular-trajectory and GRE (Fig. 2b) images, slice-selective circular-trajectory imaging yielded an SNR 9-10 times higher than that typically obtained with GRE imaging. Considering the flip-angle and sampling-time differences between the sequences, theory predicts that the circular-trajectory SNR should be 8.6 times larger, in good agreement with the experimental result. Note that the circular-trajectory image depicts all of the major features seen in the GRE image. Nonetheless, circular-trajectory images appeared blurred compared to GRE images due to the larger voxel volume (6 x 6 x 15 mm vs. 3 x 3 x 10 mm) used for these preliminary measurements and, most likely, also due to T2-decay-induced [4] blurring because of the long echo-train duration (490 ms) used for the prototype circular-trajectory sequence. For an optimized configuration, we anticipate that our echo-train duration can be shortened by a factor of 2 to 3, compared to the prototype version, thus substantially lessening the impact of T2 decay.

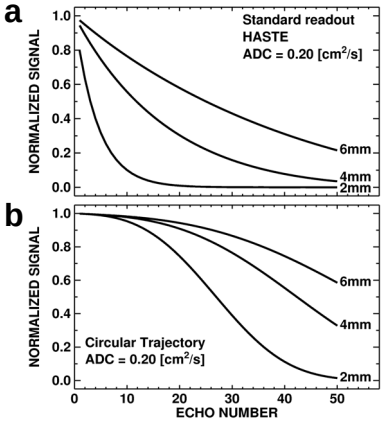

Fig. 1 (left). Theoretical calculations of normalized signal versus echo number for 2D SE-train sequences (slice thickness, 15 mm). The apparent diffusion coefficient (ADC) of 0.2 cm^2/s corresponds to that for ^{3}He in a healthy human lung. (**a**) HASTE. (**b**) Optimized circular *k*-space trajectory.

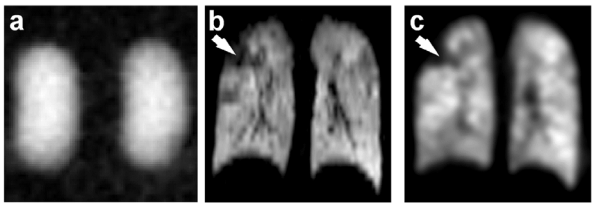

Fig. 2 (above, right). ^{3}He images of (**a**) the ^{3}He phantom and (**b**, **c**) the lungs of a volunteer that has asthma. (a) and (c) were acquired by using a circular-trajectory SE-train sequence; (b) was acquired by using a GRE sequence. The arrows indicate a ventilation defect. Circular parameters: TR, 3000 (a) or infinite (c); TE, 20 (a) or 15.3 (c) ms; matrix, 64 x 64 (32 circles); FOV, 380 mm; thickness, projection (a) or 15 mm (c). Fifty NEX were acquired for the phantom. GRE parameters: TR/TE, 6.7/2.9 ms; matrix, 80 x 128; FOV, 263 x 420 mm; flip angle, 10°; thickness, 10 mm.

Conclusions: Theoretical and experimental results indicate that a circular-trajectory RARE pulse sequence specifically designed to yield low diffusion-induced signal attenuation can provide, compared to commonly-used low-flip-angle GRE methods, a several-fold increase in SNR, and should thus permit much smaller doses of ^{3}He to be used to achieve a selected spatial resolution. Future work will focus on optimizing the pulse-sequence configuration to yield higher spatial resolution (~3 mm in-plane) in conjunction with a shorter echo-train duration.

References: 1. Saam B, et al. Magn Reson Med 1999; 42:507-514. 2. Durand E, et al. Magn Reson Med 2002; 47:75-81. 3. Mugler JP, Salerno M, Brookeman JR. Proc ISMRM 10 (2002) 2018. 4. Vignaud A, et al. Proc ISMRM 11 (2003) 1384.

Acknowledgements: Supported in part by CTRF grant IN2002-01 and Siemens Medical Solutions.