Rapid eddy current calibration and prospective distortion correction methods for diffusion-weighted MRI

M. Zaitsev[1], J. Hennig[1], O. Speck[1]

[1]Dept. of Diagnostic Radiology, Medical Physics, University Hospital Freiburg, Freiburg, Germany

Introduction

Single-shot or multi-shot echo-planar imaging (EPI) is a method of choice for numerous diffusion-weighted imaging (DWI) applications. However, the extreme sensitivity of EPI to off-resonance effects presents a significant problem associated with image distortions caused by eddy currents (EC). EC are induced in the magnet structures by the fast switching high amplitude diffusion-weighting gradient pulses. This creates time and space varying magnetic fields, which depend on the sequence timing, amplitude and orientation of the diffusion-weighting gradients. The result is a misregistration of the data acquired with multiple diffusion weightings and poses a major difficulty for the data analysis and interpretation. Several approaches have been proposed to correct for EC induced image distortions. They may operate at source by trying to diminish EC produced by the diffusion weighting. Alternatively, one of numerous retrospective correction approaches might be used. The general disadvantage of current pre-acquisition techniques is that the EC compensation is never complete. Post-acquisition techniques either rely on image registration, which is a difficult task given the varying contrast in the DW images. Alternatively, they use the additional information acquired in a calibration scan performed separately in a phantom. Typically, the reference scan requires to use special geometric phantoms and substantial measurement time to gain reliable data.

In this work we present a rapid eddy current calibration method along with a novel pre-acquisition EC compensation scheme.

Methods

Presented here is the multi-echo shim offset navigator (MESON) method for EC calibration, which is based on the idea of the "shim-NAV" method *(H.A. Ward et al. Magn Reson Med 2002;48:771-80)*. The technique was modified to enable simultaneous acquisition of the field gradients along multiple dimensions and was extended to a multi-echo version to enable sampling of the EC field dynamics. The sequence diagrams of both methods are presented in Fig. 1 along with the *k*-space trajectory for MESON. The *k*-space trajectory is repeated multiple times during a single FID in order to collect the information about the frequency and gradient offset evolution over time. Thereafter, a Fourier transform is applied to the data and phase differences between the consecutive echoes for each spatial direction are calculated. From the analysis on these phase difference data, field gradients and frequency offset for each time point and spatial direction are calculated. In order to map EC effects of a specific DW gradient, the MESON sequence is repeated twice, with and without diffusion gradients and the difference in phase evolution is calculated in the reconstruction.

The MESON technique was implemented on a Trio 3T scanner (Siemens Medical Systems GmbH, Germany) with a gradient system capable of 40mT/m per axis, 200µs rise time. Scanning parameters were: FoV=300mm, 64 samples, readout bandwidth 1.56kHz/pix; the 2D MESON variant was used with 2ms echo spacing. In order to diminish signal attenuation due to the diffusion weighting, calibration was performed in a spherical oil-filled phantom. The MESON module was used to replace the EPI module in the standard Stejskal-Tanner DW-EPI sequence. The MESON sequence was performed with 4 repetitions: once without DW gradients and three times with DW gradients along the three axes. The timing and the amplitudes for DW gradients during the calibration were selected to match the ones in the corresponding imaging scan. The acquired gradient and frequency evolutions were then smoothed using a polynomial fit of the 5th order.

The data on EC evolution were used to correct for distortions in the imaging scan in a prospective manner. Prospective correction was accomplished by manipulating the gradient and frequency offsets during the acquisition of the EPI echo train. These offsets were chosen such that they counterbalance the eddy current induced filed variations arising from the diffusion weighting at the position of the imaging slice. The proposed technique is termed dynamic offset management (DOM) and allows for a perfect prospective compensation of the EC-induced distortions, given accurate reference information.

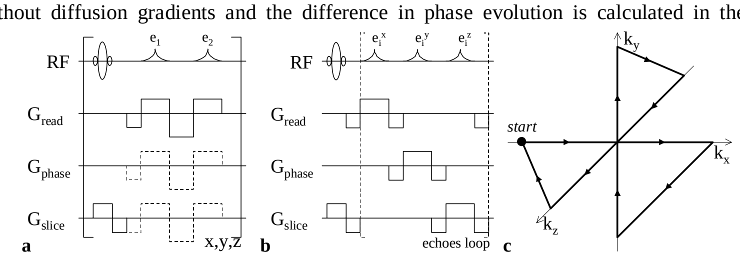

Fig. 1. *Sequence diagrams for (a) the Shim-NAV method, (b) the proposed multi-echo shim offset navigator (MESON) and the k-space trajectory for MESON.*

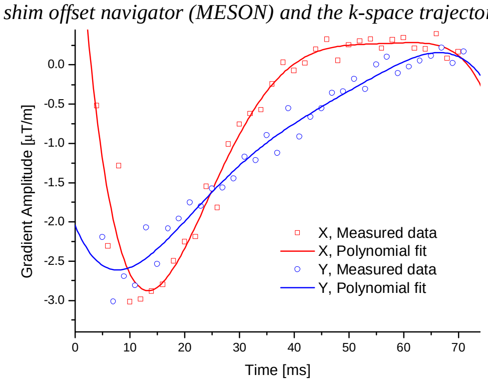

Fig. 2. *Measured EC induced gradient offset evolutions for X DW gradient and X direction (red squares, red line), Y DW gradient and Y direction (blue circles, blue line). The lines were plotted using 5th order polynomial fit.*

Results

Selected results of the MESON calibration scan are presented in Fig. 2 and described in the caption. The complicated temporal behaviour of the data seems to arise from imperfections of the hardware EC compensation.

The result of the DOM-corrected DW-EPI scan is presented in Fig. 3.

Discussion

Currently the MESON technique assumes that EC are mainly induced in the magnet structures and are independent on the examined object, which is a common assumption for calibration-scan based correction methods. The simplicity and the rapid acquisition allow to perform the MESON calibration regularly, e.g. on a daily basis. The short acquisition times of the calibration protocol even make it possible to perform the calibration for each subject. This, however, presents significant difficulties to the data analysis because the signal attenuation induced by the DW gradients in biological tissues will be more significant than in the oil phantom. Future work will try to overcome this limitation.

As demonstrated in this work, dynamic modulation of the gradient and frequency offsets during the EPI echo train allows to compensate prospectively for the EC-induced distortions with no need for post-acquisition correction via image interpolation. It is also important to note that DOM is a general concept, not focused on EPI and is compatible with other acquisition schemes, such as spirals.

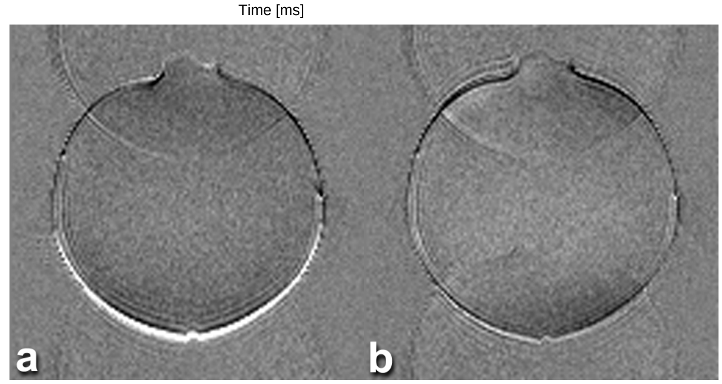

Fig. 3. *Difference images calculated form the DW-EPI data, produced via subtraction of the images acquired with the same diffusion weighting with diffusion gradients in Y(phase encode) and Z(slice) directions, respectively. (a) Non-corrected case and (b) corrected case. The images were acquired in an oil-filled phantom with b-values of 1000s/mm^2; image matrix 128^2, FoV=224mm, TE=114ms.*