SNR Performance of Q-space Formalism and Multi-Exponential Modelling for Hyperpolarized ^{3}He Gas Diffusion Spectroscopy in Human Lungs

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Introduction

Hyperpolarized ^{3}He gas diffusion measurements in lungs present an opportunity to non-invasively probe the morphology of lung airspaces. In a restricted heterogeneous environment such as the lungs, one has to employ techniques such as a multi-exponential model, geometric model or q space formalism to model the nature of diffusion [1,2,3]. For any technique, it is imperative to understand its performance in presence of noise. To our knowledge, this has not been evaluated for any of the techniques mentioned above for ^{3}He diffusion in lungs. Evaluation of SNR performance for these techniques is crucial, as it might allow us to lower the gas dose, if reasonably equivalent information can be obtained at lower SNR. This is critical, as one potential obstacle to widespread clinical utility of ^{3}He MRI is the limited world supply of ^{3}He gas and lowering the gas dose is potentially valuable for making ^{3}He diffusion a viable clinical tool in the assessment of lung morphology. In this study, we evaluated the performance of multi-exponential model as well as q-space based formalism in presence of noise and studied its implication on gas dose volumes. Geometrical model was not considered in the present study, as the model deviated significantly from the in-vivo diffusion data for b values > 65 s/cm^2.

Methods and Materials

Q-space Spectroscopy: ^{3}He diffusion-weighted spectroscopy (DWS) datasets, obtained *in vivo* from 14 volunteers (13 healthy volunteers and one COPD patient) on a 1.5T Siemens Sonata MRI system using a ^{3}He flexible coil, were investigated. The 40 point q-space diffusion data (δ=1.63 ms, Δ=6.80 ms, q_{min} = 0 m^{-1}, q_{max} = 2 mm^{-1}/ b_{max} of 100 s/cm^2, 10 kHz spectral width, 25.6 ms acquisition window, 256 complex points, nine additional interleaved q = 0 m^{-1} points for flip angle and T_1 related attenuation correction, ~2s total scan time) [3], sensitized along the A-P direction, was acquired following the inhalation of 40 cc ^{3}He gas (net polarization = ~ 33%-40%) diluted with ~1L of filler N_2 gas. **Numerical Simulations:** Since the T_2* for ^{3}He gas signal in lungs was found to be ~ 5-7 ms, the last 3 ms duration of the 25.6 ms FID was assumed to be noise. SNR was defined in time domain as the ratio of peak signal intensity to the root-mean-square value of the noise (i.e. the rms value of the last 30 points of the FID). SNR obtained with 40 cc of gas was considered as the reference (SNR_{40cc}). The datasets were chosen such that the minimum SNR_{40cc} for the dataset (usually corresponding to highest q value / b value signal) was greater than 8. Since the MR signal obtained from hyperpolarized ^{3}He gas is directly proportional to the gas volume, SNR at a particular dose level was simulated by adding zero mean Gaussian noise with different variances to the FIDs, such that for doses of 35 cc, 30 cc, 25 cc, 20 cc and 10 cc, the expected mean SNR is 0.875 SNR_{40cc}, 0.75 SNR_{40cc}, 0.625 SNR_{40cc}, 0.5 SNR_{40cc} and 0.25 SNR_{40cc} respectively. The datasets were then processed as previously described [2,3]. The datasets were analyzed using the bi-exponential model: $S = \sum_{n=1}^{m} S_{n\_fract}\, e^{-bADC_n}$, m = 2 and the q-space formalism with the displacement probability profile fit to a bi-Gaussian model: $DPP(x) = \sum_{n=1}^{m} Z_n e^{-0.5\left(x/X_{rms,n}\right)^2}$, m = 2. The variability for the parameters obtained from the bi-exponential (in terms of ADC) and bi-Gaussian models (RMS displacements and zero-displacement probabilities), at different SNR levels, was calculated as: $\text{var} = |\text{param} - \text{ref}|/0.5\times(\text{param} + \text{ref})$.

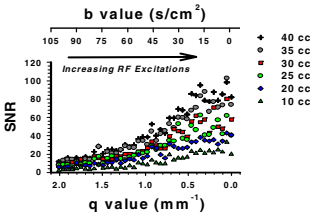

Figure 1. Variation of SNR with q value/b value for measured (40 cc) and other various simulated gas doses.

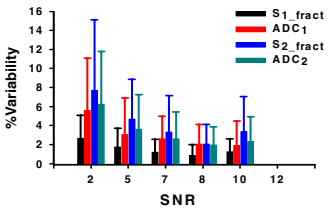

Figure 2. Variability of the parameters obtained from bi- exponential model with SNR.

Results and Discussion

In healthy volunteers, the SNR increases with the decreasing q values/ b values, despite of decrease in signal due to flip angle and T_1 related attenuation (Figure 1). The measured minimum SNR_{40cc} was 12 ± 3.3, while at reduced doses of 35 cc, 30 cc, 25 cc, 20 cc and 10cc the simulated SNR values were 10 ± 3, 7.5 ± 2.2, 7 ± 1.8, 5.3 ± 2.1, 2.5 ± 1.2 respectively which were close to the predicted values of 10.5, 9, 7.5, 6 and 3.0 for these reduced doses. The parameters obtained from the q-space formalism have much lower mean variability and standard deviation than those obtained from the bi-exponential model for each SNR level (Figures 2 and 3).

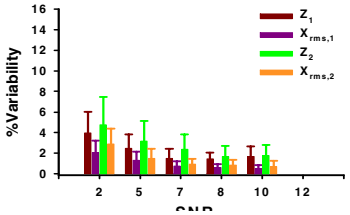

Figure 3. Variability of q-space parameters with SNR

The reduced variability of q-space formalism is primarily due to the filtering effect of the Fourier transformation, inherent in the q-space formalism. Further, it is observed form Figure 3 that the mean variability for all the four bi-Gaussian parameters that describe the DPP is ~2% or less for mean SNR of 5 or more. These values for variability are similar to or smaller compared to those obtained for global DWI repeatability studies (~ 2%) by Morbach et.al [4] as well as for the q-space intra-subject repeatability studies (Z_1 = 4.58 %, $X_{rms,1}$ = 3.16%, Z_2 = 4.81%, $X_{rms,2}$ = 2.51%,) by our group (unpublished data), thus demonstrating that the precision of lower SNR measurements. For the parameters (i.e. flip angle, gas polarization and dose, TE, TR) used in the current sequence, simulation results suggest that a dose of ~ 15cc - 20cc might be feasible for obtaining precise global information about lung microstructure, based on q-space formalism. The lowering of SNR due to reduction in gas dose can be compensated by increase in the flip angle as well. Figure 4 shows that with a reference flip angle of 6°, increasing the flip angle to 12° will increase the SNR for initial data signal points by almost a factor greater than 2. With current data collection scheme, where the low SNR data points are acquired first, this increase in flip angle will compensate for reduced SNR due to corresponding decrease in gas dose. The consequent decrease in SNR for data points collected at higher RF pulse due to to RF–related attenuation is minimal as these acquisitions inherently have higher SNR (SNR > 40, Figure 1). However this might be untrue for extreme cases of flip angle greater than 24°, where the SNR drops to 10% of the original SNR (Figure 4) and the drops the SNR below the minimum requirement of 5.

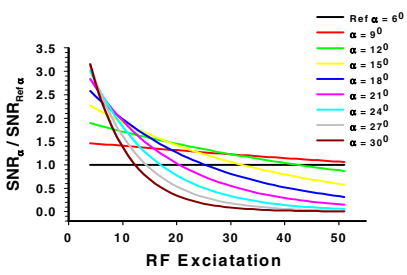

Figure 4. SNR plots at different RF flip angles as a function of RF excitation number.

Conclusion

In presence of noise, q-space based analysis of hyperpolarized ^{3}He diffusion in lungs was found to be much more robust than the multi-exponential approach. Numerical simulation suggests that precise q-space measurements can be performed at a ^{3}He gas dose as low as 10-15 cc by suitably adjusting the q-space sequence parameters. This low volume of ^{3}He gas dose makes global q-space technique particularly attractive as a screening tool for initial assessment of lung morphology and if necessary, additional gas intensive DWI scans can be performed for obtaining regional information.

References

[1]. Yablonskiy DA., et. al, *Proc Natl Acad Sci* U.S.A, 99(5):3111-3116, 2002. [2]. Shanbhag DD et.al. In: Proceedings of the 13th Annual Meeting of ISMRM, Miami Beach,FL, USA, 2005. p. 51. [3]. Shanbhag DD, et. al. *J Magn Reson Imaging*. 2006; **24**: 84-94. [4]. Morbach, AE et.al. *J Magn Reson Imaging*. 2005; **21**: 765-74.