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 $\Delta_k$. This procedure is repeated for each pixel, and then again along $k_y$, to generate $\Delta_k$ and $\Delta_k$ maps, which are converted to $G'_x$ and $G'_y$ maps and integrated to generate a $B_0$ map.

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 $k_x$ lines are first acquired, followed by the even $k_x$ lines, with a timing such that the first echo is a SE and the second one an ASE. For each echo, a few extra $k_x$ 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.

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,c), while providing comparable results as separately acquired $B_0$ maps (14) (Fig. 3c,d).

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.

References


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