Magnetic Field Monitoring of Radial Trajectories

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Introduction: Radial k-space acquisitions are widely used. In fast MRI such as undersampling techniques as well as in motion compensation approaches, continuously sampling the centre of k-space has been shown beneficial [1]. Golden angle [2] as compared to sequential spoke sampling allows retrospective re-binning of data into arbitrary time intervals permitting flexible trade-offs between sampling density and temporal resolution. . Concerns have, however, been raised about the intrinsic sensitivity of radial acquisitions to eddy currents and gradient channel delays [3]. Although phase correction methods have been developed [4], an exact re-centering of the radial interleaves may not always be achieved, in particular if radial increments are increased due to Golden angle or other undersampling schedules. These image-based phase correction techniques also become challenging in case of multi-slice radial acquisitions (radial CAIPIRINHA) introduced recently for scan time reduction [5-6] where specific phase modulations of the radial spokes are needed.

The objective of the present work was to measure k-space miscentering and gradient delays in radial acquisitions using a dynamic magnetic field camera [7]. Golden angle radial k-space trajectories were measured, analyzed and used to correct for phase offsets in single-slice, dual-slice CAIPIRINHA and cardiac cine images.

Methods: A magnetic field monitoring (MFM) camera with 16 probes mounted onto a 20 cm diameter sphere (Skope LLC, Zurich, Switzerland) was used for magnetic field monitoring. Golden angle radial scans were monitored on a 3.0T Philips Achieva system (Philips Healthcare, Best, The Netherlands). Dynamic phase coefficients, fitted to spatial spherical harmonics up to the 3rd spatial order were calculated and analyzed. Miscentering of k-space due to eddy currents and gradient delays was measured and quantified. Zeroth and 1st order k-coefficients were used to correct and grid in-vivo data. Dual slice radial CAIPIRNHA images were acquired using a multi-band excitation pulse with phase modulation of the radial spokes. Cine images were acquired in a short-axis view and re-binned into 20 heart phases.

Results: Figure 1 shows measured k-spaces for a Golden angle radial acquisition. The spatially invariant phase offset k_0 is shown along with the linear k-space coefficients. The non-uniform crossings of the spokes is demonstrated in the zoomed portion of k-space and quantified in Figure 2. It shows the distance to the centre of k-space of the sampling point closest to the centre. $k_{//}$ and $k_{\perp}$ denote the parallel and perpendicular components (along the spoke) of the vector separating the point from the centre of k-space. Gradient channel delays were found to vary for different geometries [8]. The order of magnitude of the 0th, 1st and 2nd spatial order deviation is also shown, demonstrating a predominance of 0th and 1st orders. Figure 3 demonstrates in-vivo images reconstructed using measured k-space trajectories (MFM Corrected) compared to the data reconstructed using the nominal k-space trajectories (Uncorrected). In single-slice, dual-slice CAIPIRINHA and cardiac cine acquisitions reduced levels of image artifacts were detected when employing the measured k-space trajectories.

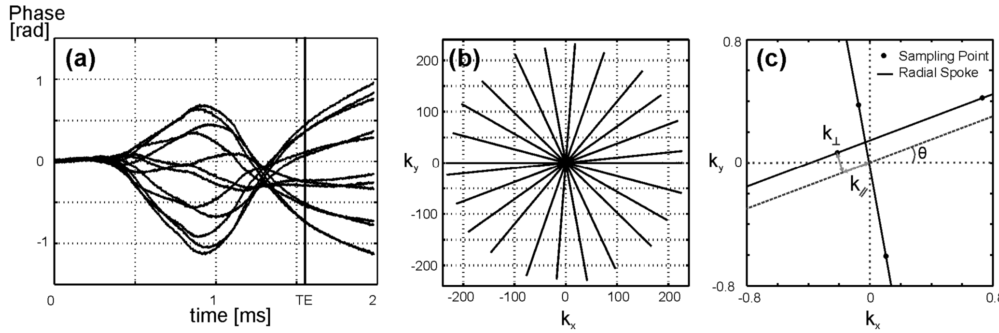


Figure 1: Measured k-space of a Golden angle radial acquisition. k_0 is plotted for a number of spokes demonstrating a spatially invariant phase offset at echo time (a) due to gradient delays. The measured linear k-space is shown in (b). Zooming into the centre of k-space (c) reveals the miscentering of k-space spokes (solid lines) resulting in a perpendicular and parallel offset of the central k-space point with respect to the k-space centre.

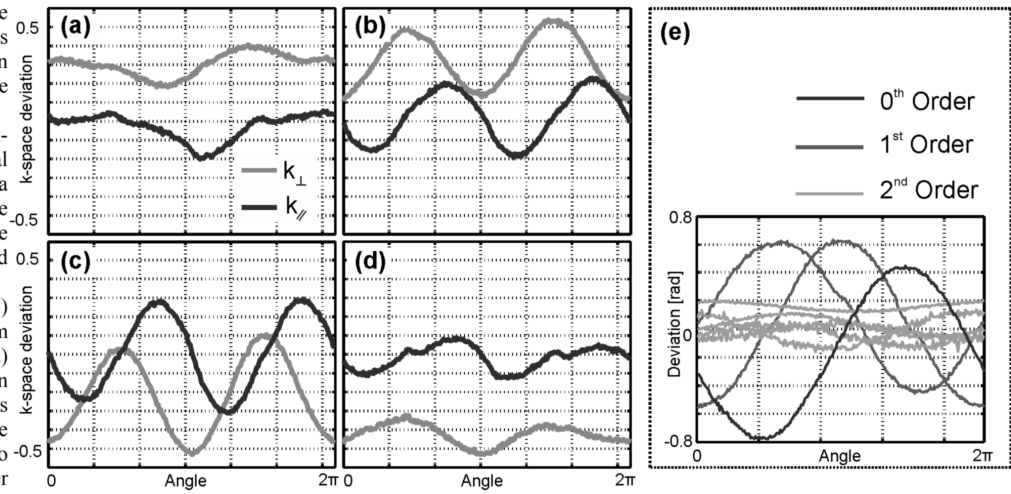
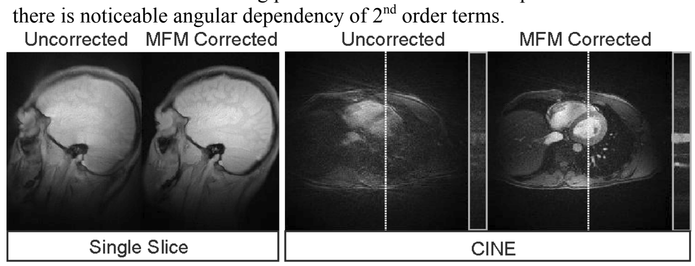


Figure 2: The miscentering of radial interleaves leads to varying components ($k_{//}$ and $k_{\perp}$) of the shortest vector between the spoke and the centre of k-space depending on angle. Strong differences are seen between acquisitions of different geometries (a): transversal, (b): sagittal, (c): coronal, (d): angulated transversal. The finding is attributed to the different delays of the three gradient channels. In (e) the phase deviations developed on a sphere of 10cm radius demonstrating predominance of 0th and 1st spatial order is shown. Despite being small in magnitude there is noticeable angular dependency of 2nd order terms.



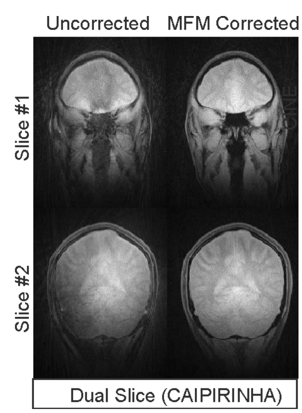


Figure 3: Reconstructed in-vivo images using the magnetic field camera (MFM corrected) for three different Golden angle radial acquisitions including single slice imaging, ECG triggered cardiac cine imaging and dual-slice CAIPIRINHA. All applications show reduced artifacts when using the magnetic field monitoring approach. Temporal behavior in the cine images is demonstrated by the dotted profile over time shown in the rectangles.

Discussion: The presented results demonstrate the potential of using a magnetic field camera to correct for phase errors in radial acquisitions. The miscentering of k-space described in [3] is measured directly by the field camera. As compared to image-based correction methods, the proposed method does not rely on special angular distributions (such as bow-tie radial trajectories). Especially in cases were an image-based correction strategy becomes challenging such as in radial CAIPIRINHA, undersampled radial acquisitions or motion, the knowledge of the exact k-space trajectory is crucial. Higher order k-space deviations were quantified but shown to be negligible in the proposed applications.

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