A Novel Technique for Functional MRI in Regions of Magnetic Field Inhomogeneity – Z-shim Asymmetric Spin-Echo (ASE) Spiral

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Introduction: The presence of magnetic susceptibility induced field gradients (SFG) in regions such as the orbital frontal cortex results in significant signal loss and image distortion in functional MRI studies. Several techniques have been developed to recover signal and fMRI activation in these areas. One class of techniques involves the acquisition of multiple spiral images in a single excitation [1,2,3], while another class of techniques involves using a blipped gradient along the slice direction just before the acquisition of an image to recover signal [4]. Since fMRI images are usually acquired axially, the latter technique is known as z-shim. Recently these two types of techniques have been combined, resulting in a z-shim spiral-in/out [5,6]. We propose a new z-shim variation on this technique called Z-shim Asymmetric Spin-Echo (ASE) spiral, based on our previously described ASE spiral technique [3]. Z-shim ASE allows for the acquisition of up to three spirals per excitation, each with a different z-shim value (optimized on a slice-by-slice basis) and matched R_2'-weighting. The use of the multiple z-shim values permits additional signal recovery in regions of SFGs as compared to ASE, resulting in a significant increase in SNR.

Methods: The Z-shim ASE spiral sequence (Figure 1) is exactly the same as the ASE spiral sequence, but also applies a short z-gradient before each individual spiral image acquisition. The gradient is then rewound immediately following each acquisition. Z-shim values are chosen through use of an automated optimization routine that assigns appropriate z-shim values to each spiral, for each slice.

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) with 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. [7] and images were interpolated using the input spiral waveforms (no measured trajectories) as well as field map and navigator correction. 18 5-mm axial slices per volume were acquired (64x64, 2-shot, 24 cm FOV, 4s TR) using a z-shimmed ASE triple spiral sequence (TE = 64 ms, $TE^*_1 = TE^*_2 = TE^*_3$ = 25 ms), traditional ASE spiral sequence (same parameters as z-shim ASE) and Z-shim Spiral-In/Out (TE = 30ms). 30 volume scans were acquired for one subject to calculate SNR and a functional MRI breath-holding protocol was done for another subject (using ASE spiral and z-shim ASE spiral). A breath-hold task was used to elicit activation in all regions of the brain. The breath-hold task involved 5 normal breathing blocks, 4 breath-hold blocks (with breath-hold on exhalation) for 30 second block length.

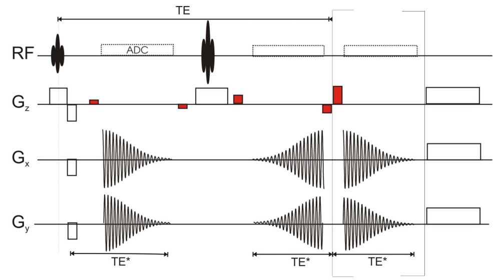

Figure 1: Z-shim ASE Triple Spiral sequence, showing acquisition of up to 3 spiral images per excitation with z-shim gradient before each acquisition. Z-shim gradients are shown in red.

SNR results were calculated in six different regions of interest (ROIs) by computing the ROI signal mean over the 30 rest volumes and then dividing by the average signal standard deviation of pixels in the ROI computed over the rest volumes. The multiple acquisitions were summed using sum of squares. An activation map was calculated for each image using a sinusoidal model in FEAT (cluster threshold = $p<0.05$) and the z-score statistics for each sequence were calculated using FEATQuery (both available in FSL [8]).

ROI	SNR relative to ASE	SNR relative to Z-shim In/Out
Brodmann Area 18	1.70	2.41
Postcentral Gyrus	1.31	1.89
Caudate Head	1.63	2.26
Brodmann Area 11	1.98	2.07
Frontal Medial Orbital	1.56	2.19
Inferior Temporal Gyrus	1.92	1.76

Table 1: Ratio of SNR of Z-shim ASE to normal ASE and Z-shim In/Out for 6 ROIs in regions with and without strong SFGs.

Results: Raw images for an inferior slice are shown in Figure 2 for ASE Spiral (2a), Z-shim Spiral-In/Out (2b), and Z-shim ASE Spiral (2c). While ASE Spiral appears to recovering comparable signal intensity for orbital frontal and inferior temporal regions relative to Z-shim Spiral-In/Out, Z-shim ASE appeared to recover the most signal (particularly in the orbital frontal area). SNR results shown in Table 1 confirm the increased signal recovery due to the use of z-shim for ASE Spiral. For ROIs in non-SFG regions (Brodmann area 18 and the Postcentral Gyrus), there is a 30-70% increase in SNR for Z-shim ASE spiral as compared to ASE spiral (and a more than 90% increase in SNR recovery compared to Z-shim In/Out). For SFG regions (particularly orbital frontal and inferior temporal regions) these increases are even larger with Z-shim ASE Spiral, having up to 100% more SNR than ASE spiral, and up to 125% more SNR than Z-shim In/Out. Z-shim ASE Spiral fMRI activation maps are shown in Figure 3 for a superior slice (non-SFG regions) and an inferior slice (SFG region).

Discussion & Conclusions: Z-shim ASE spiral has advantages both over other z-shim methods (like Z-shim Spiral-In/Out), as well as ASE spiral, because it offers significant SNR gains throughout the entire brain (as seen in Table 1). Z-shim ASE Spiral allows for SNR increases on the order of 60-100% in SFG regions while only requiring a short prescan (on the order of one minute). For temporal resolution that is equivalent to Spiral-In/Out (both with and without z-shim), it is also possible to acquire only the first two spirals with accompanying z-shim gradients. As demonstrated in Figure 3, it is possible to acquire functional MRI results using Z-shim ASE spiral and the significant increases in SNR being demonstrated may indicate considerable increases in CNR as well (which is more relevant to fMRI).

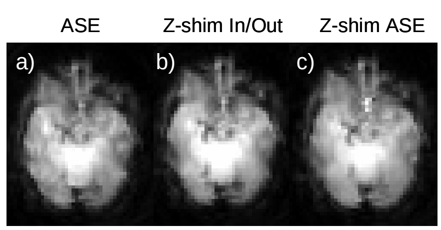

Figure 2: Raw images for a) Asymmetric spin-echo (ASE) spiral (TE*=25 ms, TE=65 ms) b) In-Out (TE=25 ms), and c) Z-shim ASE spiral (TE*=25 ms, TE=65 ms).

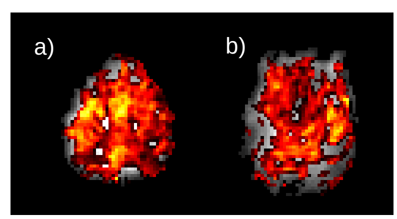

Figure 3: FMRI activation maps for Z-shim ASE Spiral for a) a superior slice and b) an inferior slice (i.e. in SFG regions). Z-scores range from 2.3-13.

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