Multiplexed EPI at 9.4T with PSF-based distortion correction

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Target Audience

This work demonstrates the implementation of M-EPI with PSF-based correction at 9.4T and should be of significant interest to the high-field fMRI community.

Purpose

The relatively high imaging speed of EPI has led to its widespread use in dynamic MRI studies such as functional MRI or diffusion weighted imaging. Since its first use, a number of approaches have been suggested to decrease its scan time. Nearly all the successful efforts shorten the acquisition time by reducing the number of sampling points required to reconstruct a single-slice image, e.g., parallel imaging or sparse data sampling approaches [1]. Although those methods decrease scan time for spatial encoding, they do not *significantly* decrease the acquisition time for an entire volume imaging. As an approach to achieve this purpose, M-EPI (Multiplexed EPI) method has been presented by Feinberg et al. [1] and achieved a large temporal acceleration in the acquisition of multiple slices. However, although having such a high temporal resolution, EPI-based methods are highly sensitive to field inhomogeneities, which results in potentially severe geometric distortions. This problem becomes more challenging at ultra-high fields such as 9.4T. The present work verifies i) the use of M-EPI at 9.4T and ii) demonstrates the application of the PSF (Point Spread Function)-based correction method [2,3] to M-EPI to remove the geometric distortions arising in the M-EPI images.

Methods

M-EPI is essentially a combination of two techniques: TM (Temporal Multiplexing) and SM (Spatial Multiplexing). An illustration of its sequence diagram and its slice-excitation profiles are depicted in Fig. 1. As shown in Fig. 1, TM uses one more selective RF pulses (RF_2) in a TR loop to excite another adjacent slice simultaneously; two echoes from the two respective slices are obtained during each readout gradient and its matrix size should be doubled to cover the sampling for two echo lines. For separation of signals, a dephasing gradient (G_{dep12}) is imposed between RF pulses. This gradient creates different phase history in each respective slice, which in turn makes each respective echo refocus at different positions during readout [4]. The idea of SM is to apply sinusoidal modulation to a sinc RF pulse to produce multiple clones each of which has a symmetric frequency offset; in this illustration, the original one (at 0 frequency offset) is also included to achieve 3-slice excitation as shown in Fig. 1. Signal separation was performed based on the parallel imaging reconstruction method by means of the distinct sensitivity profiles at each different slice position [5]. With the combination of the TM and SM above (i.e. in the M-EPI example above), in total six slices can be simultaneously excited per TR. The PSF data of M-EPI were obtained with the same sequence where the modulated RF pulses were replaced with conventional sinc RF pulses, which led to an easier calculation of the PSF for each individual slice. And the sequence was repeated several times with the phase prewinder encoding updated with a gradient table resembling a conventional gradient-echo sequence. With this sequence, an additional measurement was performed to get the PSF data. The distortion-corrected images were obtained by subsequently applying the PSF-correction method to the M-EPI reconstructed images. For this work, the above configuration was implemented on a Siemens (Erlangen, Germany) 9.4T whole-body MRI scanner with an 8-channel phased array coil.

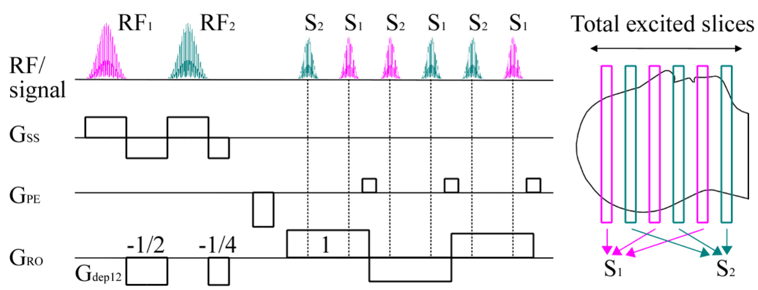

Figure 1 An M-EPI sequence diagram and its slice-excitation profiles used in this study. The value put on the gradients in the G_{RO} direction represents the relative momentum of the gradients. The RF_1 and RF_2 are generated by applying a sinusoidal modulation to a sinc RF pulse and excite three slices simultaneously marked by S_1 and S_2, respectively.

Results

M-EPI data were acquired from an oil phantom with the following imaging parameters: FOV = 224 × 224 mm^2, matrix size = 64 × 64, slice thickness = 3.5 mm (3.5 × 3.5 × 3.5 mm^3 isotropic voxel), TR/TE = 3000/40 ms, 6 slices with a distance factor of 400 % and bandwidth = 1302 Hz/Px. For comparison, single-shot EPI data were also acquired with the same imaging parameters. Figure 2a shows the reconstructed phantom slice of the M-EPI data from a conventional 2D FT (Fourier Transform). The two echoes obtained from the TM strategy caused the vertical interference pattern in the reconstructed image and the modulated RF pulses from the SM strategy generated the superimposed structures of the three slices simultaneously excited. After applying the M-EPI reconstruction to the data, six individual slices were obtained and a representative slice of them is displayed in Fig. 2b. As can be seen here, the reconstructed image exhibits geometric distortions, which is the deformation of the shape from a true circle. Further post-processing with the PSF-correction method applied to the M-EPI reconstructed image yielded a distortion-corrected version of it as shown in Fig. 2c. For comparison, the single-shot EPI image and gradient-echo image are also displayed in Fig. 2d and Fig. 2e, where we can find distortion-affected and distortion-free structures, respectively; the gradient-echo data were obtained from the PSF data. Visual inspection of the images suggests that there was no significant difference in terms of the spatial resolution between the M-EPI (Fig. 2b) and the single-shot EPI images (Fig. 2d). The geometric distortions appeared in the M-EPI image were effectively removed with the PSF-correction method (Fig. 2c), and the corrected image shows high similarity to the gradient-echo image (Fig. 2e).

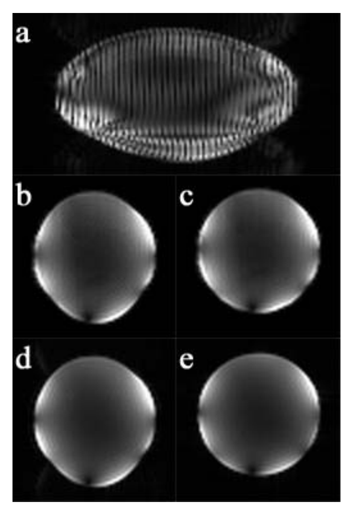

Figure 2 Oil phantom images at 9.4T (**a**) an image from 2D FT reconstruction of the M-EPI data, (**b**) a representative slice from M-EPI reconstruction of the M-EPI data, (**c**) the distortion-corrected version of (b), (**d**) a single-shot EPI and (**e**) a gradient-echo image at the same slice position.

Conclusion

M-EPI was implemented and verified at 9.4T with phantom results. For comparison, the same TR was used in both EPI and M-EPI imaging, however the effective minimum TR of M-EPI was about 13.55 ms, which is approximately 5.3-fold faster when compared to 72.18 ms in single-shot EPI case, meaning that 5.3-fold more slices can be obtained using M-EPI sequence with the same imaging time. It was also shown that the severe geometric distortions arising in the M-EPI at 9.4T were effectively removed by the PSF-distortion correction method.

References

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