Application of K-Space Energy Spectrum Analysis for Inherent and Dynamic B_0 Mapping and Distortion Correction in DTI

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Introduction

Diffusion tensor imaging (DTI) is a powerful technique for the noninvasive characterization of the microstructure of normal and pathological tissue. However, it is typically performed with echo-planar imaging (EPI) and is thus vulnerable to spatial and temporal variations of the static magnetic field (B_0) caused by susceptibility effects near air/tissue interfaces, eddy currents induced by the diffusion-weighting gradients, subject motion, physiological noise, and system instabilities. These B_0 variations result in geometric distortions and misregistration among different diffusion-weighted images, leading to errors in the derivation of the diffusion tensor and consequently in mean diffusivity or fractional anisotropy (FA) maps as well as in fiber tracking procedures.

Many correction methods have been proposed, but result in a reduced signal-to-noise ratio (SNR) (1), require a substantially longer scan time (2–6), involve the coregistration of images acquired with highly variable contrasts (7–10), and cannot effectively correct for all types of artifacts. To address these limitations, we propose a novel method integrating (*i*) a k-space energy spectrum analysis (KESA) algorithm (11) and (*ii*) a spin-echo (SE)/asymmetric SE (ASE) acquisition scheme, which can *inherently* and *dynamically* generate a B_0 map from the k-space data for each baseline ($b = 0$) and diffusion-weighted image, without requiring any additional data acquisition. These B_0 maps are then used to effectively and efficiently correct for the distortions due to both *spatial* and *temporal* B_0 variations before derivation of the diffusion tensor, resulting in a high spatial fidelity and accuracy.

Methods

KESA B_0 mapping: In gradient-echo EPI, B_0 gradients along x and y, $G'_x(x, y)$ and $G'_y(x, y)$, cause deviations of the k-space trajectory, resulting in a shift of the echo peak from the center of k-space and distortions in the reconstructed image. The KESA method measures this spatially dependent echo shift to inherently generate a B_0 map from the k-space data (Fig. 1). Specifically, a number n_x = 1, …, N_x of k_x lines are truncated from the acquired $N_x \times N_y$ k-space and N_x partial Fourier (PF) images are reconstructed. The signal intensity of a given pixel is extracted from these images and plotted as a function of n_x to form a k-space energy spectrum. A sudden drop occurs when the echo peak is truncated and this transition point is used to quantify the echo shift Δk_x. This procedure is repeated for each pixel, and then again along k_y, to generate Δk_x and Δk_y maps, which are converted to G'_x and G'_y maps and integrated to generate a B_0 map.

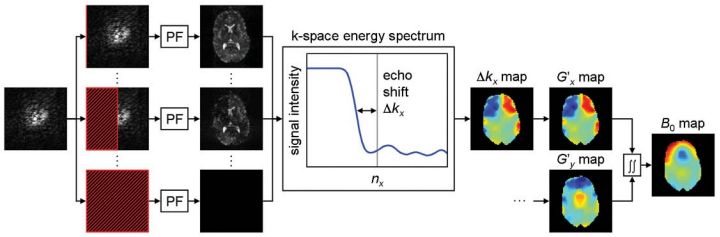

Fig. 1: Schematic diagram of the KESA B_0 mapping algorithm.

SE/ASE acquisition: DTI is typically performed with SE EPI, which is affected by distortions but does not have an echo shifting effect, so that the KESA method is not directly applicable. An ASE acquisition could be used instead, however at the cost of a lower SNR. Here, we propose a novel SE/ASE acquisition scheme, which enables KESA B_0 mapping while maintaining a high SNR (Fig. 2). Within the *same* readout window, the odd k_y lines are first acquired, followed by the even k_y lines, with a timing such that the first echo is a SE and the second one an ASE. For each echo, a few extra k_y lines are also acquired to fully sample the central k-space. Each undersampled half k-space is reconstructed using GRAPPA parallel imaging (12). The KESA method is applied to the ASE k-space data to generate a B_0 map, which is then used to correct for the (same) distortions in both the SE and ASE images using a multi-channel modulation (MCM) method (13). Finally, the corrected images are combined using weighted averaging.

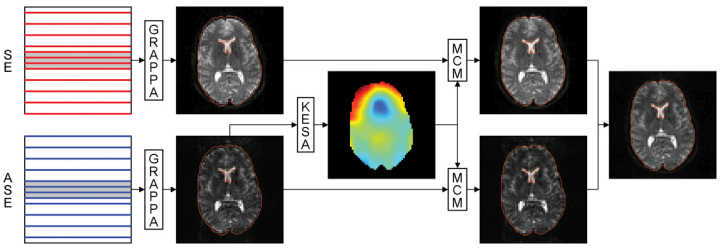

Fig. 2: Schematic diagram of the SE/ASE acquisition scheme with inherent KESA B_0 mapping and MCM distortion correction.

Results and Discussion

We studied a healthy volunteer on a 3 T scanner with TR = 5 s, TE = 78 ms, voxel size = 3.5 mm isotropic, and 6 diffusion-weighting directions with b = 1000 s/mm^2. The images are affected by susceptibility- and eddy current-induced distortions (Fig. 3a). Furthermore, since the latter vary with the diffusion-weighting direction and because of temporal B_0 variations, the misregistration among different diffusion-weighted images leads to additional errors in the FA map (Fig. 3d). The proposed method can inherently and dynamically correct for both types of artifacts without requiring any additional data acquisition (Fig. 3b,e), while providing comparable results as separately acquired B_0 maps (14) (Fig. 3c,f).

The SNR of the combined SE/ASE images is nearly identical to that of a conventional SE acquisition, because the weighted averaging gives the largest weight to the SE image, which has a reduced TE and a higher SNR. In contrast, the commonly used twice-refocused SE method (1) results in a 24% lower SNR and can only correct for eddy current-induced distortions. Note that the small amount of T_2^*-weighting introduced by the ASE image has no consequence on the derivation of the diffusion tensor.

Given these promising preliminary results, additional work is underway to further increase the SNR and accuracy of the proposed method (e.g., by integrating partial Fourier imaging). Its ability to *inherently* and *dynamically* correct for distortions due to both *spatial* and *temporal* B_0 variations will significantly improve the spatial fidelity and accuracy of FA maps and fiber tracking procedures, resulting in a more accurate mapping of complex neuronal pathways and the detection of more subtle pathologies, particularly in the more challenging pediatric, geriatric, and patient populations.

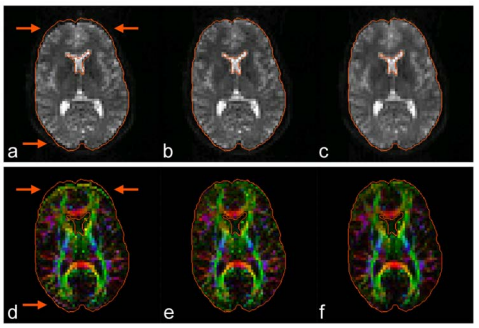

Fig. 3: SE/ASE combined images and color-coded FA maps uncorrected (a,d), corrected using the proposed method (b,e), and corrected using separately acquired B_0 maps (c,f).

References

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