Improved Interleaved Single-shot z-shim EPI via Spatial and Temporal Encoding

W. S. Hoge[1], H. Pan[1], H. Tan[2], E. Stern[1], and R. A. Kraft[2]
[1]Radiology, Brigham and Women's Hospital, Boston, MA, United States, [2]Virginia-Tech Wake Forest School of Biomedical Engineering, Winston-Salem, NC, United States

Introduction: Neuroimaging methods that use gradient-echo EPI (e.g. BOLD fMRI) consistently suffer adverse effects from magnetic field inhomogeneity in regions close to nasal sinuses and ear canals. Magnetic susceptibility at air-tissue interfaces in these regions results in both geometric distortion and signal loss due to spin dephasing. Z-shim methods [1,2] are one approach to correct this signal loss, where a *z* gradient is applied across the slice to rephase the spins prior to data acquisition. Unfortunately, rephasing spins in one location will dephase spins in another. For this reason, z-shimming is typically achieved in two shots, with the final image formed by combining two z-shimmed images, each emphasizing signal regions that are "dark" in the complementary image. Single-shot z-shim methods, e.g. [3,4], are desirable in that temporal resolution is improved, often at a cost of longer EPI echo-trains, which increases geometric distortion. In this work, we seek to shorten the EPI echo train of the interleaved single-shot method of Gu, et al, [4] through the use of parallel MR imaging (pMRI). We also employ temporal encoding to mitigate the effect of Nyquist ghosts in the pMRI calibration [5].

Methods: We implemented an interleaved single-shot z-shim sequence by adding k_z blips coincident in time with the standard EPI k_y blips. An initial z-shim value of z_1 is achieved by a z-gradient applied at the start of the echo train. The second z-shim value, z_2, is achieved by setting the k_z blips to be proportional to the *difference*, ($z_1 - z_2$). Toggling the polarity of this gradient at each k_y blip ensures that data acquired on positive readout gradients, +RO, is associated with z_1, and data acquired on negative readout gradients, -RO, is associated with z_2. With temporal encoding, the readout polarity and z-shim parameter settings are modulated to acquire four images: +RO z_1, -RO z_1, +RO z_2, -RO z_2, where {+,-}RO and $z_{\{1,2\}}$ refers to the first line of measured k-space. We employ the cycle shown in Table 1, so that data is acquired using alternating readouts {···,+RO,-RO,+RO,-RO,···} for both z-shim values.

Time point	*t-3*	*t-2*	*t-1*	*t*	...
Odd ky line polarity	(+)	(+)	(-)	(-)	...
Even ky line polarity	(-)	(-)	(+)	(+)	...
Odd line z-shim value	z_1	z_2	z_2	z_1	...
Even line z-shim value	z_2	z_1	z_1	z_2	...

Table 1: four-cycle acquisition order

The first step in image reconstruction is to calibrate the pMRI reconstruction parameters. Here we employ GRAPPA [6] with a '2x5' kernel. We interleave data from two frames, from data at *(t-3)* and *(t-1)*, to yield images S^{+}_{z1} and S^{-}_{z2}, where the superscript/subscript refers to the readout gradient polarity and z-shim value, respectively. To improve the pMRI calibration [5], a second set of frames, from data at *(t-2)* and *(t)*, are interleaved to generate images at the same z-shim setting but of opposite readout polarity, e.g S^{-}_{z1} and S^{+}_{z2}. Each pair of opposite polarity images at each *z* value are coherently combined to cancel residual Nyquist ghosts [7]. This calibration data is then used to generate GRAPPA reconstruction coefficients for each *z* value.

To reconstruct the temporal series, the +RO and -RO data is separated at each time point. This induces a 2x acceleration in each set. As the z-shim value and readout polarity are correlated, using GRAPPA parameters associated with the z-value of each set maintains proper image contrast and weighting. After GRAPPA reconstruction and combination of the multi-coil images, the data acquired at each time frame yields two images, $I_{z1}(t)$ and $I_{z2}(t)$, one for each z-shim value. To form the final composite image, we employ a root-sum-of-squares combination of $I_{z1}(t)$ and $I_{z2}(t)$ [4].

Phantom data was acquired on a 3T GE (GE Healthcare Systems, Milwaukee, WI, USA) Signa scanner (EXCITE v15), using a standard 8-channel head coil. The ball phantom was suspended off the scanner table using a plastic holder ring. The interaction between the plastic ring and the ball was sufficient to introduce magnetic susceptibility artifacts near the points of contact. 32 time frames of data were acquired using both a new single-shot EPI sequence and a legacy double-shot sequence, both with temporal encoding.

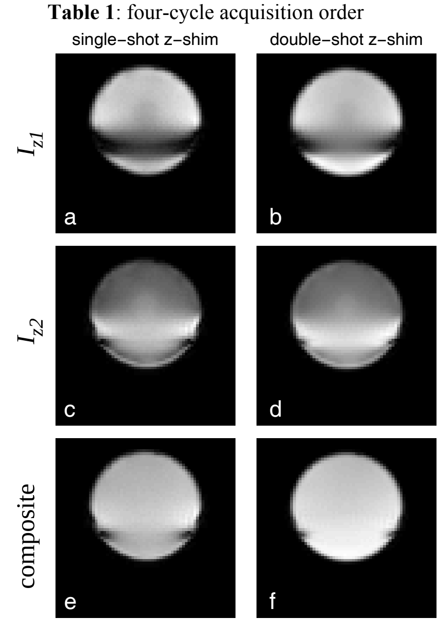

Fig 1: Individual z-shimmed and composite images for (left) single- and (right) double-shot z-shim

Results: Fig 1 shows a comparison between images acquired using both the single-shot and double-shot z-shim pulse sequences. The z-shim settings were chosen by observation, to demonstrate the method. In practice, an iterative optimization approach would be used to identify z_1 and z_2 for each slice. The images in Fig 1 show good agreement, although the single-shot z-shim images appear slightly darker. This is caused by a slight increase in EPI echo spacing, due to the fact that z-shim k_z blips are slightly longer than the EPI k_y phase-encoding blips.

Fig 2 shows the temporal signal variance between (a) single-shot and (b) double-shot images. The single-shot series has notable artifacts near the susceptibility regions. In the double-shot images, these artifacts are effectively cancelled in a manner similar to GESTE [8]. When the temporal encoding order of Table 1 is employed, these artifacts alternate in polarity at the temporal Nyquist rate. Thus they can be suppressed through the use of a 95% bandpass UNFOLD filter [9], Fig 2(c), with slight temporal resolution loss (5%).

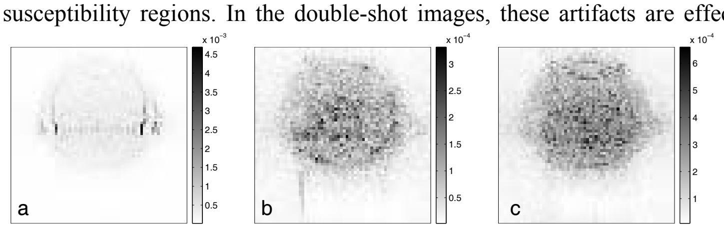

Fig 2: Temporal signal variance for (a) single-shot z-shim, (b) double-shot zshim, and (c) UNFOLD filtered single-shot zshim.

Discussion: We have demonstrated that interleaved single-shot z-shim combined with pMRI can improve temporal resolution while maintaining the same echo train length (and geometric distortion) compared to double-shot z-shim methods. While temporal encoding dramatically improves the pMRI reconstruction quality, it also inadvertently introduced flickering artifacts near susceptibility regions. This can be mitigated with the use of UNFOLD, or by using temporal encoding only occasionally (e.g. during fMRI resting state periods).

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References: [1] Frahm, et al. MRM 1988;32:474–480. [2] Constable, JMRI 1995;5:746–752. [3] Song, MRM 2001;46:407–411. [4] Gu et al, NeuroImage 2002;17:1358–1364. [5] Hoge et al, *ISMRM* 2009; 2720. [6] Griswold et al, MRM 2002;47:1202–1210. [7] Xiang & Ye, MRM 2007;57:731–741. [8] Hoge et al MRM 2010; In press. [9] Madore et al, MRM 1999;42:813–826