Asymmetric Spin-Echo Reduces Susceptibility Distortion without loss of BOLD CNR

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Introduction: The presence of magnetic susceptibility induced field gradients (SFG) in regions such as the orbital frontal lobe results in significant signal loss and image distortion in functional MRI studies. Several fMRI techniques have been proposed for overcoming these effects and one such class of techniques uses the acquisition of multiple spiral images per excitation which can then be combined to recover SNR. Spin-echo sequences can also be used to recover activation in areas of SFG but have lower sensitivity to activation. Dual Spiral-In/Out [1] has two acquisitions per excitation with both having matched R2' weighting (where R2' = R2*-R2 and R2 = 1/T2). However, the spiral-out image continues to contribute distortion to the summed image. Dual Spiral-In/In [2] is not as sensitive to the distortion but has reduced sensitivity to activation in SFG areas because the second image is acquired at a longer echo time which can cause a significant reduction in signal strength. In order to gain reduced distortions in all images as well as increased sensitivity to activation (and the ability to optimize the R2'-weighting), we recently proposed a new sequence, Asymmetric Spin-Echo (ASE) Spiral [3]. This method produces up to three images (ASE "Triple" Spiral), all with matched R2'-weighting but increasing R2-weighting and with k-space filtering equivalent to spiral-in due to the presence of a spin-echo pulse. The ASE Spiral technique results in combined images with the reduced image distortion seen in Dual Spiral-In/In, but since all images have matched R2'-weighting, the BOLD CNR is equivalent or better (in regions of SFG) to that of the Dual Spiral-In/Out method.

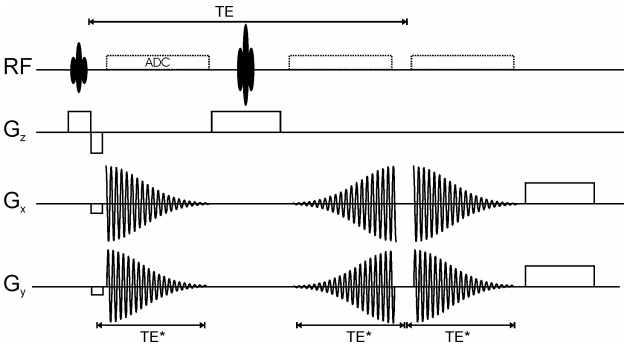

Figure 1: ASE Triple Spiral sequence, showing acquisition of up to 3 spiral images per excitation with matched R2' and k-space weighting.

		# Activated Voxels	Mean Z-Score
Inferior Slice	Dual Spiral-In/Out	1081	5.2
	Dual Spiral-In/In	976	4.6
	Spin-Echo Spiral-In/Out	308	3.3
	ASE Triple Spiral	1118	5.9
	ASE Dual Spiral	1110	5.8
Superior Slice	Dual Spiral-In/Out	1070	5.7
	Dual Spiral-In/In	989	5.8
	Spin-Echo Spiral-In/Out	435	3.9
	ASE Triple Spiral	1129	6.2
	ASE Dual Spiral	1111	6.1

Table 1: Z-score statistics for the fMRI maps shown in Figure 2.

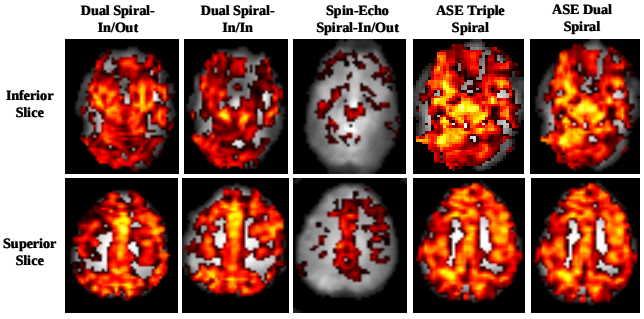

Figure 2: fMRI Breath-hold activation maps, shown for inferior and superior slices acquired using Dual Spiral-In/Out, Dual Spiral-In/In, Spin-Echo Spiral-In/Out, ASE Triple Spiral and ASE Dual Spiral.

Methods: All data were acquired using a 4T Varian INOVA whole body MRI system. Spiral waveforms were calculated using the method of Salustri et al. [4] and images were interpolated using the input spiral waveforms (no measured trajectories) as well as field map and navigator correction.

Fourteen 5-mm axial slices per volume were acquired (64x64, 2-shot, 24 cm FOV, 3s TR) using Dual Spiral-In/Out ($TE_1 = TE_2 = 25$ ms, flip = 60°), Dual Spiral-In/In ($TE_1 = 25$ ms, $TE_2 = 37$ ms, flip = 60°), Spin-Echo-In/Out (TE = 60ms) and the ASE Triple Spiral sequence (TE = 70 ms, $TE^*_1 = TE^*_2 = TE^*_3 = 25$ ms, see Fig 1). FMRI experiments using a breath-hold task (5 normal breathing periods, 4 breath-hold periods with breath-hold on exhalation, 30 second period) meant to elicit activation in all regions of the brain making it possible to compare CNR and image quality. The multiple acquisitions were summed using a signal-weighted scheme. An activation map was calculated for each image using a sinusoidal model in FEAT (cluster thresholded with a significance of p=0.05) and the z-score statistics for each sequence were calculated using FEATQuery (both available in FSL [5]).

Results: Breath-hold activation maps and statistics for a representative subject are shown in Fig 2 and Table 1. Inferior brain regions: The ASE Spiral sequence has more activated voxels and higher mean and max z-scores than all other methods tested, as well as visually appearing to have a more robust activation pattern. Dual Spiral-In/Out exhibits higher mean z-scores and activated pixels than those of Dual Spiral-In/In and the Spin-Echo sequence. As expected, the Spin-Echo In/Out has significantly less activation as well as lower z-scores due to the decrease in sensitivity. Superior brain regions: The ASE Spiral, Dual Spiral-In/In and Dual Spiral-In/Out have comparable mean z-scores and an equivalent number of activated voxels. ASE Dual Spiral and ASE Triple Spiral have similar z-score statistics even though the latter has an additional image being added to the combined image.

Discussion & Conclusions: The ASE Spiral sequence has two main features, which individually make it comparable to either the Dual Spiral-In/Out or Dual Spiral-In/In sequences, but together give it a significant advantage over both methods. The ASE Spiral method exhibits slightly improved activation patterns compared to the conventional Dual Spiral methods in regions of the brain with little to no susceptibility problems, and significantly stronger activation patterns (more activated voxels, higher z-scores, etc.) in the SFG regions of the brain. Because all of the individual images obtained using ASE Spiral have the same k-space filtering as a Spiral-In, there is also suppression of the image distortion that is present in SFG regions when using Dual Spiral-In/Out. Furthermore, ASE Dual Spiral permits temporal resolution on par with the conventional Dual Spiral techniques. The use of ASE Spiral offers the flexibility of an increase in SNR/CNR with minimal image distortion, and may offer possible benefits in BOLD specificity if the R2 contribution of the latter images is maximized.

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.* 15th ISMRM (2007). **[4]** C. Salustri *et al. J. Magn Reson.* **140**, 347-350 (1999). **[5]** S.M. Smith *et al. NeuroImage* **23** 208-219 (2004).