Breakdown of the High-Field Approximation in the context of Hyperpolarized ^{3}He MRI

J. L. Hobson[1], C. P. Bidinosti[1], K. M. Gilbert[1], C. Lei[1], G. Archibald[1], M. E. Hayden[1]

[1]Department of Physics, Simon Fraser University, Burnaby, BC, Canada

INTRODUCTION: Conventional magnetic resonance (MR) imaging is accomplished in a 'high-field' regime, where relative changes in the homogeneous static magnetic field that result from the temporary superposition of an inhomogeneous magnetic field (IMF) are small over some region of interest (ROI). In this limit, the components of the IMF that are (necessarily) directed *perpendicular* to the static field can largely be ignored. This situation leads to a natural description of spin dynamics in terms of a 'gradient field,' an idealized IMF that is directed parallel to the static field at all points in space. One of the challenges associated with recent efforts to develop apparatus for MR imaging using low (static) magnetic fields [1-4] is to devise methods that permit effects associated with *all* components of the IMF to be analyzed properly [5-6]. Here, as a demonstration of such effects, we present the results of MR experiments that effectively probe the self-diffusion coefficient of hyperpolarized ^{3}He gas under a variety of conditions, some of which clearly do not meet the criteria needed to describe the pulsed IMF in terms of an idealized gradient field. Although not strictly necessary, the data presented here were acquired in a regime where the diffusion of ^{3}He is mildly restricted. This is done so that a reasonably direct comparison can be made between our experiments and the results of polarized noble gas diffusion studies in human lungs [4,7]. The data we report exhibit a clear dependence on the strength of the static magnetic field, the symmetry of the coils used to generate the IMF, and the exact location of the ROI within the magnet.

METHODS: Metastability-exchange optical pumping techniques were used to produce nuclear polarizations of order 20% in a 5 cm ID x 3 cm long sealed cylindrical cell manufactured from Schott Duran® glass and filled at room temperature to a pressure of 1 Torr. The free diffusion coefficient of ^{3}He under these conditions is of order 0.1 m^2/s. The cell was alternately positioned at the isocentre of a 55 cm ID solenoidal low-field MRI magnet and a point 15 cm from the isocentre along the symmetry axis of the magnet. In both cases the cylindrical axis of the cell was aligned with that of the magnet. In the absence of an applied IMF the transverse nuclear relaxation time T_2 of the ^{3}He in the cell was typically of order 1 minute. The experimental sequence comprised a 90º RF tipping pulse followed by a short (typically 4 s) delay and a bipolar IMF pulse of duration 2τ (typically 1 ms) leading to an abrupt attenuation of the FID by a factor that we denote as β. Data acquisition was started immediately after the tipping pulse, and was continued for at least 4 s after the IMF pulse. We report (independently measured) IMF gradient amplitudes in terms of the magnitude g of the dominant axial or transverse field gradient at a particular location so as to conform to the high-field interpretation of this quantity as a gradient field.

RESULTS AND DISCUSSION: We have used methods similar to those described above to study the diffusion of ^{3}He under a variety of conditions and geometries. In the free- and restricted-diffusion regimes we observe good quantitative agreement between our measurements of diffusion coefficients in low magnetic fields and those derived from experiments carried out in high-magnetic fields.

Figure 1 shows the measured dependence of the attenuation of an FID on the amplitude g of a pulsed IMF with its gradient directed predominantly transverse to the cell axis. These data were acquired with τ = 0.7 ms, which is long enough for ^{3}He atoms to diffuse distances of order 1 cm. For small values of g the attenuation factor β depends exponentially on g^2, which is what one expects in both the free- and restricted-diffusion regimes. For larger values of g there is a marked departure from this behavior that signals the onset of the localization regime, in which atoms are able to diffuse distances further than that necessary to dephase by 2π radians [8]. In this regime our data for β are consistent with an exponential dependence on $g^{2/3}$ as has been observed for other systems [9]. More importantly, we note that the point at which the localization regime is encountered in these experiments depends both on the strength of the homogeneous static field and the location of the ROI within the magnet. This behavior reflects the breakdown of the high-field approximation, as components of the IMF that are directed perpendicular to the static homogeneous field can no longer be ignored. Under these circumstances one needs to consider the diffusion of atoms along the full *line gradient* of the magnetic field [5,6].

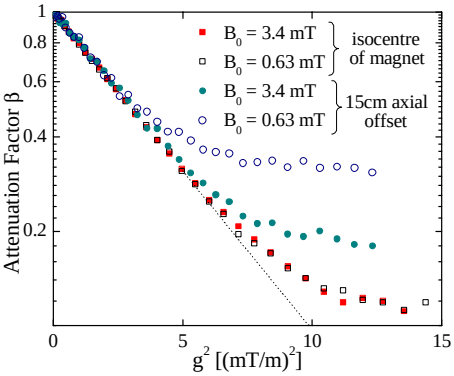

Figure 1: Attenuation of an FID induced by application of a τ = 0.7 ms pulsed IMF with its gradient directed predominately transverse to the cell axis. The initial slope of these data is proportional to the apparent diffusion coefficient (ADC) of the gas.

Further evidence of this breakdown is illustrated in Figure 2. IMFs with gradients that are predominately transverse to the axis of the magnet (produced with a quadrupolar arrangement of coils) result in enhanced relaxation when the cell is moved from the isocentre of the magnet to the axial offset position. In contrast, IMFs with gradients that are predominately parallel to the axis of the magnet (produced with a Maxwell arrangement of coils) result in weaker relaxation as the cell is displaced from the isocentre of the magnet. This behavior is consistent with the line gradients of the IMFs produced by these two different coil geometries.

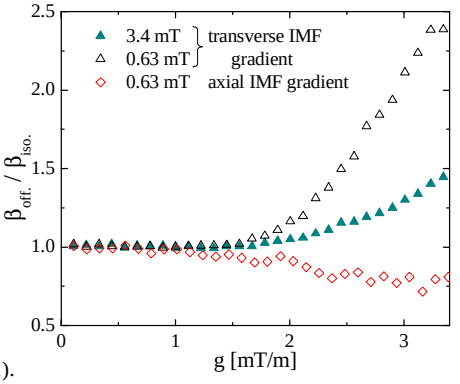

Figure 2: Comparison of FID attenuation factors measured in the axial offset position to those measured at the isocentre of the magnet.

SUMMARY: This work demonstrates a practical means for probing the breakdown of the high-field approximation as it pertains to the implementation of low-field MR imaging experiments. One of the most encouraging features of our data is that there is little evidence for the inadequacy of the high-field approximation under conditions comparable to those that have already been used for low-field polarized noble gas diffusion studies in human lungs (B_0 ~ 3 mT, g < 0.7 mT/m) [4].

REFERENCES:

[1] Callaghan *et al. Rev. Sci. Instrum*. **68**, 4263 (1997).
[2] Wong *et al., J. Mag. Reson*. **141**, 217 (1999).
[3] Schlenga *et al, App. Phys. Lett*. **75**, 3695 (1999).
[4] Bidinosti *et al., J. Mag. Reson*. **162**, 122 (2003).
[5] Stepisnik, *Z.Phys. Chem*.**190**, 51 (1995).
[6] Stepisnik *et al., J. Mag. Reson. A* **107**, 167 (1994).
[7] *e.g.* refs. in Mayo & Hayden, *Radiology* **222**, 8 (2001).
[8] de Swiet & Sen, *J. Chem. Phys.* **100**, 5597 (1994).
[9] Hurlimann *et al. J. Mag. Reson. A* **113**, 260 (1995).