A Selectable Diffusion Coefficient Phantom Based on Restricted Diffusion

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Objective

Quantitative MRI studies of diffusion require a phantom to calibrate an imaging system. One convenient diffusion phantom consists of a set of hydrocarbon liquids with diffusion coefficients (D) between that of water and ~$0.5x10^{-9}$ m^2/s. (1) Shipping constraints make commercializing phantoms containing flammable hydrocarbons more costly. We propose a diffusion phantom based on the restricted diffusion of water within tightly packed glass fibers. This phantom should give a range of diffusion coefficients less than D_{Water} using only water as the NMR signal baring liquid.

Theory

Magnetic resonance measurements of the diffusion coefficient utilize two gradient pulses of width δ, amplitude G, and separation Δ in an echo sequence. D is measured by comparing the signal from an equivalent pulse sequence with (S) and without (S_o) diffusion gradient pulses.

$$S/S_o = \exp(-\gamma^2 G^2 \delta^2 (\Delta-\delta/3)D) = \exp(-bD)$$

Clinical MRI systems often use a two-point method to calculate D with operator control of b but limited independent control of G, δ, and Δ values. On high resolution NMR spectrometers D is often measured from multiple S values with different G, δ, and Δ values, thus allowing D calculations based on varying G at fixed δ and Δ values. The theory of restricted diffusion is based on the mean diffusion distance (x) in time t where q_i is a dimensionality constant.

$$x = (q_i D t)^{½}$$

When x is less than the size of a container (x_c), diffusion is unrestricted. However, when $x \geq x_c$, diffusion is restricted. Measurements of D as a function of Δ with constant δ show the effects of restricted diffusion when $\Delta > x_c^2/q_i D$, or the measured diffusion coefficient is less than the actual diffusion coefficient. We have capitalized on restricted diffusion to create a phantom which will give selectable D values through the choice of Δ value and phantom orientation.

Experimental Methods

The phantom consists of a hydrated, hand-made bundle of approximately parallel 11±2 μm diameter glass fibers. An added feature of the phantom is that D is anisotropic. D values along the axis of the fibers ($D_{//}$) are greater than when perpendicular ($D_{\perp}$) to the fibers. The principle was first tested on a 4.5 mm diameter bundle of hydrated fibers held together with shrink tubing and fit into a 5 mm NMR tube. D values were measured as a function of Δ at fixed δ using a stimulated echo sequence (2) on a 600 MHz Varian UnityInova spectrometer with three axis gradients. D_{Water} values in a 1 mm capillary were also recorded for a reference. Diffusion images of a 28 mm diameter bundle were recorded using a 1.5 T GE Signa Excite HDx scanner using a diffusion weighted echo planar imaging sequence.

Results & Discussions

Figure 1a demonstrates the behavior of D as a function of 0 < Δ < 1.2 s for the 4.5 mm hydrated bundle and a 1 mm diameter capillary tube. The capillary represents unrestricted diffusion along its length ($D_{//}$) and restricted diffusion perpendicular to the length ($D_{\perp}$) of the tube. The fibers show the same general trend as the capillary tube sample except there is some restricted diffusion parallel to the fiber axes because of imperfections in fiber alignment. A similar but not identical dependency is observed for the 28 mm diameter bundle. (See Fig. 1b.) We attribute small difference in D between the phantoms to the 5 °C temperature difference for the measurements and our limited ability to achieve identical packing of the hand-made fiber bundles.

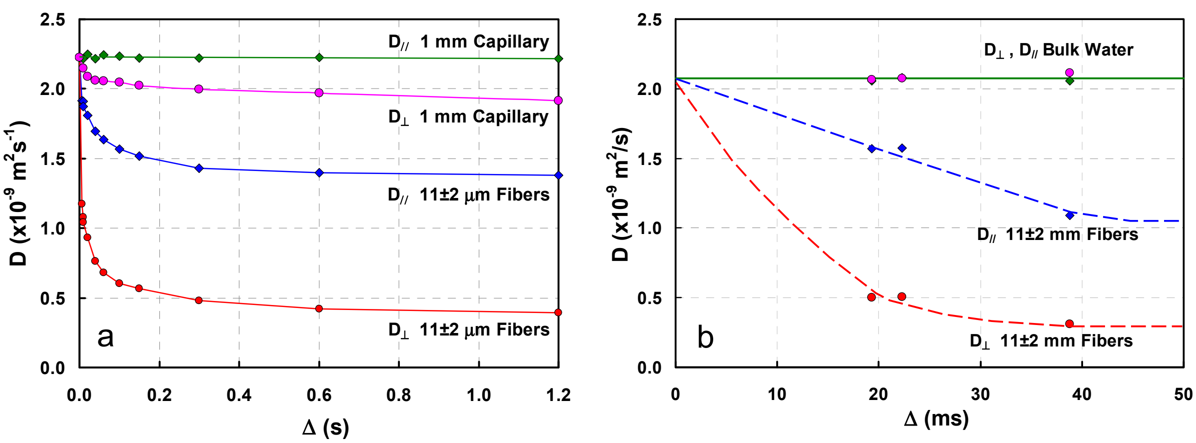

Fig. 1. D values as a function of Δ for hydrated glass fibers using a a) 600 MHz high resolution NMR at 25 °C, and b) a 1.5T clinical scanner at 20°C. Lines are drawn to guide the eye.

Conclusions

Our results demonstrate the potential of the using restricted water diffusion in fiber bundles to achieve diffusion standards with a diffusion coefficient between D_{Water} and 0.5 m^2/s without flammable hydrocarbons. Commercializing such a phantom will results in reduce shipping costs.

References

1. PS Tofts, et al. Magn Reson Med 2000;43:368-374.
2. SJ Gibbs, CS Johnson, Jr, J Magn Reson 1991;93:395-402.