Recovery of Signal using Spiral-In K-Space Trajectories: Phase Coherence or Intensity Displacement?

K. Brewer[1,2], J. Rioux[1,2], M. Klassen[3], C. Bowen[1,4], and S. Beyea[1,4]
[1]Institute for Biodiagnostics (Atlantic), National Research Council of Canada, Halifax, Nova Scotia, Canada, [2]Physics and Atmospheric Science, Dalhousie University, Halifax, Nova Scotia, Canada, [3]Robarts Research Institute, University of Western Ontario, London, Ontario, Canada, [4]Physics and Atmospheric Science, Radiology and Biomedical Engineering, Dalhousie University, Halifax, Nova Scotia, Canada

Introduction: Susceptibility field gradients (SFGs) cause persistent problems for functional MRI (fMRI) in regions like the orbital frontal lobes. This leads to difficulties like significant signal loss and image artifacts such as signal displacement and "pile-up". Spiral pulse sequences are commonly used in fMRI, and spiral-in is known to be considerably better than spiral-out at signal recovery in these SFG regions [1]. The reason for this improvement is not well understood, particularly given that spiral-in has improved signal recovery even with considerably delayed acquisition windows. Previously proposed theories in the literature [1,2] do not address the probability of signal displacement or fully explain all of the differences in signal recovery between spiral-out and spiral-in.

Previously we explored this behaviour using experimental simulations of a field-offset model consisting of concentric cylinders [3]. These results showed that R_2*-based signal dephasing accounted for only 25% of the apparent signal difference between spiral-out and spiral-in. For both techniques, signal from differing geometrical locations is "blurred" into a voxel location according to point spread functions (PSF), which have equivalent size. Additionally, signal displacement of the centre of mass of the PSF was found to occurr identically in both spiral-out and spiral-in. This is contrary to the assumption in the literature that there is little to no signal displacement present in spiral-in images. In the current work we demonstrate that the difference in image intensity is not due to differences in how signal is displaced, but rather the increased phase coherence of the displaced pixels when using spiral-in.

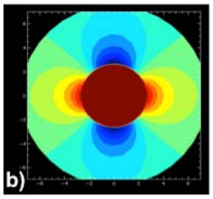

Figure 1 - B_0 field maps for 2 concentric cylinders perpendicular to B_0 with air (internal) and water.

Methods: Theoretical simulations for both spiral-out and spiral-in were performed in Matlab (The Mathworks, Natick MA). The simulations were designed to replicate transverse images of a phantom containing a single glass tube (χ = -9.77E-06) filled with air (χ = 0.37E-06) within a cylinder filled with water (χ = -9.06E-06). The data was simulated by first inputting arrays representing the cylindrical object and field map (Figure 1). This object and field map information was then combined with the k-space trajectory to calculate the free induction decay (FID) using Equation 1 [4]. K-space trajectories were calculated based on the Archimedean spiral gradient waveform patterns [5] that we typically use for data acquisition (as well as for gridding in the reconstruction program). The data were then reconstructed with the same gridding program used for experimental data.

$$FID(t) = \sum_{x}\sum_{y} object(x,y)\cdot\exp(2i\pi\cdot\Delta B(x,y)\cdot(TE+t))\cdot\exp(2i\pi\cdot(k_x(t)\cdot x + k_y(t)\cdot y) \qquad [1]$$

A variety of experimental conditions were simulated, including single and multi-shot images at both 64x64 and 128x128 matrix resolutions with several different TEs. However, all data were reconstructed with the same 5 cm FOV. For high-resolution images, the initial object data and field maps were of higher resolution than the final image (i.e. the field map was generated using a 1024x1024 matrix within the same FOV) in order to accurately simulate intravoxel dephasing. To study signal displacement, phase coherence and signal loss on a voxel-by-voxel basis, simulations were done using independent reconstructions with single voxels having signal intensity that were passed into the program alongside the full field map. The simulations were then looped over the whole object.

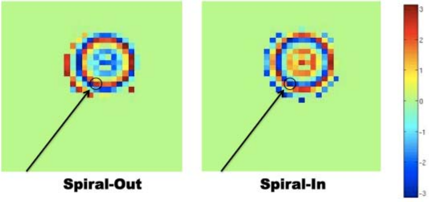

Figure 2 - Phase distribution of the point spread functions for spiral-out and spiral-in. The arrow indicates the example pixel used for calculating target maps in Figure 3. Phase patterns differ in polarity and distribution. Color scale in radians.

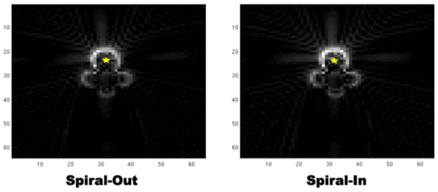

Figure 3 - Target maps of signal intensity for spiral-out and spiral-in, showing which object voxels contribute signal to the image voxel at location (32,24) (indicated by the star).

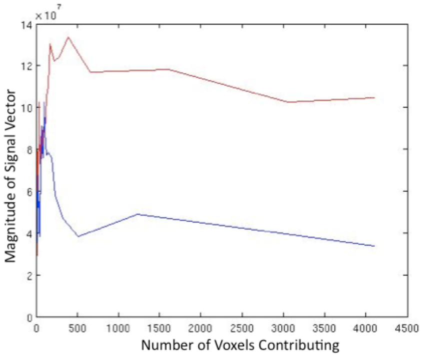

Figure 4 – The magnitude of the resultant signal vector as a function of the number of voxels contributing signal (from Figure 3). Pixels were added in order of decreasing signal amplitude. Blue is spiral-out and red is spiral-in.

Results & Discussion: In our previous work, we noted that the shape and centre of mass shift of the PSF were the same regardless of the spiral trajectory. If we examine the phase of the PSF, however, differences are apparent in spiral-out versus spiral-in. Figure 2 shows the PSF for a single voxel within the object, acquired using simulated spiral trajectories combined with the full phantom field map. The phase PSF's are relatively symmetric with predominantly opposing phase. The phase reversal is expected for time reversed acquisitions in the presence of a B_0 inhomogeneity, however, there are other differences in the PSF.

Further studies were then performed using a target-based approach; i.e. examining those physical locations within the object that contribute signal to an image voxel due to signal displacement. As expected from past work, the geometrical locations that contribute signal to each voxel in the image are identical for spiral-in and spiral-out. Results for a typical target voxel are shown in Figure 3. However, if we examine the phase of the signal from each location contributing intensity to an image voxel, differences are readily apparent. Figure 4 shows the magnitude of the signal vector obtained by summing an increasing number of the object voxels that contribute signal to a particular image voxel (32,24). For spiral-in, the magnitude of this vector increases as object voxels sum together with increased phase coherence. For spiral-out, while the signal increases initially, as more object voxels contribute, the phase interferes destructively and the signal drops. Indeed, an examination of that voxel in the simulated spiral images shows a significant decrease in image intensity for spiral-out compared to spiral-in. In non-SFG regions, both sequences have inter-voxel phase coherence resulting in increased signal intensity.

Conclusions: Differences in spiral-in versus spiral-out images, in the presence of SFGs, are not due to differences in the geometrical displacement of image intensity. R_2* effects (i.e. dephasing due to field gradients within a voxel) do not account for increased image hypointensity when using spiral-out. The primary source of differences between spiral-in and spiral-out is the degree of phase coherence between the object voxels that contribute signal, via blurring determined by the PSF, to an image voxel. This inter-voxel dephasing, as opposed to intra-voxel R_2* dephasing, dominates the signal loss in spiral-out imaging compared to spiral-in.

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]** KD Brewer *et al. Proc. of 17th Annual ISMRM* #568 (2009). **[4]** M. Haacke *et al. MRI Physical Principles and Sequence Design.* John Wiley and Sons (1999). **[5]** C. Salustri *et al. J. Magn Reson*. **140** 347-350 (1999).