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COMMUNICATIONS

Simple Correction Method for *k*-Space Trajectory Deviations in MRI

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A method is presented to correct for the imperfections of spatial encoding gradients in MRI. The approach is simple and fast, can be performed with standard scanner hardware, and does not require separate measurements with reference phantoms. The new method, using the MR signal to accurately measure the *k*-space trajectory of the imaging sequence, allows for correction of gradient hardware imperfections and eddy-current effects. Initial measurements are presented which demonstrate the efficacy of the method to correct images acquired with spiral and EPI scan techniques.

Key Words: **fast MRI; gradient hardware; *k*-space; correction methods.**

INTRODUCTION

Fast MR scan sequences such as EPI (*1*) and spiral imaging (*2*) put high demands on gradient hardware, thereby requiring highly effective suppression of eddy current effects. Inadequacies in gradient hardware or incomplete elimination of eddy current effects leads to deviations in the targeted *k*-space trajectory, and generally results in image artifacts.

One way to compensate for these gradient imperfections is to measure the actual *k*-space trajectories and use this information during image reconstruction. Several methods have been suggested to estimate this trajectory. For situations with negligible eddy currents, Spielman and Pauly (*3*) have used a method which measures the current through the gradient coils. Mason *et al.* (*4*) have proposed a method which estimates the actual *k*-space trajectory from the MR signal. It performs several calibration measurements involving a small reference phantom placed at off-isocenter locations in the magnet bore. Finally, the method described by Onodera *et al.* (*5*) and modified by Papadakis *et al.* (*6*) uses a so-called self-encoding gradient pulse preceding the acquisition interval and performs an long series of MR acquisitions with various gradient amplitudes.

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In the following we introduce an alternative method to measure actual *k*-space trajectories in MRI. This method does not involve the use of a reference phantom, is easy to implement, and requires only two pulse sequence repetitions per spatial encoding axis.

METHODS

The new method measures the actual *k*-space trajectories of small subsets of spins, at various locations in the magnet, similar to the approach proposed by Mason *et al.* (*4*). In the current method, instead of using a small reference phantom, the subsets of spins are selected by conventional slice selection, at positions displaced from the isocenter of the gradient system (Fig. 1). This requires only a minor modification of the actual pulse sequence. For each direction of spatial encoding (e.g., phase encode and readout directions), a measurement is performed with the slice select gradient switched to the corresponding gradient axis, while encoding gradients in all other axes are switched off. A second scan is performed with all spatial encoding gradients switched off (Fig. 1), in order to allow for elimination of effects of switching the slice select gradient direction on the *k*-space trajectory. From the difference $\Delta\phi$ between the accrued phases of the two measured MR signals,

$$\Delta\phi_r(t) = \int_0^t \gamma \cdot G_r(t) \cdot D_r \cdot dt = D_r \cdot k_r(t),$$

with

$$\gamma = \text{gyromagnetic ratio}$$
$$G_r(t) = \text{spatial encoding gradient amplitude}$$
$$r = \text{encoding direction } (x, y, \text{ or } z)$$
$$D_r = \text{distance of the slice to gradient isocenter,}$$

the *k*-space trajectory $k_r(t)$ can be simply derived by nor-

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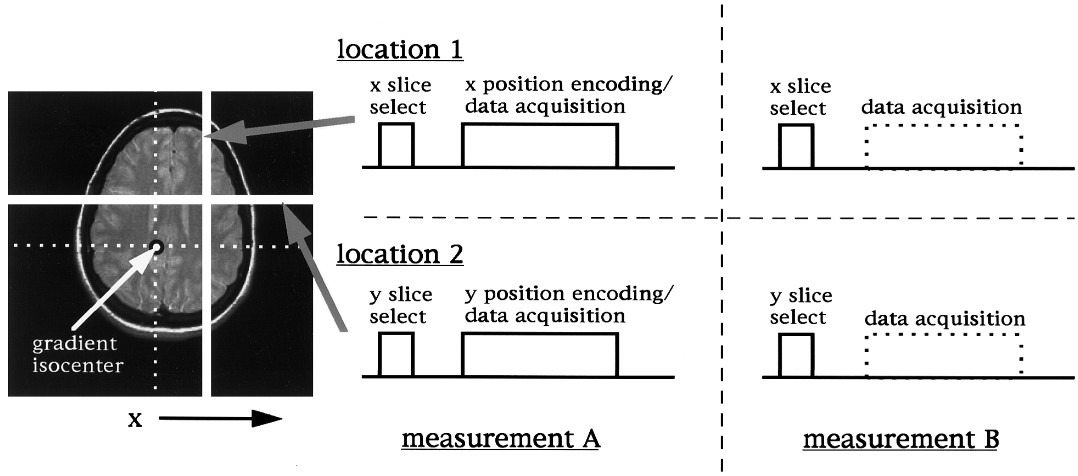

FIG. 1. Schematic overview of the protocol for measurement of *k*-space trajectories. In each spatial encoding direction, the signal phase evolution is measured following an off-center slice selection in the direction of the encoding gradient (measurement A). To correct for effects of B_o inhomogeneities and the added slice select gradient on the signal phase, reference scans are recorded with the encoding gradients turned off (measurement B).

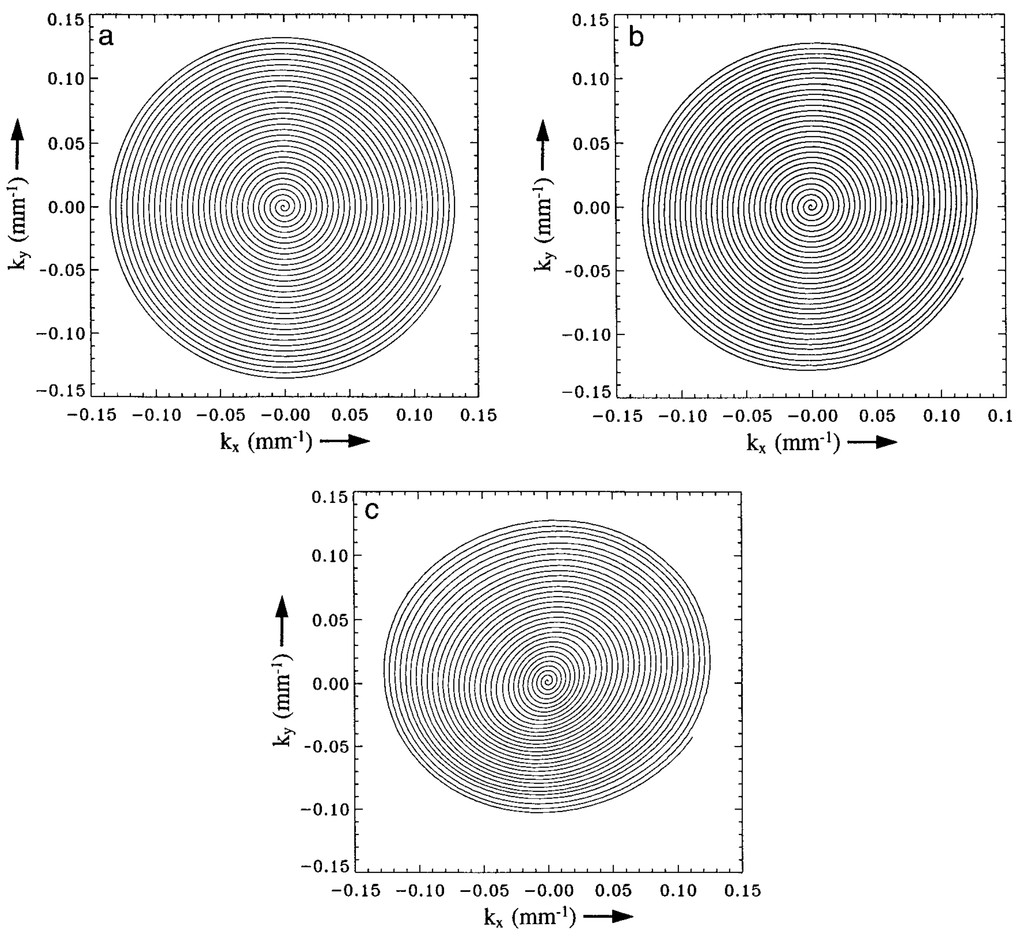

FIG. 2. Targeted (a) and measured (b, c) *k*-space trajectories for the spiral imaging sequence. The disabling of the eddy-current compensation circuitry leads to a strong distortion in measured *k*-space trajectory (c).

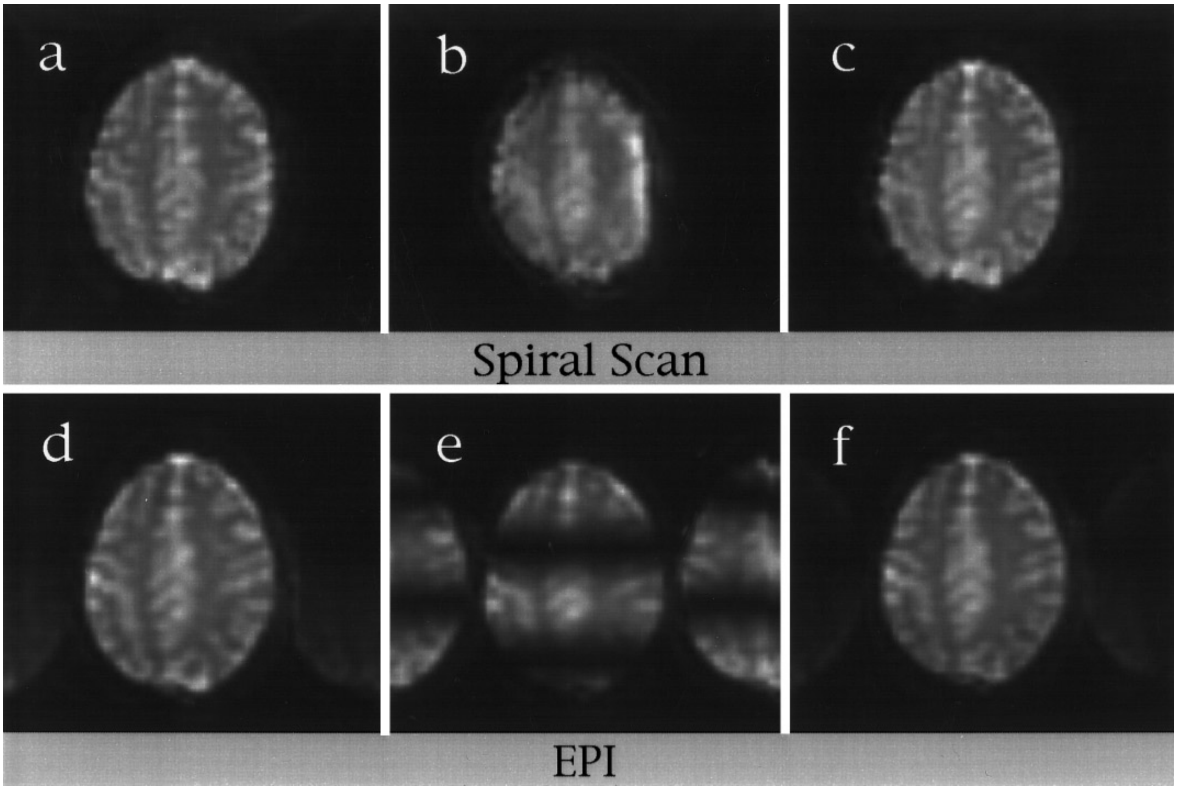

FIG. 3. Effectiveness of correction approach in the presence of eddy currents. Spiral (a–c) and EPI (d–f) reconstructions with measured (c, f) versus targeted (a, b, d, e) *k*-space trajectories show a dramatic improvement in image quality when eddy currents are present (b, c, e, f). Note that the ghosting artifacts in the EPI image in (e) could alternatively be reduced with the use of reference scans obtained with the blipped gradient switched off.

malizing $\Delta\phi_r(t)$ to D_r. The accrued phase of the MR signal can be calculated from the absolute phase by taking into account wrap-around. In the current implementation, this was done by determining the differential phase between adjacent sampling points. As long as D_r is contained within the FOV, and the sampling frequency adequately covers the signal bandwidth generated by the spatial encoding gradients (including dephasers), then the differential phase should not exhibit wrap-around. For accurate determination of $k_r(t)$, the slice thickness should be small compared to D_r. If this results in unacceptable SNR levels, signal averaging can be performed.

MR experiments were performed on a 1.5-T GE-SIGNA echo speed scanner (General Electric, Milwaukee, WI), running at the EPIC 5.6 platform. The electronic eddy current compensation circuitry in the gradient system was disabled to evaluate the feasibility of correcting for strong distortions in actual *k*-space trajectories. Single-shot spiral and EPI acquisition techniques were designed using the maximum slew rate of 120 T m^{-1} s^{-1}, and the maximum gradient strength of 2.2 G cm^{-1}. Acquisition parameters were TE = 35 ms (center of acquisition window), (overall) TR = 3 s, acquisition window duration 22/37 ms (spiral/EPI), FOV = 24 cm, 64 × 64 matrix size, slice thickness = 3 mm, D_r = 40 mm, one signal average, three slice locations. The clinical studies were performed under a protocol approved by the Intramural Review Board of the clinical center at the National Institutes of Health.

RESULTS AND DISCUSSION

For both EPI and spiral scan techniques performed under the given parameter settings, single-shot SNR was sufficient to measure *k*-space trajectories in both phantoms and human brain with high degree of accuracy. With the electronic eddy current compensation enabled, minimal differences were observed between targeted and the MR-measured (i.e. actual) *k*-space trajectories. Disabling the eddy current compensation led to strong distortions in the measured *k*-space trajectories (Fig. 2), as well as in the images reconstructed with the target trajectories (Fig. 3). The use of the measured *k*-space trajectories for reconstruction (Figs. 3c and 3f) resulted in almost complete recovery of image quality, indicating the effectiveness of the new correction approach. With spiral scan (Figs. 3a–c), a small reduction in spatial resolution was observed with the data obtained without eddy current compensation (Fig. 3c), because of the reduced area covered in *k*-space. With EPI, an alternative approach for image reconstruction is the use of the target trajectory, in combination with a reference scan obtained with the blipped gradient switched off. Applied to the data of Fig. 3e, this proved similarly effective in eliminating the strong ghosting artifacts in the presence of eddy currents.

Important advantages of the current *k*-space trajectory measurement method are its simplicity and robustness. No reference phantoms or additional scanning hardware is needed, and the measurement can be performed with only a few repetitions (TRs) of the pulse sequence. The method corrects for the effects of eddy currents, as well as gradient amplitude nonlinearities. Correction of spatial gradient nonlinearities requires *k*-space measurements at various locations (i.e., multiple D_r values), which can be done without time penalty by using a multislice approach.

The particular implementation of the correction method discussed above does not allow for correction of signal phase accumulations other than those induced by the spatial encoding gradients, for example those generated by background gradients. In both EPI and spiral, these additional phase deviations can to some extend be corrected for by using a separately acquired B_o reference map.

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