Understanding the Origin of Image Intensity Displacement in Spiral-In versus Spiral-Out Acquisitions

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Introduction: The presence of large susceptibility field gradients (SFGs) in regions such as the orbital frontal and inferior temporal lobes has been a major problem for functional MRI studies, particularly at higher magnetic field strengths where these SFGs become increasingly severe. Several groups have proposed techniques for dealing with these problems, and one of the most widely adopted techniques involves the use of reverse spiral trajectories (i.e. Spiral-In) [1]. Spiral-In waveforms have been consistently shown to recover significant amounts of signal in SFG regions and their use has been incorporated into several sequences including Spiral-In/Out [1], Spiral-In/In [2], and ASE Spiral [3]. There have been two main theories proposed for explaining why Spiral-In is superior to Spiral-Out for signal recovery. The first [1] states that it is due to the fact that the Spiral-In trajectories acquire the higher k-space spatial frequencies prior to the echo time TE, whereas in Spiral-Out, regions of large R_2* have the signal dephased by the time that the outer regions of k-space are traversed (since the spiral trajectory does not start until after TE). The second theory [2] proposes that improved signal recovery for Spiral-In is due to the presence of the internal field gradients which alters the actual k-space trajectories. The field gradients produce a linear shift in the trajectory with time and cause Spiral-In waveforms to actually pass through the centre of k-space much earlier in the acquisition window, and Spiral-Out acquisitions much later, than the anticipated effective echo time, TE. However, neither of these theories completely explains why Spiral-In images are able to recover more signal even when the Spiral-In acquisition window does not begin until after the Spiral-Out acquisition window is finished, nor why distortion patterns are different between Spiral-In and Out. In order to more completely understand this widely used technique, we examined the phenomenon further using a phantom that produces well-known field patterns as well as computer simulations.

Methods: In order to clearly distinguish the field patterns, a cylindrical phantom filled with water was placed perpendicular to the 4-Tesla magnetic field. The phantom contained five NMR tubes (cylinders also placed perpendicular to the main field) containing materials with differing magnetic susceptibility and R_2*. To maximize susceptibility induced field gradients, one of the tubes was filled only with air, while an adjacent tube was filled only with water. The other three tubes contained varying concentrations of SPIO (super paramagnetic iron oxide). An R_2* map of this phantom is shown in Figure 1. Computer simulations of the field offset patterns of a tube of air surrounded by water placed perpendicular to B_0 were done in IDL 6.2 (ITT Visual Information Solutions) using the standard field equations for a cylinder [4] and are shown in Figure 2.

All data were acquired using a 4T Varian INOVA whole body MRI system. Gradients were provided by a body coil (Tesla Engineering, UK) driven by 950 V amplifiers (PCI) at a maximum of 35.5 mT/m at 120 T/m/s. The RF coil was a quadrature driven TEM head coil (Bioengineering Inc) driven by a 7kW RF amp (AMT). Spiral waveforms were calculated using the method of Salustri et al. [5] and images were interpolated using the input spiral waveforms (no measured trajectories) as well as field map and navigator corrections. One 5-mm sagittal slice in the cylindrical phantom was acquired (64x64, 2-shot, 6 cm FOV, 2 s TR) using Spiral-In (TE = 30 ms and 52.6 ms) and Spiral-Out (TE=7.4 ms) both with flip = 60 and waveform acquisition took 23.6 ms. One 5-mm axial slice was also acquired with Spiral-In (TE = 30 ms and 41 ms) and Spiral-Out in a subject using 64x64, 2-shot, 24 cm FOV, 2 s TR and waveform acquisition took 12 ms.

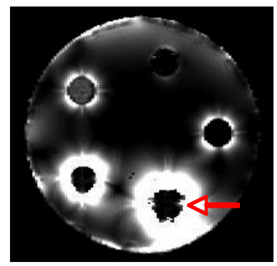

Figure 1: R_2* map of cylindrical phantom filled with tubes containing materials with varying R_2* (arrow indicates tube containing air) Tubes were placed perpendicular to B_0.

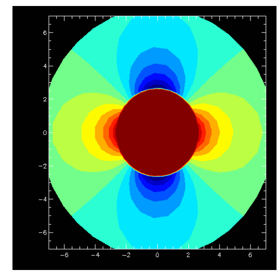

Figure 2: Computer simulations of the theoretical dipole field offset pattern around one cylinder [4].

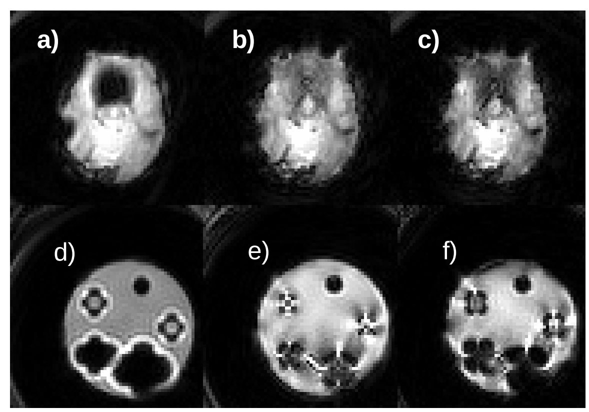

Figure 3: Spiral-In and Spiral-Out raw images in a human brain (24cm x 24cm, a-c) and cylindrical phantom placed perpendicular to B_0 (6cm x 6cm, d-f). The various TEs are a) Spiral-Out 18ms, b) Spiral-In 30ms, c) Spiral-In 42ms, d) Spiral-Out 7.4ms, e) Spiral-In 30ms and f) Spiral-In 52.6ms.

Results: Typical fMRI images of the brain for both Spiral-Out and Spiral-In images are shown in Figure 3 (a-c). Images in a) and b) are acquired during the same acquisition window (i.e. during the same time period after the excitation pulse). The Spiral-In acquisition for the image in c) begins after the acquisition window used for a) and b) is completed. The same is true for the images of the cylindrical phantom in d – f where d) and e) are acquired in the same acquisition window and f) is acquired after the window used for d) and e) is complete. Comparison of the Spiral-In versus Spiral-Out acquisitions reveals differences in both signal recovery and distortion.

Discussion & Conclusions: In general, the Spiral-In images exhibit improved signal recovery and decreased signal displacement relative to the Spiral-Out images (i.e. 3a vs. b and d vs. e) in regions of high R_2*. However, even if the Spiral-In acquisition window occurs after the Spiral-Out acquisition window (i.e. 3c and f) the images exhibit the expected increase in R_2* weighting while retaining the overall geometric features of the earlier Spiral-In.

For a cylindrical phantom, as seen in Figure 2, the well-known field offsets along the direction of Bo closely resemble the patterns of signal loss/distortion seen in Spiral-Out. However, those patterns in Spiral-In do not match this same geometric pattern, but appear rotated by about 45^0 (Fig. 3e, f). The origin of this striking difference in the geometric distortion is not immediately apparent, and numerical simulations are underway to better understand this phenomenon.

A number of questions remain regarding the ability of Spiral-In to recover signal in areas of large SFGs even when acquired later than a Spiral-Out. Our results confirm that signal recovery is related to k-space trajectory and not the acquisition window. Even more interesting is the difference in signal distortion patterns between Spiral-Out and Spiral-In. Although Spiral-In is known to have reduced signal distortion as compared to Spiral-Out, these results demonstrate that some geometric distortion remains, albeit in a different form. These differences are not explained by the current theories in the literature but initial numerical simulations indicate it may be related to the location of peak field gradient patterns in the distortion field.

References: **[1]** G.H. Glover & C.S. Law. *Magn Reson. Med.* **46** 515-522 (2001). **[2]** T.Z. Li *et al. Magn. Reson. Med.* **55**, 325-334 (2006). **[3]** K. Brewer *et al.* submitted to *NMR in Biomed.* (2008). **[4]** M. Haake *et al.* In *Magnetic Resonance Imaging – Physical Principles and Sequence Design*. p. 753 (1999). **[5]** C. Salustri *et al. J. Magn Reson.* **140**, 347-350 (1999).