Generating Noble-Gas Diffusion Maps at Very Short Time Scales

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Motivation: The structural length scale probed by diffusion-weighted NMR is given by $\sqrt{6\Delta D_\Delta}$, where Δ is the time over which the diffusion is observed, and D_Δ is the (time-dependent) diffusion coefficient measured at this diffusion time. Short-time-scale measurements of hyperpolarized ^{3}He diffusion in the human lung typically use diffusion times between 1 and 2 ms. At this time scale, the ^{3}He diffusion coefficient in normal lung airspaces is approximately 0.2 cm^2/s. Thus these measurements probe a length scale of approximately 350-500 microns, which is substantially larger than a normal alveolus. In order to probe sub-alveolar length scales, diffusion times less than a millisecond must be used. However, it is difficult to make accurate diffusion measurements at sub-millisecond time scales using conventional pulse-sequence techniques.

Purpose: We previously developed a pulse sequence for making global diffusion measurements at very short (sub-millisecond) time scales [1]. In the present work this technique is adapted to provide spatially resolved information, yielding diffusion maps much like conventional diffusion-weighted MRI.

Pulse Sequence Design: The original global diffusion pulse sequence, shown in Fig. 1, incorporates three main elements that are key to measuring very-short-time-scale diffusion: (1) multiple bipolar diffusion-sensitizing gradients are concatenated, which increases the total diffusion attenuation; (2) the diffusion-attenuated signal is sampled between each of the N bipolar gradients, which reduces measurement noise; and (3) consecutive diffusion-sensitizing gradients are applied along orthogonal axes, which reduces systematic measurement errors [1]. The series of signal measurements S_n ($n = 1, ..., N$) are normalized to an otherwise identical non-diffusion-weighted acquisition and then fit to the function $\exp(-nbD_\Delta)$, to obtain a measurement of D_Δ.

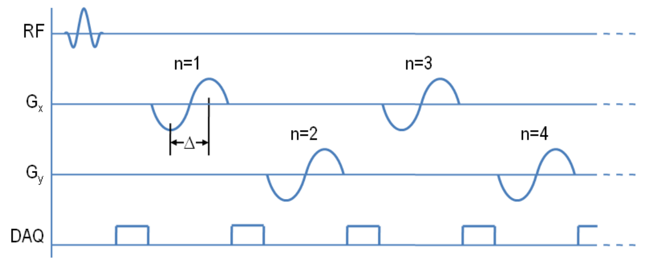

Fig. 1: Very-short-time-scale diffusion pulse sequence.

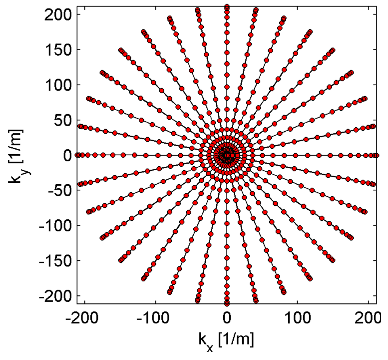

Fig. 2: Representative k-space trajectory, for $\Delta = 400$ μs, $|G| = 25$ mT/m, and $M = 32$. Points are not sampled evenly along each line, due to the sinusoidal shape of the bipolar gradients.

To generate spatially resolved information using this basic design, imaging gradients cannot simply be inserted during the data-sampling times without interfering with the diffusion-weighting scheme. Since each bipolar gradient lobe traverses a radial line of k-space, however, we can instead use the diffusion-sensitizing gradients themselves to sample k space. A 2D plane of k space can be covered in this manner (Fig. 2) by changing the directional orientation of all of the diffusion gradients following each excitation RF pulse. After M excitations, where M is the number of radial lines required to adequately sample k space, we can reconstruct N distinct diffusion-weighted images. For each value of n, the n^{th} image has a diffusion weighting of $(n-1)b$, and the entire series of N images can be analyzed on a pixel-by-pixel basis using the same formulas as in the global case [1].

Experimental Methods: The pulse sequence described above was used, with $N = 9$ and $M = 90$, to generate diffusion maps of a spherical ^{3}He phantom of diameter 8 cm. The phantom was filled with a pressurized mixture of ^{3}He and O_2, which has a free diffusion coefficient $D_0 \approx 0.39$ cm^2/s. Each bipolar diffusion-sensitizing gradient had amplitude $|G| = 20$ mT/m and $\Delta = 1000$ μs.

Results: Three of the nine reconstructed images, each with consecutively lower signal intensity due to the progressive diffusion attenuation, are shown in Fig. 3a, and the resulting diffusion map is shown in Fig. 3b. A histogram of the measured diffusivities is shown in Fig. 3c. The mean of the distribution ($D = 0.38$ cm^2/s) is slightly less than the free diffusion coefficient D_0, as expected for nearly free diffusion. The standard deviation of the Gaussian fit is $\sigma \approx 0.02$ cm^2/s.

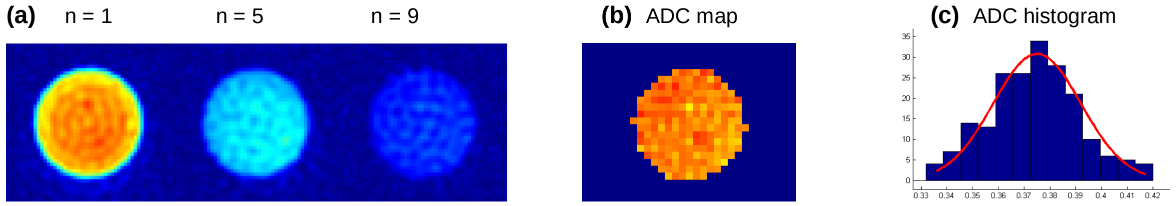

Fig. 3: Imaging results. **(a)** Diffusion-weighted images of the spherical ^{3}He phantom, acquired using our very-short-time-scale pulse sequence. **(b)** Corresponding diffusion map. **(c)** Histogram of pixel values.

Conclusion: We modified our global short-time-scale diffusion sequence to generate spatially resolved diffusion measurements, by using the bipolar diffusion gradients themselves to sample k space. Tests in a ^{3}He gas phantom yielded self-consistent diffusion maps. These results bode well for generating precise and accurate diffusion maps at sub-alveolar length scales in the lung.

References: [1] M. Carl et al., J. Magn. Reson. 189:228-240 (2007).

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