The Inner Lives of Voxels: Revisiting the basics for nonlinear gradient imaging

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Introduction

The prototypical MR echo, that of a boxcar of spins evolving under a linear gradient field, is taught in nearly every introduction to MR imaging. Namely, the magnitude evolves as sinc($\pi\gamma G t \Delta z$), and the phase of the bulk magnetization follows the frequency of the center. This work investigates the equivalent solutions for an object evolving in a quadratic gradient field, which is increasingly relevant given the growing interest in nonlinear imaging, and we report several surprising differences from the linear case. Most notably, dephasing under a quadratic gradient ($2z^2$-x^2-y^2) leads not only to modulation in the envelope of the signal, but also to nonlinear evolution in its phase. Therefore, neglecting this effect can cause intravoxel dephasing to register as evolution of the bulk magnetization, which can have significant experimental consequences even for routine experiments. For example, we verify the substantial distortions it can introduce in standard field mapping sequences, as well as the analytical expressions describing the dynamics of this phenomenon.

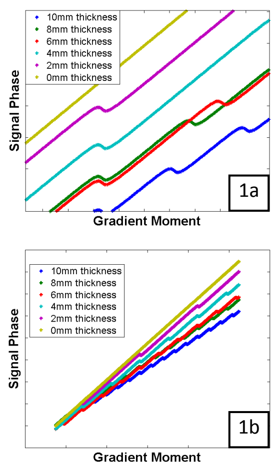


Figure 1: Simulations Under linear gradients, the phase of a uniform voxel evolving under a gradient would be linear. But a square voxel of finite dimension evolving in a quadratic field show nonlinearities. (Figure 1a) In aggregate, if these deviations are not taken into account, they can result in different apparent slopes, as shown in Figure 1b.

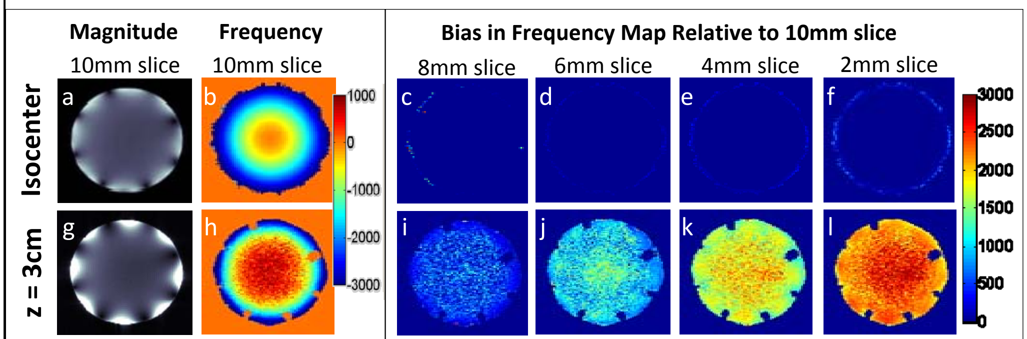
Methods The intravoxel dynamics of a square voxel evolving under a nonlinear gradient were studied via both simulations (numerical as well as analytical) and experiments. The simulations analyze the complex signal of a 1D boxcar function evolving in a nonlinear field, a case that can be interpreted in two ways: as a voxel with finite x or y dimensions in an infinitely thin slice or, more pertinently, as a voxel with infinitely small in-plane dimensions and a finite slice thickness. Because the signal equation is separable, the full three dimensional solution is a product of these cases.

In addition to a different magnitude envelope from the linear case, the analytical solution shows nonlinear phase behaviors that follow a relatively simple pattern. (Figure 1a) One effect of these nonlinearities is that they can change the apparent frequency of a pixel evolving under the gradient, thus distorting attempts to measure the true gradient strength at that point. (Figure 1b) We demonstrated this experimentally by applying a standard field mapping sequence to slices of different thickness. (Figure 2)

Results and Discussion

Linear spatial encoding gradients have a symmetry such that each spin evolving clockwise relative to the center of a uniform pixel is balanced by a spin evolving counterclockwise. However, both qualitative and quantitative analyses show that this is not the case for intravoxel dephasing when a nonlinear gradient is used for spatial encoding, and the phase evolution of a square voxel is no longer linear. Moreover, these distortions significantly alter the observed voxel phase as a function of gradient moment, which can have serious consequences for many standard field mapping sequences, particularly for larger intravoxel dimensions away from the isocenter. We explore the variables that modulate both the magnitude and phase of the signal and approaches to modeling those effects, as well as their experimental consequences and methods to correct for them.

Figure 2: Experimental Distortions
With linear gradients, the slice thickness would not be expected to affect the frequency map generated by a standard field mapping sequence. In our uniform phantom (a), the slice at isocenter yields the same frequency map (b) for the ($2z^2$-x^2-y^2) gradient regardless of slice thickness.



There is no bias introduced as the slice is narrowed to 8,6,4, or 2mm (c-f). However, at z=3cm (g), the analytical expression predicts that phase evolution from intravoxel dephasing becomes significant. If this evolution is naively interpreted as evolution of the bulk, the observed frequency of the slice becomes a function of the slice thickness (h-l).

References: [1] J.P. Stockmann, et al, Magn. Reson. in Med., 64(2):447-456. (2010)
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Acknowledgements: This work supported by NIH BRP R01 EB012289-01 and a L'Oreal for Women In Science Fellowship.