Understanding the Limitations of the Effectiveness of Z-Shim for use with fMRI

K. Brewer[1,2], J. Rioux[1,2], R. D'Arcy[1,3], 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]Psychology and Radiology, Dalhousie University, Halifax, Nova Scotia, Canada, [4]Physics and Atmospheric Science, Radiology and Biomedical Engineering, Dalhousie University, Halifax, Nova Scotia, Canada

Introduction: Over the past decade, the application of z-shim gradients has been successfully used to reduce susceptibility field gradient (SFG) effects [1,2]. Most implementations successfully use z-shim combined with sequences that traditionally suffer from severe signal loss and distortion in SFG regions, like echo planar imaging (EPI) or spiral-out [1,2]. Recently, work was done to add z-shim to spiral-in [3,4], a technique that was designed to recover signal in susceptibility regions. However, questions remain as to whether combining multiple signal recovery techniques offers additional benefits in multiple subject studies. This study examines the addition of z-shim gradients to two different techniques that use spiral-in: spiral-in/out [5] and ASE spiral [6]. Using a breath-hold task to elicit whole brain fMRI activation, this study examines the effect of z-shim and spiral-in on SNR and fMRI activation. We demonstrate that although z-shim may be efficient at recovering signal in sequences prone to SFG effects, its use does not offer significant benefits at the group level when combined with spiral-in.

Methods: 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 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. Z-shim ASE was introduced in [8]; the pulse sequence schematic is found in Figure 1. Eighteen 5-mm axial slices per volume were acquired (64x64, 2-shot, 24 cm FOV, 4s TR) using a z-shim 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). Twenty-eight 5-mm slices were acquired with TE = 25 ms for z-shim spiral-in/out and spiral-in/out (all other parameters were the same).

Sixteen subjects participated, 8 per z-shim group. Z-shim values were calculated using a variety of automated metrics: sum of squares (SS) and MIP algorithms based on a pre-scan and the B_0 algorithm described in [4]. A breath-hold task was used to elicit activation in all brain regions. The breath-hold task involved 5 normal breathing blocks, 4 breath-hold blocks (with breath-hold on exhalation) for 30 s each. 10 volumes were added to the initial rest period to calculate SNR.

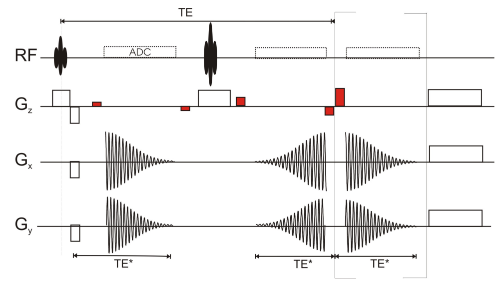

Figure 1: Z-shim ASE Triple Spiral sequence, showing acquisition of up to 3 spiral images per excitation with z-shim gradient before each acquisition. Z-shim gradients are shown in red.

SNR results were calculated in five different regions of interest (ROIs) by computing the ROI signal mean over the 15 rest volumes and then dividing by the average standard deviation of pixels in the ROI computed over the rest volumes. The multiple acquisitions were combined using a 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 [9]).

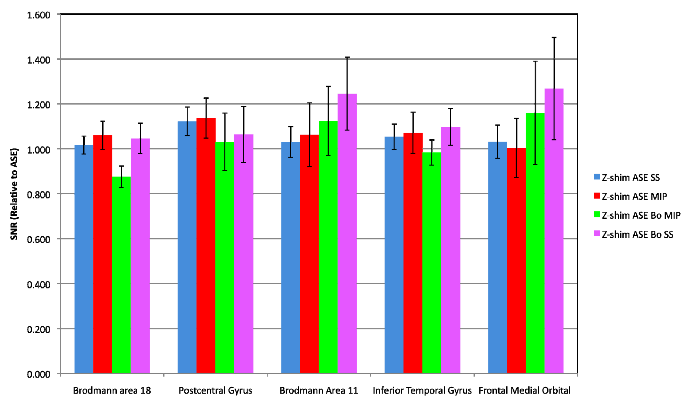

Figure 2: Relative signal-to-noise ratio of each z-shim algorithm using z-shim ASE spiral for ROIs within five different cortical regions, where the SNR in each region is normalized to the SNR obtained using ASE spiral (summed using SS). The three ROIs on the right are located in SFG regions. None differ significantly.

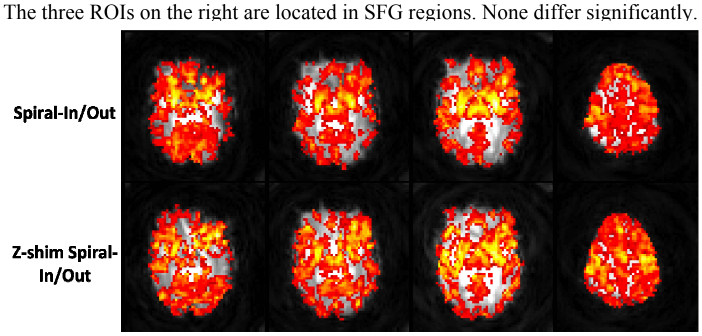

Figure 3: FMRI activation maps from a representative subject who completed the breath-hold task. The z- scores have a threshold of z = 2.3. The slice on the right is a superior slice, and the three other slices are all inferior slices with SFG regions.

Results: SNR values were calculated in both SFG and non-SFG regions. The SNR of z-shim sequences (z-shim spiral-in/out and z-shim ASE spiral) were compared to the same sequence without z-shim (spiral-in/out and ASE spiral). Z-shim spiral-in/out did not yield any significant SNR increase in any of the ROIs (data not shown), including those located in SFG regions (regardless of the automated z-shim routine used). Nor did z-shim ASE spiral yield any significant improvements to SNR in any region (Figure 2).

There were no significant increases in the extent or strength of activation for z-shim spiral-in/out or z-shim ASE spiral. Sample activation maps for spiral-in/out and z-shim spiral-in/out are seen in Figure 3 and show similar activation patterns with no additional activation in SFG regions.

Discussion & Conclusions: The results overwhelmingly indicate that the addition of z-shim gradients to each of the individual images in spiral-in/out and ASE spiral offers no real benefits for recovery of signal or fMRI activation in SFG regions.

Although there were no significant differences in the group results when comparing z-shim techniques to spiral-in/out and ASE spiral, there were often individual subjects who benefited from the addition of z-shim gradients. This variability in z-shim performance may be one of the reasons that z-shim spiral-in/out was initially found to perform better than spiral-in/out [4]. These z-shim sequences were repeatedly tested using several automated metrics for choosing z-shim values, one of which was previously published by another group [4], with no significant difference in the SNR or fMRI results. Some of the inter-subject variability in performance may be linked to the global shim values. Unfortunately, the variability meant that there were also individual subjects whose SNR and activation decreased significantly with the addition of z-shim gradients. Although it is clear from the literature that adding a z-shim to spiral-out is beneficial, spiral-in is already very good at recovering signal in SFG regions and additional z-shim gradients offer no extra benefits (and may in fact offer disadvantages for some subjects).

References: **[1]** R. Constable. *J Magn Reson Imag* **5** 746-752 (1995). **[2]** A. Song *Magn Reson. Med* **46** 407-411 (2001). **[3]** H. Guo and A. Song. *J Magn Reson Imag* **18** 389-395 (2003). **[4]** T.-K.Truong and A. Song *Magn. Reson. Med* **59** 221-227 (2000). **[5]** G.H. Glover & C.S. Law. *Magn Reson. Med.* **46** 515-522 (2001). **[6]** KD Brewer *et al. NMR in Biomed.* **22** 654-662 (2009). **[7]** C. Salustri *et al. J. Magn Reson*. **140**, 347-350 (1999). **[8]** KD Brewer *et al. Proc. of 17th Annual ISMRM* #1541 (2009). **[9]** S.M. Smith *et al*. *NeuroImage* **23** 208-219 (2004).