Self-Correction of Image Distortion in High-Field EPI Using EPI Phase

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At high fields echo-planar imaging (EPI) becomes increasingly distorted due to imperfections in the magnetic field. This study presents a novel technique for correcting EPI distortion at 3T and 7T using the phase of the EPI itself.

As shown in Figure 1, field imperfections are caused by both hardware effects (e.g. eddy currents) and patient effects (e.g. susceptibility effects of sinuses), which scale with field strength. While an adjustment scan[1] can correct field effects in the frequency encode (FE) direction, such as N/2 ghosting and shearing, the field imperfections will cause geometric distortions due to gradient imperfections and pixel shift due to off-resonances in the phase encode (PE) direction. The PE direction is especially prone to field effects because the bandwidth per pixel is lower than in FE by at least a factor of the number of PE lines in kspace. Fortunately, the field imperfections also cause phase in the EPI image that can be used to correct the image distortions.

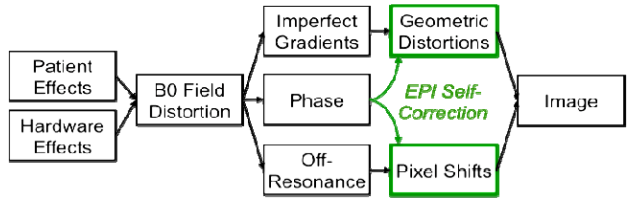

Figure 1. Flowchart of EPI image distortion*. The phase is used to correct the geometric distortions and pixel shifts.*

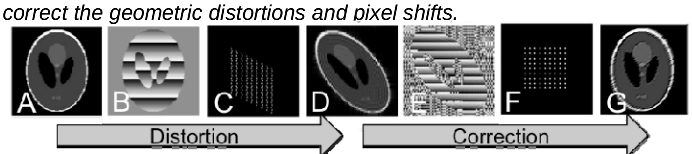

Figure 2. Simulations*. In the forward (distortion) simulation, the phase (B, magnitude A) was used to simulate pixel shift and kspace distortion (C) to produce (D). In the reverse (correction) simulation, the phase of the distorted image (E) correctly regridded kspace (F) and corrects pixel shifts to produce (G).*

Methods:

An EPI image distortion technique was developed in simulations and phantoms and applied to in-vivo human scans at 3T (N = 3) and 7T (N = 2). The simulation was a Modified Shepp-Logan phantom with an inhomogeneous field and the phantom was a doped water phantom with a field set using the high order shims. The gradient-recalled echo (GRE) EPI was acquired with a 128X128 matrix over a 24cm FOV and 20° flip angle. At 7T the TE/TR was 49.3/3000ms and the bandwidth was 250Hz. At 3T the TE/TR was 65.8/500ms and the bandwidth was 167Hz. Non-EPI images with minimal image distortion were acquired for comparison: GRE images at 7T and fluid-attenuated inversion recovery (FLAIR) images at 3T. EPI distortion was corrected by:

(1) Creating a multichannel field map (as done for GRE images)[2] from the EPI phase (Fig 4B-C).
(2) Using the gradients of the field to calculate and correct geometric distortion (Fig 4D).
(3) Using the off-resonance at each field pixel to calculate and correct the pixel shift (Fig 4E).

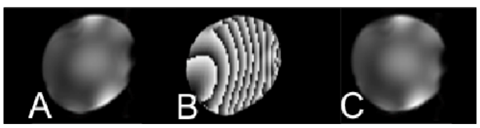

Figure 3: Phantoms*. 7T magnitude (A) and phase (B) used to correct the EPI (C). Pixel-by-pixel comparison of predicted to actual distortion measured with a non-linear spline warp[3] showed good agreement ($R^2 > 0.8$).*

Steps 2 and 3 are accomplished by regridding the complex image *C* in image space:

$$C_{mid} = C\left(x \to x-(shear)y,\ y \to \frac{1}{scale}y\right) \text{ where } scaling = \left(\frac{d\theta}{dr_{PE}}\right)\Big/G_{PE},\ shearing = \left(\frac{d\theta}{dr_{FE}}\right)\Big/G_{FE}$$

$$C_{cor} = C_{mid}(y \to y - shift) \text{ where } shift = \left(\frac{\theta_{C_{mid}}}{2\pi TE}\right)BW$$

Note that while the adjustment scan should theoretically correct shearing, the method developed here will correct any residual shearing from imperfect adjustments or dynamic changes.

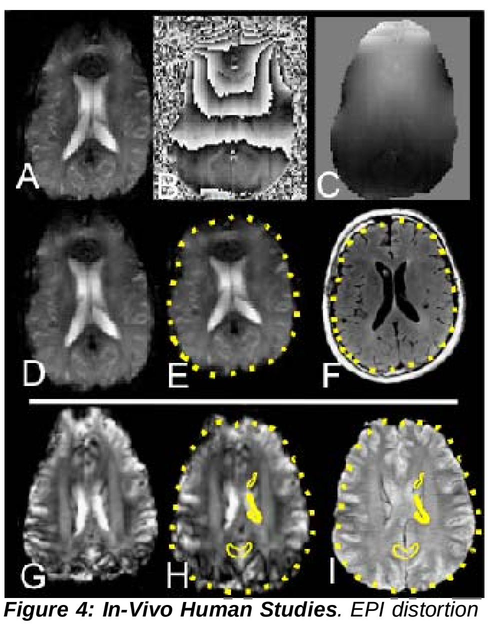

Figure 4: In-Vivo Human Studies*. EPI distortion self-correction at 3T (A-F) and 7T (G-I). The distorted EPI magnitude (A) was corrected by unwrapping the EPI phase (B) to produce a field map (C), corrected for geometric distortions (D) and pixel shifts (E). The image showed good agreement with the undistorted FLAIR (F). Similarly, the 7T EPI magnitude (G) was corrected (H) and showed good agreement with the undistorted GRE (I).*

Results and Discussion:

The corrected EPI images consistently showed good agreement with the minimally distorted GRE and FLAIR images (Figs 3 and 4). The expected limitation of this technique was having sufficient signal-to-noise ratio (SNR) and voxels across each phase wrap for field unwrapping. Our initial experience suggests both are sufficient at 3T and 7T. Future iterations of the method will correct intensity variation due to voxel stretching and compression and develop asymmetric EPI spin echo techniques compatible with diffusion-weighted imaging (DWI). Advantages of this technique over previous techniques include:

- **EPI phase maps the field *in the actual EPI scan***. Previous techniques[4,5] have used the phase of a GRE or offset spin-echo to correct pixel shift in the EPI. However, the eddy currents from EPI gradients induce additional field imperfections not present in the asymmetric spin-echo or GRE scans. Acquiring field maps of the actual EPI acquisition would be especially important for DWI because eddy currents from the strong diffusion-weighting gradients would cause different distortions in each diffusion direction and hinder the anisotropy calculations. Using the EPI phase also **includes dynamic changes that might evolve over the imaging experiment** due to, for example, heating or divergence of acquisition parameters from the adjustment scan.
- **Using the EPI eliminates the need for additional data acquisition** to correct images, such as extra EPI data with reversed gradients[6] or scans for field maps[4,5]. It also **eliminates the computationally expensive need for image registration**[4,5,7].

Conclusion

This study implemented a technique for using the phase of the EPI to self-correct image distortion and demonstrated its application to images acquired at 3T and 7T.

References and Acknowledgements:

[1]Schmitt, Echo Planar Imaging, Springer 1998, [2]Hammond NeuroImage 2008, [3]Lupo, JMRI 2006, [4]Jezzard MRM 1995, [5]Chen NeuroImage 2006, [6]Morgan JMRI 2004, [7]Huang MRI 2008

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