Optimizing 3D EPI with k-space energy spectrum analysis (KESA)

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Introduction

3D EPI with volume excitation, because of its reduced blood inflow effect, is superior to multi-slice 2D EPI for functional MRI studies. Other advantages of 3D EPI based fMRI include high signal-to-noise ratio (SNR) [1-3] and high tolerance to intra-scan subject movement [2,4]. However, in phase-encoded 3D EPI, the k-space energy may shift along the z-direction due to the background susceptibility field gradients. The k-space echo-shifting effect may result in signal loss in the reconstructed images, when the echo energy peak is shifted outside of the k-space sampling area. To address this issue, we use the recently developed k-space energy spectrum analysis (KESA) algorithm [5] to optimize both acquisition and reconstruction strategies for phase-encoded 3D EPI. The KESA was previously proposed as a tool to quantify the k-space energy shift that enables self-calibrated correction for in-plane distortion [5]. With the k-space energy shift information calculated by KESA, we are able to further integrate the 3D z-shim method [6] effectively so that the SNR can be improved with only a minor reduction in the temporal resolution of dynamic scans. In this study, the application of KESA to optimize signal loss compensation strategy is demonstrated with 3D EPI of the amygdata, a fMRI anatomic region of interest usually affected by pronounced susceptibility signal loss artifact.

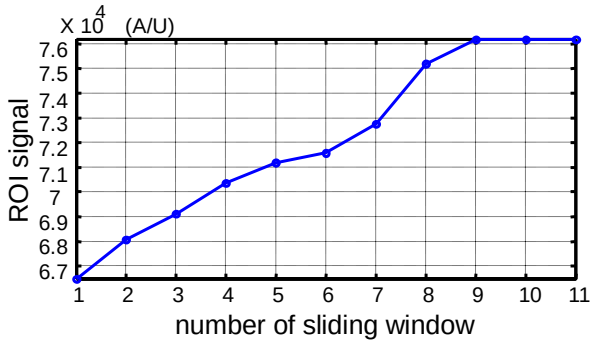

Figure 1. 3D EPI amygdala signal intensity as a function of the number in 3D z-shim sliding window reconstruction. A total of 11 windows were used with center *kz* shifting from 0 toward +10.

Materials and methods

In typical phase-encoded 3D EPI, the signal loss may occur in critical brain regions, such as the amygdala, as a result of (1) susceptibility induced echo-shifting effect and (2) insufficient k-space coverage. To fully quantify the k-space energy distribution, we propose to firstly perform a calibration scan, prior to actual fMRI experiments, with an extended *kz* coverage. The k-space energy distribution pattern will be measured from the calibration scan using KESA, and the k-space sampling scheme in subsequently performed fMRI scans will be optimized accordingly.

In our study, a phase-encoded coronal slab 3D EPI dataset was acquired from a volunteer at a 3 Tesla GE MRI scanner (TR: 2.5sec, matrix size: 64x64x40, voxel size: 3.75 x 3.75 x 5 mm). Data were then analyzed by KESA to quantify the k-space energy shift on a pixel-by-pixel basis. Bilateral ROIs in the amygdala, where pronounced susceptibility signal loss frequently occurs, were selected for measurement of local echo-shifting effect. To simulate the typical conditions with a smaller *kz* coverage, 20 central *kz* planes (-9 to +10) out of 40 were excerpted for reconstruction. The 3D z-shim sliding window reconstruction [6] was then implemented with each sliding window covering 20 *kz* planes. The total number of *kz* planes included for z-shim reconstruction was determined by examining KESA results at amygdala, aiming at compensating for the local signal loss. Data reconstructed from each sliding window were combined using maximum intensity projection (MIP) method.

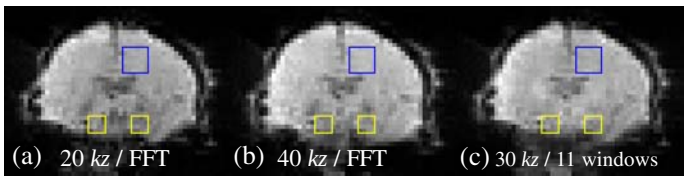

Figure 2. Images from different reconstruction strategies. Yellow boxes show amygdala ROIs and blue boxes show brain ROIs. It can be seen that both brain and amygdala signals are higher in (b-c) than in (a). ROI based SNR measurements are shown in Table 1.

Results and Discussion

The KESA analysis shows that the k-space energy of most amygdala voxels distribute between *kz* = 0 to +10. Therefore, to effectively sample the k-space energy for amygdala and the majority of the cortical areas, we excerpted 30 *kz* planes (covering *kz* -9 to 20) from full sampled data which allows 11 sliding-window reconstruction (20 *kz* planes in each window). Figure 1 shows the amygdale signal intensities corresponding to different numbers of sliding windows. Amygdala signal increased with the z-shim step and reached the plateau at 9, as expected from our KESA analysis. Figure 2 compares reconstructed images from three methods. Fig. 2(a-b) show images reconstructed by FFT with central 20 *kz* and full 40 *kz*, separately. Fig. 2(c) shows the image reconstructed from the z-shim sliding window approach. It can be seen that both brain (blue boxes) and amygdale (yellow boxes) signals are higher in fig. 2(b-c) than fig. 2(a), showing the benefit of extending the *kz* coverage. Table 1 compares the SNR and the minimal TR of the three methods. As shown in method two and three, the *kz* coverage extension improves the SNR in brain parenchyma, either with FFT or sliding window reconstruction. The sliding window reconstruction improves the overall SNR in comparison to the conventional reconstruction. It has to be noted that, in the third method, *kz* coverage selection based on KESA results in SNR improvement in the amygdala (25%) more than in the brain parenchyma (14%), which illustrates the KESA can be designed to effectively improve the image quality in any desired region of interest.

Acquisition / Recon.	Brain SNR	Amygdala SNR	minimal TR (s)
1) 20 *Kz* / FFT	203	152	1.25
2) 40 *Kz* / FFT	225 (+11%)	164 (+8%)	2.5
3) 30 *Kz* / 11 windows	232 (+14%)	190 (+25%)	1.875

Table 1. SNR and the minimal TR available for three imaging protocols. The extension of *kz* coverage improves the SNR in methods 2 and 3. It has to be noted that, in the third method, the *kz* coverage selection based on KESA results in SNR increment in amygdale (25%) more than that of brain parenchyma (14%).

In this study, we have successfully demonstrated that the combination of KESA and 3D z-shim sliding window reconstruction method can effectively recover the susceptibility signal loss without much degradation of the dynamic scan temporal resolution. Even though the susceptibility signal loss may potentially be recovered by blindly increasing the *kz* coverage, the degradation of the temporal resolution is highly undesirable. We have also demonstrated that the KESA algorithm can be applied to optimize the scan strategy for a certain anatomic region of interest, for example the amygdala, after mapping the local k-space energy distribution patterns. Based on the experimental results we conclude that the combination of KESA and 3D z-shim sliding window reconstruction is a valuable tool for 3D EPI based fMRI.

Reference

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