Simple Method for Adaptive Gradient-Delay Compensation in Radial MRI

K. T. Block[1], and M. Uecker[2]
[1]MR Application and Workflow Development, Healthcare Sector, Siemens AG, Erlangen, Germany, [2]Biomedizinische NMR Forschungs GmbH, Göttingen, Germany

Introduction: Radial sampling of k-space has gained strong interest over the past years due to inherent advantages such as lower sensitivity to motion and flow artifacts, continuous coverage of the k-space center information, and the absence of any ghosting artifacts. Further, because undersampling for radial trajectories leads to incoherent streaking artifacts instead of discrete aliasing, radial sampling is frequently used in the context of compressed sensing [1]. Although changing the trajectory from parallel lines to overlapping spokes appears straight-forward at first glance, the implementation is accompanied by several technical difficulties, which hampered the availability for routine applications in the past. A major problem is that by changing the read-out orientation from a uniform direction to a different angle for each k-space line, the trajectory gets vulnerable to inaccuracies of the gradient timing. Hence, imperfections of the gradient system translate into inconsistencies of the acquired k-space information and degrade the image quality.

Several approaches have been proposed in the past to correct for deviations of the gradient fields. One strategy is to measure the actually generated k-space trajectory and to use the estimated trajectory for aligning the samples in k-space. This can be achieved either using a separate calibration scan [2], or using special hardware that monitors the gradient field strength during the scanning [3]. However, such measurements are quite complicated, and the resulting image quality is sensitive to the accuracy of the estimated k-space positions. In [4], Speier et al. proposed a method for radial sampling where the pre-phasing gradient is adapted such that the traversal of the k-space center coincides with the assumed time-point for the k-space center. Their work showed that it is possible to perform radial sampling in a robust way on standard MR systems without the additional effort of a trajectory measurement. However, it turned out that a fixed equation for the calculation of the pre-phasing correction is not sufficient for obtaining consistent image quality on different systems at high read-out bandwidths. Therefore, this work presents a novel method for the compensation of system-dependent gradient delays, which proved to yield reliable image quality for radial sampling on a large number of unmodified commercial MR systems.

Theory: The key idea of the proposed method is to perform an estimation of the sample shift along the read-out direction prior to each scan, and to compensate for the gradient delay during the gridding procedure by re-aligning the acquired data according to the estimated shift distance. To estimate the shift distance, multiple calibration lines are acquired using the same sequence parameters that are also used for the data acquisition itself (same bandwidth and base resolution). These calibration spokes are measured at opposing orientations, e.g. 0° and 180°. For an ideal gradient timing, the signals at 0° and at 180° should be identical after reflecting the samples of the 180° spoke. However, if a delay is present, the two signals differ by a translation where the shift distance represents the strength of the gradient delay. This shift distance is estimated with a cross-correlation analysis to obtain the displacement needed for compensating the delay within the gridding procedure. The detailed procedure is as follows:

1. The 180° spoke is reflected and the magnitudes are calculated for the 0° and 180° spoke.
2. The Fourier transforms (FT) of the signals are calculated.
3. The 0° transform is multiplied by the complex conjugate of the 180° transform: $g(x) = FT(|S_0(t)|) \cdot Conj(FT(|S_{180}(t)|))$
4. Performing the FT of $g(x)$ would yield the cross-correlation function, showing a peak at the desired shift distance. However, to achieve higher precision, the shift is estimated from the slope of the signal's phase using linear regression. Because the phase is only defined in areas with non-zero signal intensity, the fitting procedure is constrained to the support of the object.
5. The support is identified by Fourier transformation of the 0° spoke and localization of the magnitude maximum. From this position, the boundaries are enlarged in both directions until the magnitude value drops below 10% of the maximum value. Only values inside these boundaries are considered for the fitting procedure.
6. The shift distance is obtained from the estimated phase slope with: $\text{Shift} = -\text{Slope} \cdot \text{Baseresolution} / (2 \cdot \pi)$

The shift distance is calculated separately for each receive channel. These values are averaged where each channel is weighted with the L2 norm of the corresponding spoke to exclude elements that receive only weak or no signal intensity. In the basic form of the method, the procedure is conducted for the x-direction using spokes at 0° and 180°, and for the y-direction using spokes at 90° and 270°. It is then possible to derive an angle-dependent shift by interpolating between both values. Thus, the delay can be corrected by shifting the samples along the spoke Φ according to:

$$\Delta k = ((\cos(2 \cdot \Phi) + 1) \cdot \text{Shift}_x + (-\cos(2 \cdot \Phi) + 1) \cdot \text{Shift}_y) / 2$$

To increase the stability, several repetitions of the calibration should be performed where the mean should be used for the reconstruction.

Methods: For evaluation, the method was implemented for a radial 2D FLASH sequence and a "stack-of-stars" 3D FLASH sequence using the IDEA development environment (Siemens AG, Erlangen, Germany). In these sequences, the calibration is done by employing preparation shots that are performed at the beginning of the scan to drive the magnetization into a steady-state. Therefore, the procedure does not prolong the scan time. Both sequences were tested extensively on 18 different MR systems including the types MAGNETOM Avanto, Trio, Espree, and Verio (Siemens AG, Erlangen, Germany). Measurements included phantom scans as well as approved volunteer and patient studies. The method worked reliable for a wide range of read-out bandwidths on all of these systems. No significant image quality problems remained after applying the correction. As an example, Figure 1 and 2 compare uncorrected and corrected slices from 3D phantom scans acquired with a MAGNETOM Avanto at 1090 Hz/pixel (256 pixels, 240 mm FOV, 402 spokes, 60 calibration spokes). The improvement in image quality is clearly visible.

Conclusion: We described a simple and robust mechanism for adaptive correction of system-dependent gradient delays that does not add scan time for sequences with preparation shots. For other sequences, it can be modified to an integrated calibration by using spokes that are approximately anti-parallel. Further, it can be extended to include multiple calibration angles to improve the accuracy for systems with strong gradient anisotropy.

References:
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2. Duyn, JH et al, JMR 132:150-153, 1998
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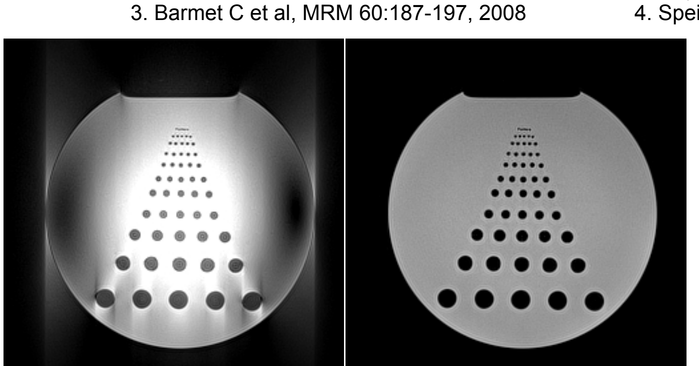

Fig 1: Axial phantom scan (left) uncorrected and (right) after correction.

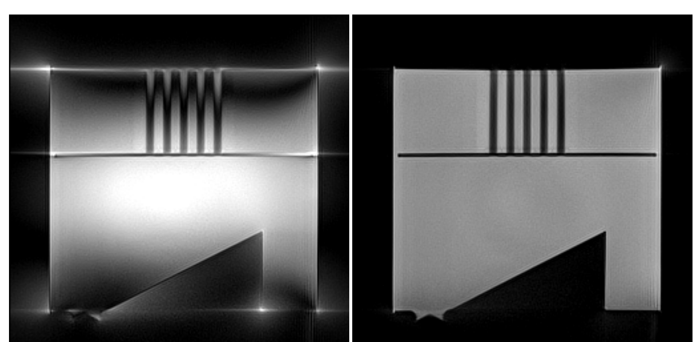

Fig 2: Coronal phantom scan (left) uncorrected and (right) after correction.