Comparison of 3D and 2D Gradient Echo for Human Lung Ventilation with Hyperpolarized 3He

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Introduction In-vivo images of inhaled hyperpolarized ^{3}He were acquired at breath-hold with a 3D gradient echo sequence. The images demonstrate favorable SNR and equal spatial resolution when compared to equivalent 2D gradient echo methods, currently the first choice for imaging ventilation. The in-vivo experimental findings were substantiated with in-vitro experiments and theoretical simulations for both 2D and 3D methodologies. The increased SNR of 3D was most noticeable when imaging thin slices where 2D images suffer from increased diffusion dephasing due to the strong slice gradient. The advantages of a high resolution 3D acquisition are highlighted with multi-planar reformatting of the contiguous 3D data and volume rendering of the gas volume in the lung airspace.

Theory In breath-hold studies of HP ^{3}He, the SNR and spatial resolution of 2D and 3D sequences are influenced by : the inherent SNR/unit time of 3D versus 2D ($=\sqrt{N_z}$ where N_z is the number of 3D phase encodings /2D slices), slice profile effects and diffusion of gas out of slice, diffusion attenuation, RF depletion of polarization during imaging ($M_n = M_0(\cos\theta)^{n-1}\sin\theta\, exp(-nTR/T1)$ - for the nth RF view) and the choice of k-space trajectory. These factors were previously investigated for a 2D methodology [1]. In 3D imaging the signal from the whole lungs is sampled throughout the entire breath-hold and so the contribution of the T1 effect of oxygen to the 3D k-space filter needs to be considered when choosing the optimum flip angle. Simulations were performed for 2D and 3D imaging sequences (see MRI methods) using Matlab. The 3D phase encoding loop structure was a sequential z (slice) loop nested within a centric y (phase) loop ($cen_y\, seq_z$). Comparisons with a 2D centric (cen_y) sequence were made and the optimum 3D flip angles were derived from the theoretical k-space filters –see Fig.1. Having derived the optimum flip angle (θ), the ratio of SNR of a 3D sequence compared to 2D should be given by $SNR_{3D}/SNR_{2D} = \sqrt{N_z}\sin(\theta_{3D})\exp(-b_{s3D}D)/\sin(\theta_{2D})\exp(-b_{s2D}D)$ where N_z is the number of slices and b_s denotes the diffusion weighting b value imposed by the slice gradient. The theoretical values are compared against those observed *in-vivo* and *in-vitro* in Table 1.

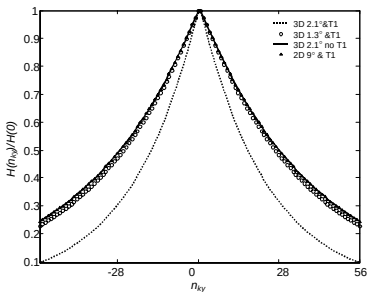

Fig. 1 Simulations to determine choice of flip angle: The plot of triangles in Fig. 1 shows the k-space filter function in the y phase encode direction H(k_y), (normalized by magnitude of the k_y=0 point), for the 2D cen_y trajectory with θ=9°[1]. The values of the horizontal axis n_{ky}, are integers in the range $N_y/2 < n_{ky} \leq N_y/2$ for N_y=112. The solid line, is the normalized filter for the 3D $cen_y seq_z$ acquisition assuming negligible *T1* decay during the image time course with θ=2.1°. The series of solid dots shows the filter if the effects of *T1* decay are included (assuming an in-vivo *T1* of 20 seconds) with the same flip angle of θ=2.1°, a harsher apodization of the high spatial frequencies results. The open circles represent the filter for the 3D acquisition for θ=1.3° with *T1* decay included and indicates a very similar degree of apodization in k_y to the 2D filter.

Materials All work was performed on a 1.5T whole body MRI system. The ^{3}He gas was polarized on site to 30% with rubidium spin exchange apparatus. *In-vitro* studies were performed using Tedlar bags containing 100ml of ^{3}He diluted with 900 ml of N_2 at a total pressure of 1 atm. *In-vivo* studies on four healthy volunteers were carried out during a breath-hold following inhalation from a Tedlar bag filled with 300 ml ^{3}He and 700 ml N_2.

Methods For direct comparison, the 2D and 3D gradient echo sequences were designed with the same number of RF pulses, identical sampling bandwidth(31kHz), RF bandwidth, RF pulse, FOV(43 cm), TE (4.5 ms), TR (9 ms) and total imaging time. The studies used the same gas volumes and polarization for fair comparison. For the *in-vitro* study N_z = 19 contiguous partitions of 9.3 mm were acquired sequentially from posterior to anterior to match the 2D acquisition acquired with (θ=9°). The 3D flip angle (θ=2.1°) was chosen to impart a comparable degree of blurring in the y direction of the 3D images as found with the standard 2D acquisition in the absence of oxygen -see Fig.1. In-vivo studies were performed on three healthy volunteers with θ=1.3° and 2.1° with N_z=19 for comparison with the simulations and a 2D acquisition –see Fig.1. A further 3D exam was performed on a fourth volunteer at higher resolution N_z=48: voxel size =4.0×3.8×1.7 mm and total breath-hold 48 s.

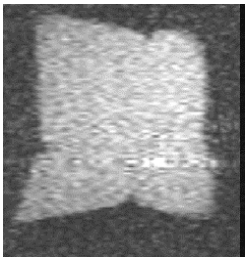

Fig.2a

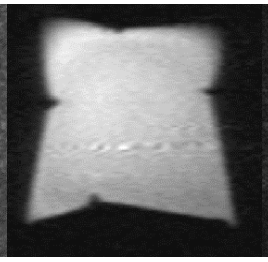

Fig. 2b

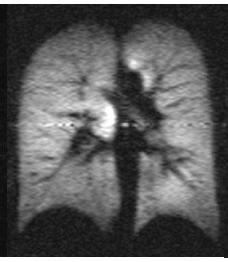

Fig.3a

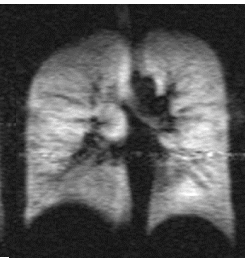

Fig. 3b

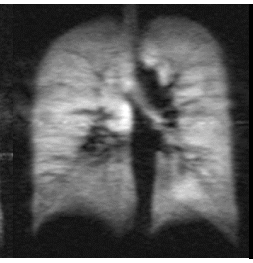

Fig. 3c

Fig. 4

Experiment	Δz mm	b(sm^{-2})	D m^2s^{-1}	exp(-*b*D)	SNR_{3D}/SNR_{2D} theory	SNR_{3D}/SNR_{2D} in-vitro	SNR_{3D}/SNR_{2D} apex	SNR_{3D}/SNR_{2D} airway
1 (in-vitro, N_z19, θ=2.1°)	9.3	1.27×10	9.00×10^{-5}	0.318	3.2	4.6	N.A.	N.A.
2a (in-vivo, N_z19, θ=2.1°)	13	6.63×10	2.00×10^{-5}	0.876	1.2	N.A.	2.3	6.5
2b (in-vivo, N_z19, θ=1.3°)	13	6.63×10	2.00×10^{-5}	0.876	0.7	N.A.	1.4	1.7
3 (in-vivo, N_z32, θ=1.4°)	9.3	1.27×10	2.00×10^{-5}	0.775	1.1	N.A.	1.2	3.0

Results The results of the in-vitro experiments are shown in Fig. 2, The 3D images (Fig. 2b) exhibit the same degree of spatial resolution (blurring) but more than four times the SNR of the 2D images (Fig. 2a). Fig. 3a shows the N_z=19, in-vivo 2D image from a central slice in volunteer 1, Fig 3b and 3c are the 3D images acquired with θ=1.3° and 2.1°both exhibit higher SNR (most noticeable in the major airways) but 3c shows slightly more blurring due to the increased flip angle which is consistent with the simulations of Fig.1. The SNR findings averaged over all slices in all three subjects are summarized in Table 1. Fig. 4 is a 3D surface rendering of the high resolution 3D images which demonstrates the contiguous nature of the data. Such high resolution would not have been attainable with the 2D sequence at the echo times used as the slice gradient would have violated the 27 mTm^{-1} max.

Conclusion We have demonstrated that 3D gradient echo imaging can offer favorable SNR compared to 2D slice selective sequences when imaging lung ventilation with ^{3}He. As gas polarization levels increase and gradient switching performance improves then an increased spatial resolution in HP gas imaging will be sought. This work demonstrates an increased SNR for 3D particularly when imaging thin slices since diffusion dephasing due to the slice gradient is minimized. The ability to reformat 3D data in any plane, allows direct comparisons with axial CT the current clinical imaging modality of choice for anatomical depiction of lung parenchyma. As ^{3}He is an expensive and finite resource any methods to increase SNR through prospective pulse sequence optimization should be pursued an alternative 3D encoding strategies [2] may show further increases in SNR compared to 2D sequences.

References [1] Wild JM, et al Magn Reson Med 2002; 47:687-695. [2] Ruppert K, Muggler JP III.. Proc. ISRMRM 2001, 945.