# Accelerated Three-Dimensional $Z$-Shimming for fMRI

**J-J. Hsu[1], and G. H. Glover[2]**
[1]Department of Radiology, University of Miami School of Medicine, Miami, Florida, United States, [2]Lucas Center for Imaging, Stanford University, Stanford, California, United States

**Introduction.** Uniform imaging magnetic field ($B_0$) required for MRI cannot be realized for the entire brain because of the shape of the brain and the magnetic susceptibility difference between tissue and air. Consequently, severe signal loss and image distortion are commonly seen in fMRI in, for example, the inferior portion of the frontal lobe. Correcting this problem is essential because the affected brain areas are of great interest in understanding higher level brain functions. One type of approaches is the so-called $z$-shimming, which corrects through-slice inhomogeneity and is generally implemented with two-dimensional (2D) imaging methods. It was shown [1] that three-dimensional (3D) imaging is more efficient because it offers more choices of shims in less time, which is not an available feature in 2D imaging. With more choices of shims, fMRI images of higher quality can be obtained. In this work, we further increase the temporal efficiency of 3D $z$-shimming with an accelerated data acquisition technique known as UNFOLD [2].

**Methods.** ***§3D z-shimming.***—In 2D $z$-shimming, a gradient pulse in the through-slice ($z$) direction is inserted between the rf pulse and the signal acquisition. The $z$-gradient pulse, whose amplitude and length depend on the through-slice $B_0$ inhomogeneity, re-phases the magnetization and thus reduces the inhomogeneity-related signal loss. In 3D $z$-shimming, the $z$-gradient pulse is used for both $z$-encoding and shimming. Shimming is accomplished by acquiring additional $z$-encoding steps [1], that is, if the desired number of slices is $N$, then more than $N$ encoding steps are performed and a 3D image is reconstructed from data of every $N$ consecutive encoding steps. The final $z$-shimmed image is a composite constructed pixel by pixel from the image that has maximum intensity, *i.e.*, least signal loss, for the given pixel (a.k.a. maximum intensity projection, or MIP). ***§Accelerated data acquisition by UNFOLD.***—In an fMRI scan with 3D $z$-shimming and UNFOLD, only even- (odd-)number-indexed $z$-encoding steps are executed in each even- (odd-)number-indexed time frame. Consequently, in each time frame, the $k$-space is undersampled and thus the resultant image will have aliasing. The parity of the alias alternates along the time course. By Fourier-transforming the (complex-valued) images and applying a low-pass filter in the time-course direction, the alias can be removed. With this UNFOLD technique, the number of $z$-encoding steps per unit time is doubled. ***§Experiment.***—To demonstrate accelerated $z$-shimming, the functional task consisted of nine cycles of evenly distributed 17.5-s breath-hold and 17.5-s normal-breathing blocks. $T_E = 30$ ms, $T_R = 70$ ms, FOV = 20 cm or 64×64, and $z$-slab width 48 mm. Each 3D image had 16 slices (*i.e.*, $N = 16$). Twenty-five even- (odd-)number-indexed encoding steps were executed in each time frame, which generated 35 3D images per time frame, or per 1.75 s, after UNFOLD; then MIP was applied. The total number of time frames was 180. Spiral sampling was used for the $xy$-plane. The scans were performed at 3 T and were conducted in accordance with a protocol approved by the University's IRB.

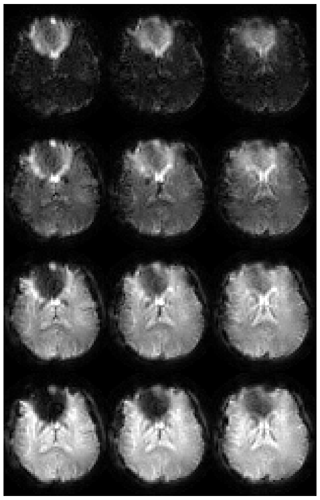

**Figure 1** Four samples of the 35 3D z-shimming images obtained for each time frame after UNFOLD. Each row is a 3D image (only three sample slices are shown).

**Results and Discussion.** Figure 1 shows examples of the 35 3D images; the image that has best pixel intensity depends on the local field homogeneity. The 35 3D images represent 35 $z$-shims. In 2D $z$-shimming, the number of $z$-shims is typically only one or two; thus the shimming effect is coarse and is an averaged effect across a slice. 3D $z$-shimming offers more shims, even more with acceleration by UNFOLD, and can improve the shimming effect to the individual pixel level. In Figure 2, the results of the breath-hold fMRI of a normal volunteer are shown. As seen in the figure, the magnetic field inhomogeneity results in serious signal loss in the frontal areas. Our accelerated 3D $z$-shimming can restore the signal in these areas considerably and, consequently, more activation (red pixels) is detected in these areas. In this experiment, the pulse sequence was set to acquire 35 $z$-shims per time frame (*i.e.*, per 1.75 s) to allow us to examine the capacity and the potential of accelerated 3D $z$-shimming. The speed and results show 3D shimming can outperform 2D shimming. For practical application, the number of $z$-shims can be reduced and the time saved can be used to further increase fMRI temporal resolution. The success of this novel development suggests that accelerated (partial $k$-space) acquisition can significantly increase the number of shims and improve temporal resolution of 3D $z$-shimming without the activation detectability being compromised. With adequate rf-coil sensitivity profile, acceleration by parallel imaging would be an interesting pursuit.

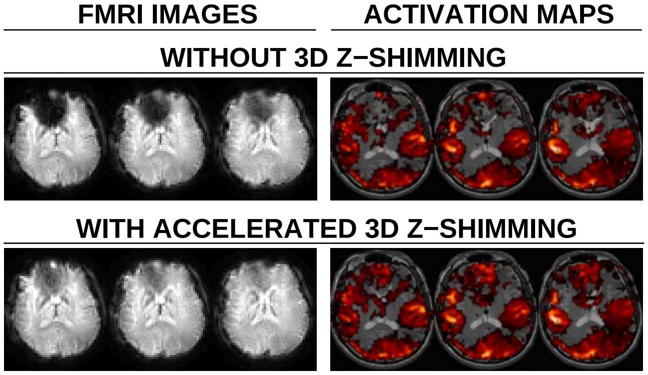

**Figure 2** Signal recovery by accelerated 3D $z$-shimming. The image at lower left is the composite image reconstructed by MIP from the 35 3D images exemplified in Fig. 1.

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**References:** [1] GH Glover, Magn Reson Med **42**, 290 (1999). [2] B Madore, GH Glover, and NJ Pelc, Magn Reson Med **42**, 813 (1999).