Distortion Correction for Echo Planar MR Imaging using the Regularized Inverse Solution of the Point Spread Function (PSF) Map ©

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Abstract:

Point Spread Function (PSF) mapping techniques have shown promise for geometric distortion correction in Echo Planar Imaging (EPI)(1), where the distortion information is mapped by applying additional phase encoding gradients with a constant time (PSF encoding). However, currently existing post-processing methods of PSF techniques assume that the distortion information can be approximated as a shifted delta function. Therefore, through determining a voxel's largest signal displacement in the PSF map, it is possible to shift this voxel signal back to its correct position, referred to as DFA hereafter. One major limitation with this approach is that it does not take into account the distortion induced by magnetic susceptibility, which could result in voxel signal split and overlap. These effects are worsening as the magnetic field strength increases. We hypothesize that an inverse solution of the PSF map with the Tikhonov regularization (Tikhonov method) (2) will overcome the limitations associated with the current approaches and correct for the magnetic susceptibility-induced distortion. The proposed approach along with the currently available methods were evaluated at 1.5T and 3.0T with human subjects while at 9.4T with rats.

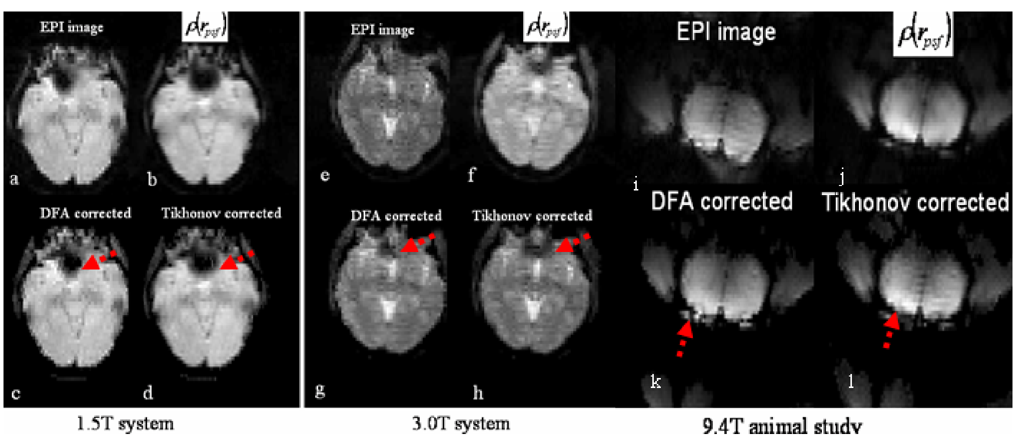
Methods:

Human Studies at 1.5T and 3.0T: Two healthy normal volunteers were scanned on the GE 1.5T and the Siemens 3.0T scanner, after obtaining written informed consent. Shimming was carefully adjusted according to the vendors' procedures. A gradient echo EPI sequence was employed with the imaging parameters: axis plane, phase encoding L-R direction, FOV = 240mm×240mm, TR = 2500ms, slice thickness = 4.0mm, number of slices = 15, receiver bandwidth = ±62.5kHz, matrix size = 64×64, AND TE = 40ms(1.5T)/25ms(3.0T). The PSF encoding direction was identical to the phase encoding in EPI. Acquisition parameters for the PSF technique were FOV = 120 mm and number of PSF encodings = 64.

Animal Studies at 9.4T: The animal studies were performed on a Bruker BioSpec 9.4T spectrometer after receiving approval from the Institutional Animal Care and Use Committee. To boost the SNR, a receive-only surface coil was used. Shimming was performed according to Bruker's FASTMAP protocol. The gradient echo EPI acquisition parameters were, axis plane, phase encoding A-P direction, FOV = 28mm×28mm, TE = 24ms, TR = 2500ms, slice thickness = 1.0mm, number of slices = 8, receiver bandwidth = ±100kHz, and matrix size = 128×64. The PSF encoding direction was identical to the phase encoding in EPI. Acquisition parameters for the PSF technique were FOV = 14 mm and number of the PSF encodings = 64.

Post-Processing: The undistorted reference image $\rho(r_{psf})$, PSF map H and the DFA method were processed based on the approaches reported in reference (1); For the proposed approach, the inverse solution of PSF map H with the standard form of the Tikhonov regularization method, the cost function $arg\{||g-Hf||^2+\lambda^2||f||^2\}$ as a function f was minimized, in which g is the distorted EPI image, f is the distortion corrected image, and λ^2 is the regularization parameter. We chose λ^2 = 0.6 in our study.

Results:



It is evident that both the DFA and the proposed (Tikhonov corrected) methods are equally effective at 1.5T (Figs a-d) and provide similar results as that of $\rho(r_{psf})$. In contrast, the geometry of the frontal sinus cavity in the DFA corrected image still remains shifted to the right side (Fig. c arrow) and the geometric symmetry is not restored at 3T (Fig g) while the Tikhonov method successfully restores the symmetry of the frontal sinus cavity (Fig. h, arrow). For the 9.4T animal study (Fig. i-l), distortion is evident at the interface of brain-bone and the geometry of the brain is stretched along the A-P direction. While both the DFA and our approach can correct the stretched geometry, the DFA method performs poorly in restoring the brain interface (Fig. k arrow) when compared with the Tikhonov method.

Conclusion:

The PSF mapping technique for distortion correction of EPI images can be improved by solving for the inverse solution of the PSF map using Tikhonov regularization. Compared with the original DFA method, the Tikhonov regularization-based method is robust for the correction of distortion caused by magnetic susceptibility. In particular, in light of the continuing increase of the magnetic field strength in both clinical and research arenas, the proposed Tikhonov method should further improve the image quality of high field MRI.

1. Zeng H, Constable RT. Image distortion correction in EPI: comparison of field mapping with point spread function mapping. Magn Reson Med 2002;48(1):137-146.
2. Tikhonov AN, Arsenin VIFAF. Solutions of ill-posed problems. Washington New York: Winston ; distributed solely by Halsted Press; 1977. xiii, 258 p. p.