Turbo-Segmented Z-Shim EPI for Reduced Susceptibility-Induced Effects and Improved Temporal Resolution in fMRI

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INTRODUCTION The gradient-recalled echo-planar imaging (EPI) technique is sensitive to the bulk susceptibility differences between tissue and air or bone in the inferior part of the human brain. The susceptibility differences induce severe static field inhomogeneities and result in two major consequences: image distortion and signal dropout. The z-shim method, which applied compensation gradients at various magnitudes along the slice selection direction for local background gradients in different brain regions (1), has been used to recover the signal dropout. Usually, the z-shim pulse sequences require multi shots, thereby reducing temporal resolution and magnifying motion artifacts in fMRI experiments. Several single-shot z-shim techniques have been proposed to improve the temporal resolution (2-4). These methods have worked effectively in recovering signal. Yet, they have failed to reduce image distortion, another major susceptibility-induced artifact. The multi-segment technique can be used to reduce image distortion. The conventional multi-segment technique is vulnerable to subject motion due to its long effective repetition time (TR). The turbo-segmented imaging (TSI) technique uses multiple-variable flip angles and consecutive excitations to fill the segmented k-space (5) to minimize the motion artifacts. In this study, we propose a turbo-segmented z-shim EPI pulse sequence (TSZ-EPI) to reduce both the signal dropout and image distortion artifacts, and improve the temporal resolution for blood oxygen-level dependent (BOLD) fMRI.

METHODS The turbo-segmented EPI sequence (6) is used to generate two two-segmented images with one of the images z-shimmed, within a single repetition for each slice. Figure 1 shows the schematic diagram of the proposed TSZ-EPI sequence. The flip angles of the four RF pulses are calculated according to $\tan(\theta_n) = \sin(\theta_{n+1})$, where n is the index of the RF pulses and the flip angle of the last RF pulses is 90°, to ensure equal signal for each segment, assuming the magnetization recovery is negligible (5). A desired full k-space is segmented into two (Segments #1 and #2) in an interleaved mode, and after each RF pulse, one of them is acquired. With the four continuous excitations to a single slice, two full k-spaces can be sampled critically, and hence, two images (Images #1 and #2) can be generated. The slice refocusing gradients for the latter two excitations are modified to have the z-shim compensation gradients incorporated. The optimal amplitudes of the slice-specific compensation gradients are determined from a preparation scan (see below). Images #1 and #2 are combined by computing the square root of the sum of their squares (7) to generate the final TSZ-EPI image. An internal reference scan method, in which two additional lines around the k-space center with zero phase-encoding are acquired, is employed to correct the intra-segment ghosting and inter-segment inconsistent artifacts (6).

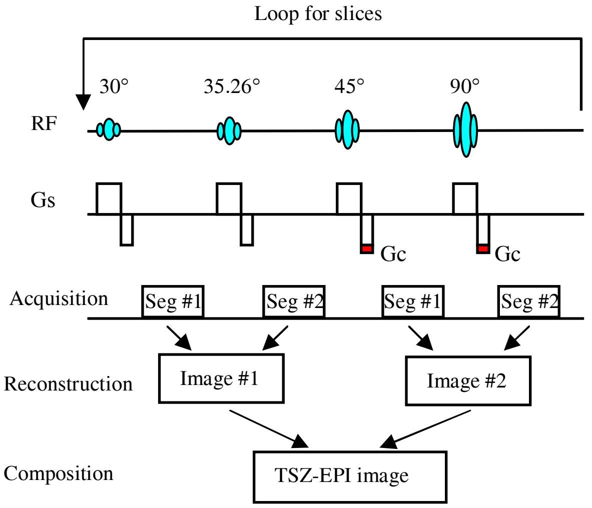

Fig. 1 Schematic diagram of the proposed TSZ-EPI sequence. Gs represents the gradients along the slice selection direction, and Gc, highlighted in red, is the z-shim gradients as modifications to the slice refocusing gradients.

The TSZ-EPI sequence was implemented on a GE Signa EXCITE 3T system. One healthy subject was recruited and an IRB-approved consent form was obtained before experiments. The imaging parameters were a FOV of 24 cm, a matrix of 64×64, a bandwidth of 125 kHz, a TR (repetition time of the set of four RF pulses for one specific slice) of 3 s, a TE of 30 ms. Fifteen axial slices, 5-mm thick and 1-mm spacing, with readout direction of right-left and phase-encoding direction of anterior-posterior, were acquired. Most brain regions, especially the inferior parts, were covered. Two scans were conducted. The first one was a preparation scan lasting a total of 70 repetitions: the first 10 repetitions with Gc = 0 and the following with Gc varied from -0.9 to +0.9 ms·gauss/cm (step length: 0.03 ms·gauss/cm), which corresponds to compensating a nominal background gradient from +0.03 to -0.03 gauss/cm (step length: 0.001 gauss/cm) at a TE of 30 ms. With this preparation scan, an optimal value of the z-shim compensation gradient in respect to a region of interest (ROI) in a slice could be determined. The second scan was an evaluation scan lasting a total of 100 repetitions with Gc fixed as the predetermined value. For comparison, one additional scan using a conventional single-shot EPI (SS-EPI) pulse sequence with the same imaging parameters as above and number of repetitions as that of the TSZ-EPI evaluation scan was conducted.

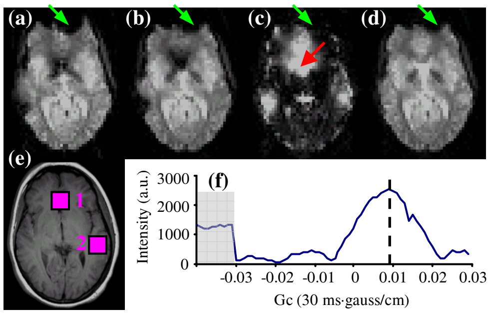

Fig. 2 Image quality comparison: (**a**) the SS-EPI image, (**b**) Image #1 of TSZ-EPI, (**c**) Image #2 of TSZ-EPI with Gc = 0.27 ms·gauss/cm, (**d**) the composite TSZ-EPI image. (**e**) is the T1-weighted anatomical image, and (**f**) is a signal intensity series of the voxel from Image #2 of TSZ-EPI, as indicated by the red arrow in (**c**), with Gc set as 0 in the gray area and then varied from -0.9 to +0.9 ms·gauss/cm. The pink boxes 1 and 2 in (**e**) are two ROIs for SNR comparison in Table 1.

RESULTS AND DISCUSSION Figure 2 compares the qualities of the images acquired from one slice around the orbitofrontal cortex region: (a) the SS-EPI image, (b) Image #1 of TSZ_EPI, (c) Image #2 of TSZ_EPI with Gc = 0.27 ms·gauss/cm, and (d) the composite TSZ-EPI image. By comparing the anterior part of the brain, indicated by the green arrows, image distortion is clearly seen in the SS-EPI image (a) and is reduced in the TSZ-EPI images (b, c and d). (f) is a signal intensity series of the voxel in the orbitofrontal cortex region, as indicated by the red arrow in (c), of Image #2 of TSZ-EPI from the preparation scan. The signal intensity at Gc = 0.27 ms·gauss/cm reaches a peak and is more than twice larger than that at Gc = 0. The optimal compensation gradient Gc used to acquire (c) was determined with the series in (f). The composite TSZ-EPI image (d) is more uniform than either the SS-EPI image (a) or Image #1 of TSZ-EPI (b). This is due to the signal recovery with the z-shim compensation gradient, as seen in (c). Table 1 quantitatively compares the temporal signal-to-noise ratio (SNR) between the TSZ-EPI evaluation scan and the SS-EPI additional scan in two ROIs indicated by the two pink boxes in Figure 2e. ROI #1 is the orbitofrontal cortex region with severe susceptibility effects and ROI #2 is a normal region. It is predictable that the SNR of Image #1 of TSZ-EPI is approximately half to that of the SS-EPI image, because of the partial excitation of each RF pulse, as shown in Figure 1. Apparently, the TSZ-EPI method makes the SNR in the region with severe susceptibility effects comparable to that in the other normal regions. In conclusion, we have developed a turbo-segmented z-shim EPI pulse sequence that can reduce both the image distortion and signal dropout artifacts induced by the susceptibility effects. Furthermore, it will not compromise the temporal resolution in fMRI.

Table1 SNR Comparison

Images	ROI #1	ROI #2
SS-EPI (a)	19.48	93.42
Image #1 (b)	8.47	55.86
Image #2 (c)	55.18	8.28
TSZ-EPI (d)	55.87	56.63

REFERENCES **1.** Frahm J *et al. MRM*, 6: 474-480, 1988; **2.** Song AW. *MRM*, 46: 407-411, 2001; **3**. Gu H *et al. NeuroImage*, 17: 1358-1364, 2002; **4**. Heberlein KA and Hu X. *MRM*, 51: 212-216, 2004; **5**. Wang D *et al. Proc ISMRM 13th Meeting* 2005, p2409; **6**. Wu G and Li S-J. *Proc ISMRM 14th Meeting* 2006, p3206; **7**. Constable RT and Spencer DD. *MRM*, 42: 110-117, 1999.

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