EFFICIENT SINGLE-SHOT Z-SHIM EPI VIA SPATIAL AND TEMPORAL ENCODING

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ABSTRACT
Echo planar imaging (EPI) is used widely for neurological fMRI studies. However, in regions of magnetic field inhomogeneity—particularly near the nasal sinuses—EPI suffers from signal dropout. Z-shim methods are one approach to recover this lost signal, where a z gradient is employed prior to the EPI readout echo train to counter phase accumulation in the signal dropout region. Typically, two separate images of the same region are acquired under different z-shim gradient strengths, and then combined into a composite image. Single-shot z-shim methods give improved temporal resolution, but with a cost of longer echo trains, which increases geometric distortion. Here, we combine parallel MR imaging (pMRI) with a single-shot z-shim method to achieve short echo train lengths. We also employ temporal encoding to counter Nyquist ghost effects, which improves the pMRI calibration. We demonstrate the method with phantom images, and evaluate its suitability for fMRI applications.

Index Terms— Parallel imaging, susceptibility artifact correction, single-shot EPI

1. INTRODUCTION
MR images of the brain acquired using gradient-echo EPI—common in BOLD fMRI studies—consistently suffer adverse effects from magnetic field inhomogeneity in regions close to nasal sinuses and ear canals. The presence of both air and tissue causes magnetic susceptibility at the boundary of the two regions, resulting in both geometric distortion and signal loss. Signal loss occurs due to phase accumulation, which pushes the signal outside the slice encoding region. This signal can be recovered back into the imaging plane via z-shim methods, where a z gradient is applied across the slice prior to data acquisition [1, 2]. This is commonly implemented as a two-shot protocol, which necessarily reduces the temporal resolution by half: each final image is formed through a combination of two z-shimmed images, each emphasizing signal regions that are “dark” in the complementary image.

Single-shot z-shim methods, e.g. [3, 4, 5], are attractive in that data can be acquired for both components of the final image after a single RF excitation pulse. These methods commonly require longer EPI echo-trains, however, which can increase susceptibility effects resulting in increased geometric distortion. We focus here on interleaved z-gradient compensation, which has the advantage of acquiring two z-shimmed images at almost the same echo time and similar signal phase evolution. This ensures that both contributions to the final image will have the same contrast and similar geometric distortion. In this work we employ temporal and spatial encoding to improve the clinical applicability of the interleaved single-shot method of Gu, et al [4]. The combination of temporal and spatial encoding has shown to be beneficial in EPI Nyquist ghost correction [6], and is directly applicable here.

The primary goal of introducing parallel MR imaging (pMRI) to interleaved single-shot z-shim is to reduce the echo train length (ETL), and thus reduce geometric distortion and other magnetic susceptibility artifacts. In interleaved single-shot z-shim EPI, a z-shim setting, $z_1$ or $z_2$, is associated with a particular readout gradient polarity, either positive or negative. Separating the positive readout data from the negative readout data introduces a natural 2x sub-sampling, which limits the overall acceleration rate one can achieve. In this work, we examine the effectiveness of single-shot interleaved z-shim combined with parallel imaging at 1x and 1.6x acceleration rates. This implies effective accelerations of 2x and 3.2x at the parallel imaging reconstruction stage. The suitability of this approach for fMRI is considered, by measuring the temporal signal variance at each pixel. This enables artifacts correlated with the data acquisition to be quickly identified.

2. METHODS
2.1. Acquisition Strategy
Our pulse sequence implementation built off the work of Gu, et al, in [4]. Single-shot z-shimming is achieved by applying a z-shim gradient simultaneous in time with the EPI $\hat{h}_y$ blips. An initial value of $z_1$, proportional to the area $A_1$ shown in Fig. 1, is applied prior to the EPI echo train. A second pulse, $A_2$, is set to be proportional to the difference, $(z_1 - z_2)$. Repeated application of $A_2$, using alternating polarities, is then applied to achieve $z_1$ or $z_2$ shimming prior to each sampling window. For the example shown, all data associated with $z_1$
is acquired on positive readout gradients, +RO, and data associated with \( z_2 \) is acquired on negative readout gradients, -RO.

With temporal encoding, the readout polarity and z-shim parameter settings are modulated to acquire four images: +RO, -RO, +RO, -RO, where the classification refers to the first line of measured k-space. The cycle we employ here is shown in Table 1. This order ensures that data is acquired using alternating readouts \{ \cdots , +RO, -RO, +RO, -RO, \cdots \} for both z-shim values.

For accelerated acquisitions, the \( k_y \) sampling pattern employed a non-uniform distribution, as per Hoge et. al. in [7]. In the results below, the values of \( z_1 \) and \( z_2 \) were selected by observation, simply to demonstrate the technique. In clinical fMRI scans, an optimization scheme testing a number of parameter combinations would be employed.

<table>
<thead>
<tr>
<th>data frame</th>
<th>1</th>
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<th>3</th>
<th>4</th>
<th>\cdots</th>
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<tr>
<td>odd readout line polarity</td>
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<td>even readout line polarity</td>
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<tr>
<td>odd readout z-shim value</td>
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<tr>
<td>even readout z-shim value</td>
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</table>

Table 1. 4-cycle acquisition order

![Fig. 1. Pulse sequence timing diagram for single-shot interleaved z-shim EPI](image)

2.2. Reconstruction Strategy

**Parallel MR calibration:** Data from two frames are interleaved, e.g. frames 1 and 3, to yield images, \( s_{z_1}^p \) and \( s_{z_2}^p \). Here, the superscript/subscript refers to the readout gradient polarity and z-shim value, respectively. While ghosting in these images should be minimal, as all k-space lines are acquired on the same polarity, our experience has been that this is not necessarily true [6]. To ensure ghost free images in the pMRI calibration [8], a second set of frames, 2 and 4, are interleaved to generate images acquired at the same z-shim setting but of opposite readout polarity, e.g \( s_{z_1}^p \) and \( s_{z_2}^p \). For pMRI coefficient calibration, each pair of images for each z-shim value are coherently combined as in Xiang et. al.[9]. In this work we employ a 2-by-5 (PE-x-FE) GRAPPA [10] kernel. A diagram describing this signal flow is shown in Fig. 2(a).

**Image reconstruction:** Once the GRAPPA reconstruction coefficients have been identified, images at each time point in the temporal series can be generated. At each time frame, the +RO and -RO data is separated. This induces an effective 2x acceleration in each data set corresponding to a single z-shim parameter setting. This data can then be reconstructed using the GRAPPA coefficients determined previously. GRAPPA estimates the missing k-space data for each coil. To combine the individual coil images into a single image for display, we employ a virtual body coil (VBC) calculation [11]. Although root-sum-of-squares could be used to combine coil images instead, VBC has the advantage of a more homogeneous image illumination appearance, as well as the ability to maintain signal phase. This yields images corresponding to each z-shim value, \( I_{z_1}(t) \) and \( I_{z_2}(t) \). To form the final composite image, we follow the approach of Gu, et. al. [4], and employ the root-sum-of-squares to combine the two z-shim images at each time point. The complete image reconstruction process is illustrated in Fig. 2(b).

![Fig. 2. Signal-flow diagrams: (a) steps to interleave and combine multiple temporally encoded EPI acquisitions to form ghost free data suitable for pMRI calibration for each z-shim value, and (b) steps to reconstruct a z-shim image from a single EPI frame. Dashed boxes represent multi-coil data.](image)

2.3. Materials and Particulars

Phantom data was collected on a 3T GE (GE Healthcare Systems, Milwaukee, WI, USA) Signa EXCITE scanner, OS ver 15m4, using a standard product 8-channel head coil. A prod-
uct EPI pulse sequence was modified to accommodate both the readout gradient polarity reversal for temporal encoding, as well as the addition of z-shim blips to coincide with the standard \( k_y \) blips. In practice, the z-shim blips may be longer in time than the \( k_y \) blips. This can effectively increase the echo spacing, which will slightly increase geometric distortion and susceptibility dropout compared to double shot z-shim methods. This is the motivation for further shortening the echo train using pMRI. The phantom consisted of a doped ball of water, suspended off the scanner table using a plastic holder ring. The interaction between the plastic ring and the plastic in the ball was sufficient to introduce magnetic susceptibility artifacts near the points of contact.

Data of the doped water phantom was acquired using both the new single-shot EPI sequence and a legacy double-shot sequence. Each temporal series was 32 frames long, to facilitate measurement of the composite image signal variance along the temporal domain.

### 3. RESULTS

A comparison of images acquired using both the single-shot and double-shot z-shim EPI sequences are shown in Fig. 3. The images appear comparable for each z-shim setting, although the effect of the z-shim gradient is slightly different in each, due to different echo spacing introduced by the z-shim blips. The more interesting comparison is shown in Fig. 4, which shows the signal variance over the temporal image series for the (upper left) single-shot and (lower left) double-shot images.

Susceptibility artifacts vary slightly depending on the readout polarity. In a temporally encoded single-shot z-shim image series, this will increase the temporal signal variance at those locations. There are a number of ways to compensate for this effect. As the artifacts are equal-and-opposite in adjoining +RO and -RO pairs, they can be suppressed (Fig. 4 upper right) by coherently averaging the two images together as in PLACE [9], at a cost of reduced temporal resolution. An alternate approach is to use a high frequency notch filter, similar to UNFOLD [12]. Fig 4 (lower left) shows the temporal signal variance that results from using such a Fermi filter with a pass band covering 95% of the temporal bandwidth, and only filtering the highest 5% of the temporal frequency bandwidth. This approach is notable in that the artifacts associated with magnetic susceptibility can be effectively removed, with only a small loss in temporal resolution.

Images generated from the accelerated data are shown in Fig. 5. We note that both the individual z-shim and the composite image are again similar in appearance to the double-shot images of Fig. 3. The associated image signal variances are shown in Fig. 6, under the two correction methods mentioned previously. The images show increased levels of pMRI artifacts, due to the effective 3.2x acceleration rate at reconstruction. Again, however, the artifacts appear equal-and-opposite in +RO and -RO pairs. Thus, artifacts can be again cancelled through coherent combination. The signal variance of a temporal series so processed is shown in Fig 6 to be similar in appearance but slightly larger in magnitude to variance in the filtered 1x single-shot images shown prior.

### 4. SUMMARY

We have shown that introducing spatial- and temporal-encoding into a interleaved single-shot z-shim method enables higher temporal resolution than a comparable double-shot z-shim method. This is advantageous in that geometric distortion can be minimized, by maintaining the same echo train length (ETL) between single- and double-shot acquisitions. We further showed that the ETL can be modestly shortened further via accelerated parallel imaging.

A negative consequence of temporal encoding was the appearance of significant artifacts in the signal variance near regions of magnetic susceptibility. Through careful selection of the temporal encoding pattern, these artifacts can be mitigated at 1x through temporal filtering, with only a slight loss in temporal resolution. The resulting signal is stable enough for in-vivo fMRI experiments, the results of which will be presented at the meeting. In the accelerated data, these artifacts were more pronounced. Temporal filtering was unable to suppress them to a level comparable to coherent averaging, which implies that more sophisticated methods will be
needed with accelerated single-shot z-shim if temporal resolution greater than the double-shot method is required. This is an area of future work.

5. REFERENCES


