Application of K-Space Energy Spectrum Analysis for Inherent and Dynamic B Mapping and Deblurring in Spiral Imaging

T-K. Truong , N-K. Chen , and A. W. Song

Brain Imaging and Analysis Center, Duke University, Durham, NC, United States

Introduction

Spiral imaging is a fast MRI technique, which benefits from an efficient k-space coverage and a low sensitivity to flow artifacts, with applications in cardiovascular and functional MRI. It is however vulnerable to static magnetic field (B_0) inhomogeneities caused by susceptibility differences at air/tissue interfaces as well as temporal B_0 variations due to subject motion, physiological noise (e.g., respiration), and system instabilities (e.g., resonance frequency drift), resulting in image blurring. Many deblurring methods have been proposed, but typically require the additional acquisition of a B_0 map, which increases the scan time and precludes the correction of temporal B_0 variations. Automatic deblurring methods (1), which estimate the off-resonance frequencies directly from the data, are less robust than field map-based methods, whereas dynamic B_0 mapping methods, which inherently generate a time series of B_0 maps by acquiring the central k-space twice (2) or by using a dual-echo spiral-in/out sequence (3) with different TEs, only provide low-resolution B_0 maps or result in a reduced slice efficiency and increased gradient duty cycle.

To address these limitations, we propose to apply a novel method termed *k-space energy spectrum analysis* (KESA) (4), which can inherently and dynamically generate a full-resolution B_0 map from the k-space data at each time point, without requiring any additional data acquisition or pulse sequence modification, and without relying on phase unwrapping, which is problematic in the presence of large B_0 inhomogeneities. The resulting B_0 maps, however, are in distorted coordinates and cannot be used with conventional deblurring methods such as conjugate phase (CP) reconstruction (5). We thus propose to apply a *multi-channel modulation* (MCM) method (6), in which the demodulation is performed in image space rather than in k-space. The KESA and MCM methods were originally developed for inherent B_0 mapping and distortion correction in echo-planar imaging (EPI), respectively. Here, we further develop these methods for inherent and dynamic B_0 mapping and deblurring in spiral imaging to achieve a high spatial fidelity and temporal stability.

Theory

In gradient-echo spiral imaging, the ideal k-space trajectory is: $k_j(t) = \gamma \int G_j(t')\mathrm{d}t'$ (for $T_{\mathrm{pre}} < t < T_{\mathrm{pre}}+T_{\mathrm{acq}}$; $j = x, y$), where γ is the gyromagnetic ratio, G_x and G_y the readout gradients along x and y, T_{acq} the readout duration, and T_{pre} = TE for spiral-out or TE – T_{acq} for spiral-in imaging (Fig. 1a). B_0 gradients along x and y (G'_x and G'_y) cause deviations of the k-space trajectory: $k'_j(t) = \gamma\, G'_j\, T_{\mathrm{pre}} + \gamma \int(G_j(t') + G'_j)\mathrm{d}t' = k_j(t) + \gamma\, G'_j\, t$ (Fig. 1b). These errors result in a spatially dependent echo shift in k-space: $\Delta k_j = k'_j(\mathrm{TE}) = \gamma\, G'_j$ TE [1] (since $k_j(\mathrm{TE}) = 0$) and blurring in the reconstructed image. Furthermore, in spiral-in/out imaging, the blurring is different for spiral-in and -out images because of the opposite k-space trajectories, leading to misregistration in the combined images.

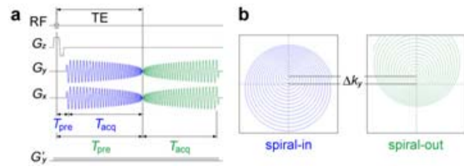

Fig. 1: Spiral-in/out pulse sequence (a) and k-space trajectories (b) in the presence of a B_0 gradient G'_y.

Methods

KESA algorithm for B_0 mapping (Fig. 2): The raw k-space data is first regridded to a Cartesian N_x×N_y k-space (a). A selected number n_y of k_y lines are truncated (b) and replaced by values computed with Cuppen's algorithm (7) (c), using the phase information from the full k-space data. A partial Fourier image is then reconstructed with 2D Fourier transform (d), and this procedure is repeated for $n_y = 1, \ldots, N_y$ (e). For each pixel, the signal intensity is extracted from these N_y images and plotted as a function of n_y to form a k-space energy spectrum (f). A sudden drop of signal intensity occurs when the echo peak is being truncated, and the transition point can be used to quantify the echo shift Δk_y from the center of k-space. Unlike in EPI, the k-space sampling density, and hence the spacing between k_y lines in the regridded k-space, is not uniform in the presence of B_0 inhomogeneities (Fig. 1b), so that an appropriate scaling factor needs to be used in the derivation of Δk_y. This procedure is repeated for each pixel to generate a Δk_y map (g), and the same approach is used to generate a Δk_x map. These maps are then converted using Eq. [1] to G'_x and G'_y maps, which are in turn integrated to generate a B_0 map.

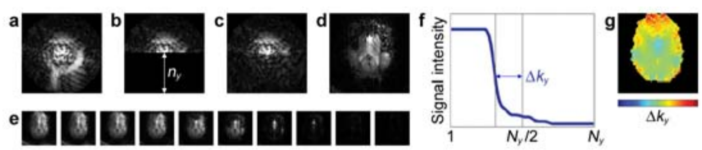

Fig. 2: KESA algorithm for B_0 mapping (see text).

MCM algorithm for deblurring (Fig. 3): A blurred image is first reconstructed from the raw k-space data (a) and multiplied by the phase image $\exp(-\mathrm{i}\ \gamma\ B_0\ n\ \mathrm{d}t)$ for $n = 1, \ldots, N$, where dt is the dwell time and N the number of points in the spiral trajectory, resulting in N demodulated images (b). Each image is transformed back to k-space (c). The n^{th} data point is extracted from the n^{th} k-space and these data points are combined to generate a new k-space (d), which is used to reconstruct the corrected image (e). Since a spiral trajectory is spatially smoothly varying (i.e., consecutive data points along the trajectory are in close proximity in k-space), the computation time can be drastically reduced by performing (b) only for $n = s, 2s, 3s, \ldots, N$, and extracting the n^{th} data segment from the n^{th} k-space in (d).

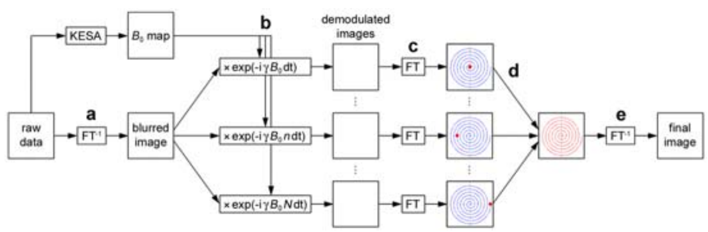

Fig. 3: MCM algorithm for deblurring (see text).

Results and Discussion

Representative phantom spiral-out (Fig. 4a) and human brain spiral-in (Fig. 4b) gradient-echo images acquired at 3 T (TR 2 s, TE 38 ms, flip angle 60°, FOV 24 cm, matrix 64×64, slice thickness 3.8 mm) show the blurring due to a y-shim offset or to susceptibility-induced B_0 inhomogeneities in the inferior frontal lobes, respectively. Our preliminary results demonstrate that the proposed KESA B_0 mapping and MCM deblurring methods can inherently and dynamically correct for these artifacts, while providing comparable results as a separately acquired B_0 map using a multiecho spin-echo sequence (8) and conventional CP deblurring (5). (Note that the KESA and multiecho B_0 maps are in distorted and undistorted coordinates, respectively.) Further studies are currently underway to demonstrate the advantages of the proposed method in dynamic MRI applications such as fMRI.

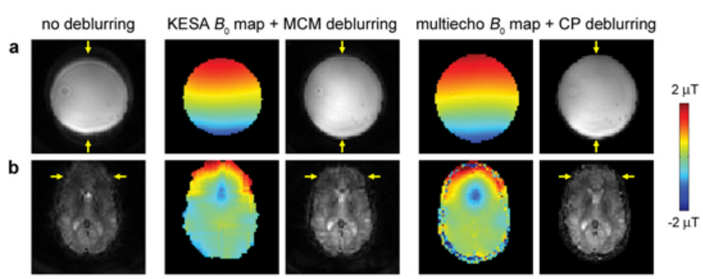

Fig. 4: Phantom spiral-out (a) and human brain spiral-in (b) results.

References

(1) Man et al. MRM 1997;37:906 (2) Nayak et al. MRM 2001;45:521 (3) Sutton et al. MRM 2004;51:1194 (4) Chen et al. NeuroImage 2006;31:609 (5) Noll et al. IEEE Trans Med Imaging 1991;10:629 (6) Chen et al. MRM 1999;41:1206 (7) Cuppen et al. Med Phys 1986;13:248 (8) Truong et al. NeuroImage 2008;40:53.

This work was supported by NIH grants NS 050329 and EB 005690.