Triple Spiral with Asymmetric Spin Echo: A New Method for Improved BOLD fMRI in Regions of Magnetic Susceptibility Induced Field Inhomogeneity

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Introduction: A variety of functional MRI (fMRI) techniques have been proposed for overcoming the effect of Blood Oxygen Level Dependent (BOLD) signal loss and image distortion in cortical regions within regions of magnetic susceptibility induced field gradients (SFG). One such class of techniques are those that utilize multiple spiral images per excitation, which are then combined to obtain images with increased signal-to-noise ratio (SNR), particularly in regions of SFG (e.g. orbital frontal lobe). Alternatively, spin-echo methods also recover image intensity in regions of SFG, however such techniques have greatly reduced sensitivity to functional activation. The optimal fMRI method for overcoming this issue would exhibit minimal image distortion, maximal SNR, and echo time (TE) optimized for BOLD contrast-to-noise ratio (CNR), i.e. $TE^{-1} \approx R_2'$ (where $R_2' = R_2^*-R_2$ and $R_2 = 1/T_2$).

The Dual Spiral-In/Out sequence [1] permits the acquisition of two images per excitation, each with the same R_2' weighting. However while this method permits partial recovery of SNR in severe SFG, significant image distortions remain due to the use of spiral-out trajectory, and the spiral-out image adds little signal in regions of SFG. It has more recently been shown that the use of a Dual Spiral-In/In [2] exhibits decreased sensitivity to spatial distortions, however the second spiral-in image is acquired with a longer echo time and therefore is strongly R_2^*-weighted. This second image has reduced image intensity in regions of SFG (particularly at high magnetic field), and only one of the two images may be acquired at the optimal TE for BOLD CNR. To produce both minimal image distortion and optimal BOLD CNR, each acquisition readout would ideally have matched R_2' weighting (at an effective echo time we call TE*) and increased signal intensity during spiral acquisition of the k-space periphery (resolution enhancement).

In order to satisfy both conditions, we propose the use of a spin-echo based spiral sequence, called Triple Spiral with Asymmetric Spin-Echo, in which multiple images per excitation are acquired with equal R_2'-weighting and minimal image distortion in SFG regions for each spiral acquisition.

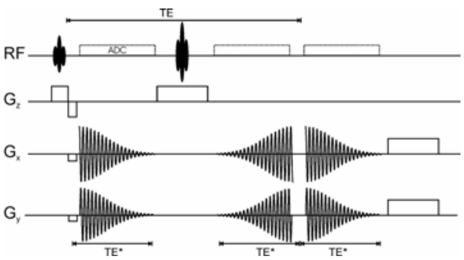

Figure 1: Triple Spiral SE sequence diagram, showing acquisition of up to 3 spiral images per excitation with matched R_2' and k-space weighting, but increasing R_2-weighting.

Methods: The proposed sequence, shown in Fig. 1, involves the collection of up to three spiral acquisitions, with spiral-in, spiral-out and spiral-in gradient waveforms, respectively. The latter two spiral acquisitions are asymmetric spin-echoes, with the k-space center collected a time TE* before and after the spin-echo center, respectively. In this way, three individual spiral images are obtained per slice, all having identical R_2' weighting (proportional to $\exp[-R_2' \bullet TE^*]$) and resolution enhanced k-space weighting to ensure minimal image distortion (i.e. akin to a spiral-in trajectory). 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. Given that BOLD contrast is predominantly defined by R_2' rather than R_2 relaxation, this may permit more consistent, and optimal, BOLD contrast from each echo.

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 v.6.0 (CMRR, Minneapolis, USA).

Functional volumes were acquired using the Dual Spiral-In/Out ($TE_1 = TE_2 = 25$ms), Dual Spiral-In/In ($TE_1 = 25$ms, $TE_2 = 39$ms), and Triple Spiral SE sequences ($TE^*_1 = TE^*_2 = TE^*_3 = 25$ms, TE = 62 ms), using eighteen 6 mm axial slices (64x64, 2-shot, 24cm FOV, TR = 4s). Initial experiments using an 8 Hz alternating checkerboard (6 rest periods, 5 stimulus periods, 20 second period), in order to compare overall image quality, stability and CNR using an established fMRI task. The multiple spiral acquisitions were summed using a signal-weighted scheme. Activation maps were calculated as the pixel cross-correlation map (correlation threshold of 0.4), with no temporal filtering, spatial smoothing or motion correction.

Results: Mean image intensity was calculated within regions-of-interest (ROIs) of the resulting axial images, corresponding to superior lateral temporal, inferior temporal, and orbital frontal cortex. The combined image noise and physiological fluctuation in the images was calculated as the standard deviation of the image intensity from the ROIs during the first 20 second rest period, σ_N. This noise level therefore takes into account both the random image noise, as well as signal fluctuations due to respiration etc. Using this, the "physiological" SNR was calculated. These results, summarized in Table 1, show increased SNR for the Triple Spiral SE images in all cortical regions. This was due in part to the decreased σ_N that resulted from the summed Triple Spiral images, particularly in regions of SFG. Decreased signal fluctuation is expected to increase the statistical power and/or decrease the likelihood of "false" activation, particularly in regions of SFG. Visual activation maps from a representative subject, obtained using each of the three methods are shown in Fig 2.

	Superior Lateral Temporal	Inferior Temporal	Frontal
Dual Spiral-In/Out	0.77	0.56	0.48
Dual Spiral-In/In	0.79	0.51	0.55
Triple Spiral-SE	1.00	0.91	0.78

Table 1: Relative "Physiological" Signal-to-Noise for ROIs within 3 different regions, normalized to the SNR obtained using the Triple-Spiral SE method within the superior lateral temporal lobe.

Discussion & Conclusions: The use of the Triple Spiral SE sequence permits the acquisition of fMRI data with improved SNR and image stability relative to other spiral methods. The use of the spin-echo significantly improves the SNR, particularly in regions of increased R_2', which is particularly important for fMRI at high field. While the use of three spirals decreases the temporal resolution, in situations where high temporal resolution is required, this sequence can also be implemented using only the first two spirals. This will result in fMRI improvements in regions of SFG intermediate to that provided by the Triple Spiral SE and Dual Spiral-In/In methods.

Asymmetric acquisition relative to a spin-echo allows for up to three images with TE* set to the optimal R_2'-weighting for BOLD CNR, while the acquisition of all data with equivalent "resolution enhancement" k-space filtering results in fMRI data sets with minimal spatial distortion. We believe Triple Spiral SE acquisitions will provide image distortion suppression in regions of SFG which are comparable to Dual Spiral-In/In, and may eventually provide more consistent, and optimal BOLD contrast encoding for fMRI studies which are expected to elicit brain activity in orbital frontal, as well as inferior and medial temporal cortex.

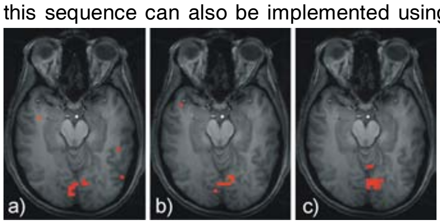

Figure 2: fMRI visual activation maps, shown for a) Dual Spiral-In/Out, b) Dual Spiral-In/In, and c) Triple Spiral SE

References: **[1]** G.H. Glover & C.S. Law *Magn. Reson. Med.* **46** 515-522 (2001). **[2]** T-Q. Li *et al* *Magn. Reson. Med.* **55**, 325-334 (2006). **[3]** C. Salustri *et al* *J. Magn. Reson.* **140**, 347-350 (1999).