Magnetic Field Monitoring during MRI Acquisition Improves Image Reconstruction

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Introduction: Standard Fourier MRI relies on the assumption that the homogeneous field component (B_0) is constant and the gradient fields closely follow the prescribed encoding scheme. In practice these requirements are met only approximately. Self-induction in the gradient coils, coupling between the various hardware components, and timing imperfections cause distortions of the k-space trajectory and dynamic variation of B_0 ('B_0 eddy currents'). Such effects can result in a range of image artifacts, including ghosting, distortions, and blurring. Deviations in the effective magnetic field evolution can be accounted for at the reconstruction stage if they are precisely known. However, the underlying effects vary from sequence to sequence and are difficult to model accurately. For specific scanning schemes, such as EPI, field perturbances can be controlled by separate calibration scans (1). Error in the k-space trajectory can also be assessed by k-space mapping techniques (2). These, however, are time-consuming and require some modification of the gradient scheme; hence they do not map quite exactly the situation of interest. To overcome these limitations, in the present work we propose monitoring B_0 and the field gradients directly during the actual scan, using NMR field probes.

Methods: Field monitoring was performed in a 1.5 T MRI unit (Philips Gyroscan Intera, Philips Medical Systems, Best, NL), using four NMR probes placed close to a phantom in the x-z plane (Fig. 1). The probes were based on small water samples, contained in 2.2 mm glass capillaries in solenoid receiver coils. The probes were placed such that the excitation pulses of the monitored imaging sequences excited NMR in the probes as well. The probes' signal responses were preamplified and recorded simultaneously with imaging signals from two surface coils, using the multiple-channel receive unit of the MRI system. The phase of each monitoring signal was then extracted and unwrapped. The resulting phase time course was modeled as

$$\varphi_i(t) = \mathbf{k}(t)\cdot\mathbf{r}_i + \varphi_{B_0}(t) + \Delta\omega_i t\,, \qquad [1]$$

where i counts the probes, $\mathbf{k}(t)$ denotes position in 2D k-space, $\mathbf{r}_i$ the 2D position of the i-th probe, $\varphi_{Bo}(t)$ the phase accrual due to the spatially homogeneous field component, and $\Delta\omega_i$ the probe's constant local frequency offset due to its own magnetic susceptibility. $\mathbf{r}_i$ and $\Delta\omega_i$ were determined by imaging with a robust gradient-echo sequence and from FIDs, respectively. $\mathbf{k}(t)$ and $\varphi_{Bo}(t)$ were then calculated by solving the remaining affine equation [1] separately for each time point.

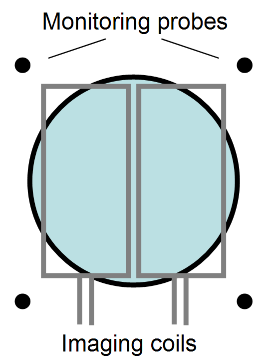
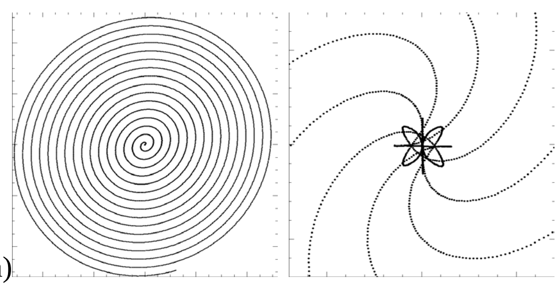


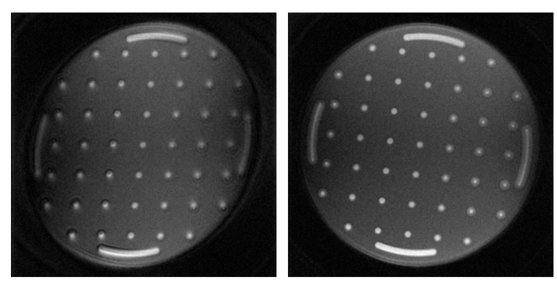
Fig.1 Experimental setup.

For image reconstruction, the error phase $\varphi_{Bo}(t)$ was removed from the imaging signals in a first step. Based on the knowledge of the actual $\mathbf{k}(t)$, image reconstruction is then possible with any of the known methods for non-uniform k-space data (3). Here, to avoid the need for assessing the k-space density, an iterative algorithm was chosen (4). It was performed separately for each of the two imaging coils, followed by root-sum-of-squares combination.

Results: The described procedures were used for monitored spiral imaging in the presence of anisotropic gradient delay, which is a common source of error in k-space trajectories. A segmented spiral scan of an x-z slice with 8 spiral arms and a target image matrix of 256x256 was performed. A gradient delay of 50 µs was deliberately introduced in the x gradient channel. The monitoring results for this scan are shown in Fig. 2a. Image reconstruction was then performed based on the nominal k-space pattern and using the monitoring data (Fig. 2b). The nominal trajectory yields a sheared and blurred image. The monitoring data enable clearly more accurate reconstruction, despite some remaining local blurring due to static B0 inhomogeneity.

Fig.2
8-segmented spiral scan with anisotropic gradient delay.
a) Monitored k-space trajectories. Left: one full segment. Note slight shearing. Right: all 8 segments zoomed at origin. Note anisotropic effects on initial backswing.
b) Image reconstruction from nominal trajectory (left) and using the monitoring results (right).

a) 

b) 

Discussion: Field monitoring with NMR probes reveals actual field perturbances during an individual MRI scan. It does so with minimal additional scanning effort for assessing the probe positions and local frequency offsets. Even with a preliminary hardware implementation highly accurate and sufficiently long-lived monitoring signals were obtained, as illustrated by successful image reconstruction based on these data. The present hardware solution is limited by the need to align the probes with the image slice, calling for more advanced implementations.
Making gradient inaccuracy and eddy currents more tolerable, field monitoring has the potential to reduce hardware requirements and cost. Furthermore it may facilitate the use of sophisticated k-space sampling patterns with even more involved field perturbation behavior.

References: 1. SB Reeder et al. Magn Reson Med 1997;38:429-439. 2. JH Duyn et al. J Magn Reson 1998;132(1):150-153. 3. JI Jackson et al. IEEE Trans Med Imag 1991;MI-10:473-478. 4. KP Pruessmann et al. Magn Reson Med 2001;46:638-51.