How to unwind in the low field limit

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INTRODUCTION: Implementations of MRI in very-low [1-4], ultra-low [5,6], and even zero [7] static magnetic field have been recently demonstrated. This effort has motivated new and detailed theoretical investigations into effects and limitations imposed by the presence of concomitant gradients [8-11], which are associated with transverse magnetic field components that necessarily accompany any gradient one wishes to apply. Conventional MRI is accomplished in a 'high field' regime, where concomitant gradients have little effect on the direction of the static field B_0 and thus can largely be ignored. The same is not always true for small B_0. We examine here the issue of phase encoding in the low field limit. In particular, we explore the effect of concomitant gradients on the two principal methods used to 'unwind' phase, exemplified by the GRSE (gradient recalled spin echo) and PGSE (pulse gradient spin echo) sequences shown in Fig. 1. The GRSE is commonly used in high field applications, but suffers dramatically from concomitant-gradient induced asymmetries that limit spin rephasing in the low field regime (see Fig. 2). In contrast, the PGSE sequence is seldom used for biological measurements in the high field regime because of the danger of RF heating and the challenge of producing homogeneous π-pulses. Here we demonstrate that the PGSE sequence can be used to eliminate artifacts associated with concomitant gradients during a GRSE sequence. When combined with the fact that RF heating is greatly reduced [12] and excellent RF homogeneity is much easier to achieve [1,3], the PGSE approach to sequence design looks promising.

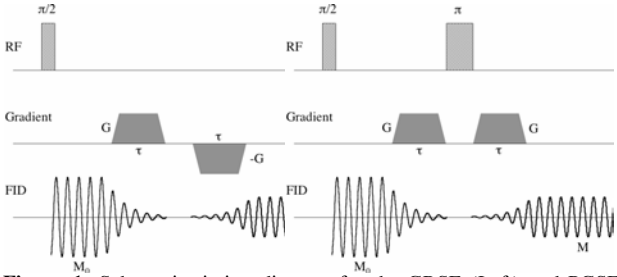

Figure 1: Schematic timing diagram for the GRSE (Left) and PGSE (Right) pulse sequences. In the 'high-field' regime, the FID attenuation ($\beta = M/M_0$) is due solely to spin diffusion, and for a given gradient amplitude (G) and duration (τ) will be the same for either sequence.

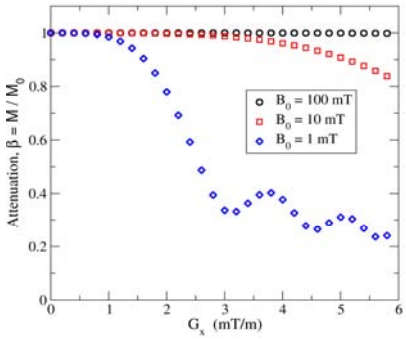

Figure 2: Theoretical attenuation curve for a GRSE sequence assuming static spins and a transverse (G_x) gradient. Complete unwinding of phase is not possible in low field because of concomitant gradients. The interference-like behavior at 1 mT has a period set by the dimensions of the pore.

METHODS: Experiments were carried out using a single cylindrical pore (glass cell) filled with ^{3}He gas at a pressure of 6 Torr; the free diffusion coefficient of ^{3}He under these conditions is of order 0.02 m^2/s. The cell (ID ~ 5 cm and 9 cm long) was positioned 3.8 cm from the isocenter along the symmetry axis of a low field MRI scanner operating at $B_0 = 0.6$ mT. Prior to the application of the spin echo sequence (GRSE or PGSE), metastability-exchange optical pumping was employed to produce nuclear polarizations of order 20%. The FID was monitored for 4 s before and after the applied gradient pulses (total duration < 1.5 ms) allowing us to accurately determine β from a fit of the data to a damped complex sinusoid. Further methods and general experimental details can be found in Reference [13].

RESULT AND DISCUSSION: The FID attenuation data shown in Fig. 3 are typical for both the GRSE and PGSE sequences. At low gradient strength G, the measured amplitude ratio β is the same for both sequences (see Fig. 4); at higher gradient strengths, however, results for the GRSE sequence clearly show greater attenuation and exhibit distinctive features that we associate with incomplete phase unwinding caused by concomitant gradients (compare with Fig. 2). In contrast to this, results for the PGSE sequence are consistent with the expected exponential behavior: ln(β) is proportional to G^2 in the low-G, free diffusion regime and is proportional to $G^{2/3}$ in the high-G, localization regime [13]. In other words, the PGSE experiment does not appear to exhibit any deleterious effects from the presence of concomitant gradients.

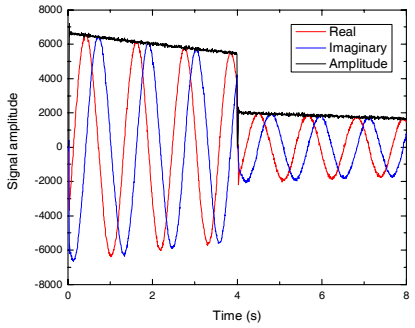

Figure 3: FID data from a GRSE sequence.

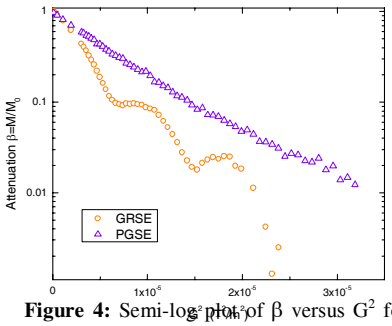

Figure 4: Semi-log plot of β versus G^2 for GRSE and PGSE experiments with identical timing. The result of the GRSE experiment is strongly affected by concomitant gradients.

SUMMARY: Our measurements demonstrate that a bipolar gradient sequence (*e.g,* the GRSE) is not the best choice for unwinding phase in low field implementations of MRI. A better strategy is to employ unipolar gradient pulses separated by an RF π-pulse (*e.g,* the PGSE). This technique is, of course, well known and established (*e.g,* in RARE imaging or CPMG diffusion measurements [1,3]), but tends not to be used in conventional MRI involving human subjects where RF heating is a concern and RF homogeneity is difficult to achieve. At low field (hence low frequency) RF power deposition is low [12] and one may safely use such methods to avoid the imperfect rephasing caused by concomitant gradients.

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