A New Acquisition Strategy for Improved Signal Recovery and Artifact Suppression in Regions of Susceptibility Induced Field Gradients: Triple Spiral with Asymmetric Spin-Echo

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Introduction: The use of standard functional MR imaging (fMRI) methods results in significant signal loss and distortion in cortical regions within regions of magnetic susceptibility induced field gradients, SFG (e.g. in orbital frontal lobe). While the BOLD fMRI contrast is enhanced in strong magnetic fields (> 3-Tesla), SFG signal loss is also exacerbated when performing fMRI in these areas.

A variety of schemes have been proposed for overcoming this problem, with varying degrees of success. One such class of techniques is "Dual Spiral" methods [1,2], which include multiple spiral trajectories (i.e. "In/In", or "In/Out") for a single RF excitation. Images obtained using the Dual Spiral-In/Out technique [1] have the same R_2'-weighting ($R_2' = R_2^*-R_2$ and $R_2 = 1/T_2$), which may be optimized for BOLD fMRI contrast-to-noise ratio (CNR), but also exhibits significant residual image distortion in regions of SFG. The Dual Spiral-In/In method [2] has demonstrated significant improvement with respect to image distortion by acquiring the periphery of k-space during the period of increased signal intensity (i.e. resolution enhancement). However, these images do exhibit some residual signal loss in areas of SFG, particularly in regions where R_2' is much greater than R_2.

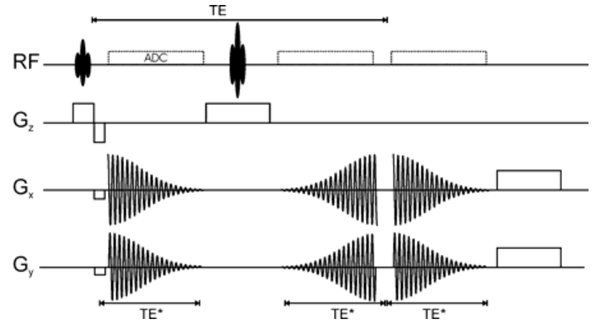

Figure 1: Triple Spiral SE sequence, showing acquisition of up to 3 spiral images per excitation with matched R_2' and k-space weighting, but increasing R_2-weighting.

We have therefore explored the use of a new pulse sequence, called Triple Spiral with asymmetric Spin-Echo, in which up to three spiral images are acquired per excitation. This sequence, implemented here on a 4-T scanner, utilizes a 180° refocusing pulse in which the latter spiral acquisitions are obtained asymmetrically with the spin-echo, and therefore all spiral acquisitions have the same R2'-weighting at an effective echo time, TE*.

Methods: Using the scheme shown in Fig. 1, the first data collection period takes place during a standard spiral-in gradient trajectory, with the centre of k-space being acquired at a time TE*. A spin-echo refocusing pulse is then applied, and data is acquired using a spiral-out waveform, starting at a time TE* before the peak of the spin-echo. Following the echo peak, a third acquisition may also be obtained, using a spiral-in waveform, with the centre of k-space again occurring at TE*. This effectively results in three spiral-in images that can be summed together, all having identical R_2'-weighting (proportional to $\exp[-R_2'\bullet TE^*]$) and resolution enhanced k-space weighting to ensure minimal image distortion. The echoes differ only by the amount of irreversible signal decay (R_2) described at echo times of TE*, TE-TE* and TE+TE* for each echo, respectively. Therefore, in regions where $R_2' \gg R_2$, the second (and third) spiral images obtained using the Triple Spiral SE method will have improved signal recovery, relative to the Dual Spiral-In/In method.

The scanner used in these experiments was a 4-T whole-body Varian INOVA system, combined with a body gradient coil (Tesla Engineering, UK) driven by 950V gradient amplifiers (MTS Inc, USA), and a quadrature driven TEM head RF coil (Bioengineering Inc, USA). Spiral waveforms were calculated using the method of Salustri *et al* [3]. Images were interpolated and reconstructed using the input spiral waveforms (i.e. no measured trajectories), as well as field map and navigator correction. Data analysis was performed using Stimulate 6.0 (CMRR, Minneapolis, USA).

	Superior Lateral Temporal	Occipital	Inferior Temporal	Orbital Frontal
Spiral-Out	0.54	0.45	0.40	0.20
Dual Spiral-In/Out	0.64	0.53	0.43	0.51
Dual Spiral-In/In	0.57	0.57	0.50	0.48
Triple Spiral-SE	1.00	0.95	0.99	1.01

Table 1: Relative Signal-to-Noise for ROIs within 4 different cortical regions, normalized to the SNR obtained using the Triple-Spiral method in the superior lateral temporal lobe.

Results: Ten 6-mm axial slices per volume were acquired (64x64, 2-shot, 24cm FOV, 2s TR) using the conventional Spiral-out (TE = 22 ms), Dual Spiral-In/Out ($TE_1 = TE_2$ = 22 ms), Dual Spiral-In/In (TE_1 = 22 ms, TE_2 = 36 ms), and the Triple Spiral SE sequence (TE = 55 ms, $TE^*_1 = TE^*_2 = TE^*_3$ = 22 ms). The resulting summed (signal-weighted) images are shown in Fig. 2, with the Triple Spiral SE images exhibiting noticeable improvement in image quality, signal-to-noise ratio (SNR), and artefact level within inferior slices.

The images were analyzed by defining 4-by-4 pixel regions-of-interest (ROIs) in four different areas of a representative image, corresponding to superior lateral temporal, occipital, inferior temporal, and orbital frontal regions. The SNR was then calculated as the mean image intensity within those voxels, divided by the standard deviation of the pixel intensity in "air" over 110 repeated image volumes (with all 110 images having been acquired as a series during data acquisition). These results, summarized in Table 1, demonstrate improved SNR when using the Triple Spiral SE sequence, particularly in regions of severe SFG such as orbital frontal cortex. Specifically, the overall SNR is relatively flat over the head, with the SNR in the occipital cortex being the same as that in regions of susceptibility inhomogeneity such as orbital frontal cortex.

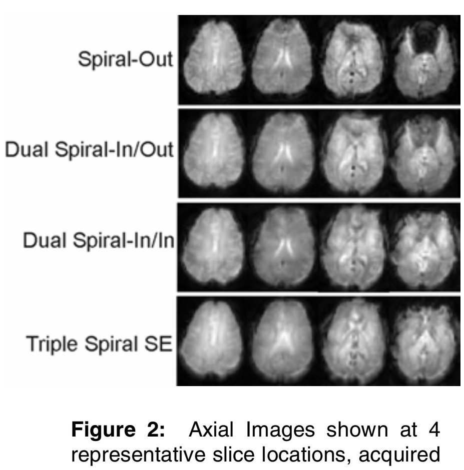

Figure 2: Axial Images shown at 4 representative slice locations, acquired using Spiral-Out, Dual Spiral-In/Out, Dual Spiral-In/In and Triple Spiral SE.

Conclusions: This new Triple Spiral SE technique provides the ability to acquire up to three spiral-in images per excitation, with all images having identical R_2'-weighting and k-space weighting. The summed images exhibit improved SNR and uniformity relative to conventional dual-spiral techniques. While the use of a third spiral does decrease ultimate temporal resolution (relative to dual-spiral methods), if higher temporal resolution is required this sequence can also be implemented with only the first two spirals, resulting in the same temporal resolution as conventional dual spiral. Dual Spiral SE will have the same temporal resolution as the conventional Dual Spiral sequence, with SNR improvements intermediate between Dual Spiral-In/In and the Triple Spiral SE method.

We believe Triple Spiral SE acquisitions will provide similar image artifact suppression in regions of field inhomogeneity as Dual Spiral-In/In approaches, superior SNR in regions of SFG, and may eventually provide more consistent, and optimal fMRI in regions such as orbital frontal cortex via the summation of three images each with equal R_2'-weighting optimized for BOLD contrast.

References: **[1]** G.H. Glover & C.S. Law "Spiral-in/out BOLD fMRI for increased SNR and reduced susceptibility artifacts" *Magn. Reson. Med.* **46** 515-522 (2001). **[2]** T-Q. Li *et al* "Dual-Echo Spiral In/In Acqusition Method for Reducing Magnetic Susceptibility Artifacts in BOLD Functional Magnetic Resonance Imaging" *Magn. Reson. Med.* **55**, 325-334 (2006). **[3]** C. Salustri *et al* "Simple but reliable solutions for spiral MRI gradient design" *J. Magn. Reson.* **140**, 347-350 (1999).