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-space phase coefficients were used to correct and grid in-vivo data. Dual slice radial CAIPIRINHA 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, $k_1$ and $k_2$ 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.

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 where 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.