Correction of Geometric Distortions due to Static Magnetic Field Inhomogeneities and Eddy Currents in SENSE DTI

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Introduction

Diffusion-weighted images acquired with echo planar imaging (EPI) suffer from geometric distortions due to magnetic field inhomogeneities caused by both susceptibility differences at air/tissue interfaces as well as eddy currents induced by the diffusion-weighting gradients. In diffusion tensor imaging (DTI), the misregistration between images acquired with different diffusion-weighting directions in turn leads to errors in the pixel-by-pixel derivation of the tensor and resulting apparent diffusion coefficient (ADC) or fractional anisotropy (FA) maps. Several correction methods have been proposed, but require either a substantially longer acquisition time or the coregistration of images acquired with highly variable contrasts. Chen *et al.* [1] developed an effective and efficient method based on magnetic field (B_0) maps acquired with the same diffusion-weighting scheme as the DTI data set, *i.e.*, without and with diffusion-weighting along different directions. The non-diffusion-weighted B_0 map is used to correct for the susceptibility-induced distortions, whereas the diffusion-weighted B_0 maps are used to correct for the eddy current-induced distortions. At high resolution, the distortions due to both susceptibility effects and eddy currents are exacerbated because of the longer readout window, further necessitating the need for an effective and efficient correction procedure. Here, we incorporate the methodology proposed by Chen *et al.* into a high-resolution DTI acquisition scheme with sensitivity encoding (SENSE) [2] parallel imaging and partial Fourier encoding.

Methods

The DTI data is acquired using a single-shot diffusion-weighted spin-echo EPI sequence. For each image, an internal reference line is acquired at the center of k-space to correct for the offset between the odd and even lines that would otherwise result in Nyquist ghosts [3]. Both SENSE and partial Fourier encoding are used to increase the spatial resolution while limiting the readout window duration and echo time, and hence the distortions and signal loss due to T_2 relaxation. The images are reconstructed using a combined SENSE and homodyne reconstruction method, in which the phase correction is performed after the SENSE reconstruction to preserve the coil sensitivity information [4]. The B_0 maps are acquired using a diffusion-weighted multiecho spin-echo sequence, wherein a train of gradient-echo images are acquired before and after the spin-echo with a short readout duration to avoid distortions. The phase images can then be reliably unwrapped pixel-by-pixel along the echo dimension and accurate B_0 maps computed by pixel-wise linear regression of the unwrapped phase images.

The magnetic field gradients along the frequency- and phase-encoding directions induced by the eddy currents result in shearing and scaling (*i.e.*, stretching or compression) of the EPI images in the phase-encoding direction, respectively. To correct for these distortions, the non-diffusion-weighted B_0 map is subtracted from each diffusion-weighted B_0 map to yield residual field maps. The gradients along the frequency- and phase-encoding directions of these maps are then computed to derive the shearing and scaling factors, respectively, for each diffusion-weighting direction. To minimize blurring, the correction of both susceptibility-induced and eddy current-induced distortions is performed in a single step by linearly interpolating the distorted image at the shifted locations determined from the non-diffusion-weighted B_0 map as well as the shearing and scaling factors. Since the eddy currents induced by the diffusion-weighting gradients are independent of the subject being imaged, the diffusion-weighted B_0 maps can be acquired on a phantom, provided identical parameters are used. As such, only the non-diffusion-weighted B_0 map needs to be acquired for each subject, which significantly reduces the acquisition time.

A healthy volunteer who provided informed consent was studied at 3 T using an 8-channel RF coil. Axial B_0 maps were acquired using TR 2000 ms, TE 64 ms, FOV 19.2 cm, matrix 64×64 (interpolated to 128×128), slice thickness 3 mm, and 24 echoes. The DTI data set was acquired using identical parameters except for a matrix size of 128×40 with a SENSE reduction factor of 2 and 63% partial Fourier encoding, as well as 10 averages to increase the signal-to-noise ratio. Both the B_0 maps and DTI data were acquired without and with diffusion-weighting along 6 non-collinear directions with a b-factor of 800 s/mm^2. All B_0 maps were acquired on a uniform phantom, whereas only the non-diffusion-weighted B_0 map was acquired *in vivo*.

Results and Discussion

The B_0 maps acquired in the phantom (**Fig. 1A**) and the resulting residual field maps (**Fig. 1B**) clearly show the different magnetic field gradients induced by the eddy currents for each diffusion-weighting direction, whereas the non-diffusion-weighted B_0 map acquired *in vivo* (**Fig. 1C**) shows the susceptibility-induced B_0 inhomogeneities near air/tissue interfaces in the inferior frontal and temporal lobes. This map, along with the scaling and shearing factors derived from the phantom residual field maps, were used to correct for the distortions in the acquired DTI data set (**Fig. 1D**).

A comparison between the distorted and corrected images (**Fig. 1E**) clearly shows differences in the regions affected by the susceptibility-induced B_0 inhomogeneities, as well as the different scaling and shearing effects in the phase-encoding direction (anterior/posterior) caused by the eddy currents for each diffusion-weighting direction. The latter can be better seen by comparing images corrected using both the B_0 map and residual field maps or the B_0 map only (**Fig. 1F**). It is important to note that the scaling and shearing do not merely result in pixel displacements at the edges but also intensity changes over the whole image for different diffusion-weighting directions, which, if not corrected for, can lead to substantial errors in the computation of ADC and FA maps or in fiber tracking.

In conclusion, our method can effectively and efficiently correct for geometric distortions due to both susceptibility effects and eddy currents in high-resolution SENSE DTI acquisitions.

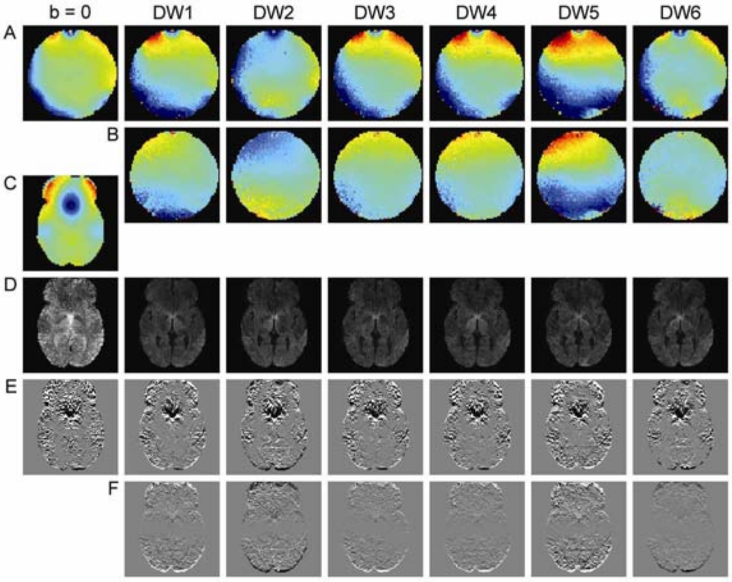

Fig. 1: (**A**) Phantom B_0 maps acquired without and with diffusion-weighting along 6 non-collinear directions and (**B**) residual field maps (scale: 0–0.4 μT). (**C**) Human non-diffusion-weighted B_0 map (scale: 0–2 μT). (**D**) Distorted DTI images. (**E**) Difference between the distorted and corrected images. (**F**) Difference between images corrected using both the B_0 map and residual field maps or the B_0 map only.

References: [1] Chen *et al.* Neuroimage 2006;30:121–129. [2] Pruessman *et al.* MRM 1999;42:952–962. [3] Jesmanowicz *et al.* Proc SMRM 1993, p. 1239. [4] King *et al.* Proc ISMRM 2000, p. 153. This work was supported by NIH grants NS 41328 and NS 50329.