Effects of Concomitant Fields on Short-Time-Scale Noble Gas Diffusion Measurements

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Introduction: Hyperpolarized ^{3}He diffusion NMR is a powerful tool for probing lung microstructure at length scales that are too short to access with conventional *k*-space MRI. Finer length scales can be probed by decreasing the diffusion time Δ, and in the limit as Δ → 0 time dependent diffusion measurements are sensitive to the surface-to-volume ratio of the alveolar airspaces [1,2]. In previous work we described a specialized pulse sequence (Fig. 1) designed to access very short diffusion times using noble-gas NMR, in order to probe smaller length scales than previously possible [3]. This pulse sequence is based on concatenating many bipolar diffusion gradients to amplify the diffusion attenuation. Since the pulse sequence involves relatively large oscillating gradients and does not use refocusing RF pulses, the effects of concomitant magnetic fields may be significant. In the present work we study the quantitative effects that concomitant fields have on the resulting diffusion measurements, and develop strategies for minimizing or correcting for these effects.

Theory: Maxwell's equations dictate that a linear magnetic field gradient G along a given direction must be accompanied by concomitant magnetic field variations along orthogonal directions. The concomitant background field B_c and resulting concomitant phase Φ_c derived from Maxwell's equations are, to first order [4]:

$$B_c \equiv \frac{1}{2B_0}\left[\left(G_x z - \frac{G_z x}{2}\right)^2 + \left(G_y z - \frac{G_z y}{2}\right)^2\right] \geq 0 \quad \Rightarrow \quad \phi_c = \gamma\int B_c(G_x, G_y, G_z, x, y, z)dt \qquad [1]$$

Ignoring T_2* decay and assuming that the diffusivity and MR spin density ρ are approximately uniform throughout the sample of volume V, the diffusion-attenuated signal $S(n)$ following the n^{th} bipolar diffusion gradient of the pulse sequence in Fig. 1, including concomitant field effects, is given by:

$$S(n) = A\exp(-nbD)\int \rho(x,y,z)\exp[i\phi_c(n,x,y,z)]dV \equiv \exp(-nbD)\cdot S_c(n) \qquad [2a]$$

$$S_c(n) \equiv A\int \rho(x,y,z)\exp[i\phi_c(n,x,y,z)]dV \qquad [2b]$$

where b is the conventionally defined b value of a single bipolar diffusion gradient, and A is the constant of proportionality that relates the MR spin density to the signal magnitude. The concomitant contribution $S_c(n)$ to the signal attenuation can be calculated using Eq. [2b] if ρ is known. If the concomitant signal attenuation is significant compared with the diffusion-induced signal attenuation, this can lead to an overestimation of D.

The effect of concomitant fields becomes more prominent with larger mean sample size R, because the rate of signal dephasing increases the farther one moves away from the iso-center of the magnet. We derived an approximate threshold criterion to determine under what circumstances concomitant field distortions remain insignificant compared to the desired diffusion attenuation:

$$\xi \equiv \frac{G^2\pi^2R^4n}{4608B_0^2\Delta D} << 1 \qquad [3]$$

One can reduce concomitant effects by observing that B_c in Eq. [1] can be minimized by only applying diffusion gradients along the x or y axes, in combination with using a thin imaging slice in z. If the concomitant effects cannot be avoided, an alternative method of dealing with them is to correct for their effects using Eq. [2]. The pure diffusion attenuation can be obtained by dividing Eq. [2a] by Eq. [2b] to yield:

$$S(n)/S_c(n) = \exp(-nbD) \qquad [4]$$

Experimental Methods: In order to verify our theoretical calculations, diffusion experiments were performed in a long cylindrical phantom of diameter 3 cm and length 14 cm. The phantom contained a pressurized mixture of ^{3}He and O_2 with a free diffusion constant of $D_0 \approx 0.3$ cm^2/s. With the phantom aligned parallel to the magnet bore, we applied the multiple gradient diffusion sequence (Fig. 1) using non-selective RF excitation pulses, with Δ ranging from 400 µs to 1400 µs. Diffusion gradients were applied alternately along only the x and y axes. In addition, a 1D image $\rho(z)$ of the signal profile was acquired along the z direction. Evaluation of Eq. [3] yields $\xi > 1$ for the longest diffusion time used and $\xi \approx 0.01$ for the shortest diffusion time used, indicating that only the shorter diffusion times should be significantly affected by concomitant fields.

Experimental Results: Fig. 2 shows a plot of the diffusion attenuated signal (normalized for T_2* decay as in Ref. [3]) for Δ = 800 µs. The red data points are the raw measurements, which represent the combined effect of diffusion attenuation and concomitant attenuation. The green curve is the theoretically determined correction using Eq. [2b]. Finally, the blue data points are the corrected values using Eq. [4] along with the linear fit (black line) that yields the diffusivity. The effect that such corrections have on all the measured diffusivities is shown in Fig. 3. Shown here again are the uncorrected diffusivities (red) and the corrected values (blue). Note that while the uncorrected diffusivities are systematically overestimated, especially for shorter diffusion times (as expected), the corrected diffusivities lie on a horizontal line consistent with the free diffusion constant $D_0 \approx 0.3$ cm^2/s, showing that the corrections were successful.

Conclusion: We investigated the effects that concomitant magnetic fields have on a specialized multi-bipolar diffusion sequence designed for accessing very short time scales. These effects are most prominent when the sample is large and more bipolar pairs are applied. Two solutions were proposed: One can avoid concomitant background fields altogether by only applying G_x or G_y in combination with using a thin imaging slice in z. Alternatively, because the concomitant fields are quantifiable, one can correct for them in post-processing, after making an auxiliary measurement of the spin-density profile. The fact that a conventional diffusion-weighted pulse sequence uses only one bipolar gradient is a major reason why concomitant effects have not interfered with these experiments.

References: [1] P.P. Mitra et al., Phys. Rev. B 47:8565-8574 (1993). [2] G.W. Miller et al., IEEE Trans. Med. Imaging 26:1456-1463 (2007). [3] M. Carl et al., J. Magn. Reson. 189:228-240 (2007). [4] M. A. Bernstein, *Handbook of MRI Pulse Sequences* (2004).

Acknowledgments: Supported by NIH grants R21-HL089525 and R01-HL079077. Authors JPM and GWM receive research support from Siemens Medical Solutions.

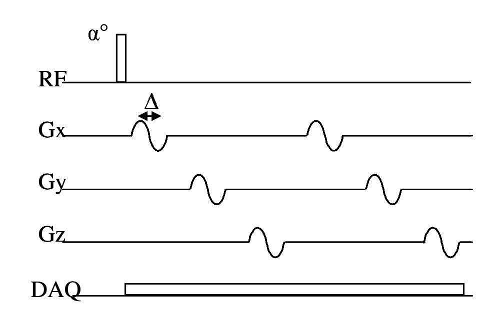

Fig.1: Specialized short-time-scale diffusion sequence. Several bi-polar diffusion gradients are concatenated to enhance the diffusion attenuation.

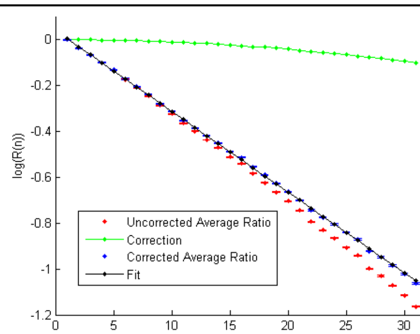

Fig.2: Log of experimental signal attenuation vs. n for a multi bipolar diffusion sequence for Δ = 800µs.

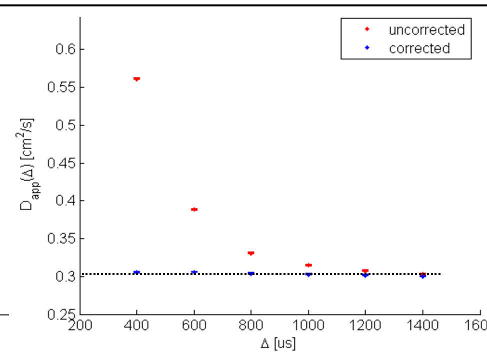

Fig.3: Experimental verification of the concomitant gradient corrections.