Self-calibrated gradient delay correction for golden angle radial MRI

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TARGET AUDIENCE: Researchers interested in MRI reconstruction and data correction.

PURPOSE: To correct for gradient delays in golden angle radial MRI with no additional measurements or calibration.

METHODS: Gradient echo data on a picture image quality test (PIQT) phantom was acquired on a Philips 7 T MRI scanner (Philips Healthcare, Cleveland, OH, USA) using a 16-channel SENSE head coil (Nova Medical, Wilmington, MA, USA). A total of 5000 radial profiles were obtained using Ref. 1 to describe the 3D orientations of the profiles so as to follow the golden ratio. The raw complex data for each radial profile was retrieved, and the magnitude of the Fourier coefficients for each radial profile was fit to the following distribution using a Levenberg-Marquardt algorithm:

$$P(k_r) = [a + b(|k_r| - c)^q]^{-1}\,, \qquad (1)$$

where q = 2 for 3D data (to fit 2D data, use q = 1.5) and k_r describes the spatial frequency along the readout direction, taken here to be -0.5 to 0.5-1/N_{ro}, where N_{ro} is the number of readout points. The coefficient c in the fit gives the trajectory shift parallel to the readout direction. If we assume that these delays are due to constant but independent delays in each of the three (x, y, and z) gradient channels, then we can form a matrix equation that describes these trajectory shifts as a function of the gradient channel delays. First, we define the matrix $\boldsymbol{U}$ as the N x 3 orientation matrix that describes the 3D orientation of each profile in k-space, where

$$\boldsymbol{U} = (\boldsymbol{u_1}, \boldsymbol{u}_2, \dots, \boldsymbol{u}_N)^T, \text{ and } \boldsymbol{u}_p = \left(\cos(\phi_p)\sin(\theta_p), \sin(\phi_p)\sin(\theta_p), \cos(\theta_p)\right)^T,$$

where N is the number of phase encodes and (θ_p, ϕ_p) is the spherical polar angle pair describing the orientation of profile p. The rows of matrix $\boldsymbol{U}$ are equivalent to unit vectors pointing along the readout direction of the corresponding profile.

The measured delays taken from the c coefficients in Eq. 1 are then stacked into an N x 1 column vector $\boldsymbol{c}$, leading to the following matrix equation:

$$\boldsymbol{U}^2\boldsymbol{\delta} = \boldsymbol{c}, \qquad (2)$$

where $\boldsymbol{\delta}$ is a 3 x 1 vector describing the constant k-space shift imparted by each gradient axis due to timing delays, and $\boldsymbol{U}$ is squared to account for the proportion of total delay that is parallel to the readout direction. Since Eq. 2 is highly overdetermined, a least squares solution for $\boldsymbol{\delta}$ yields robust estimates of the shifts even for noisy data. The shift $\boldsymbol{\delta}$ is then added directly to each k-space coordinate triplet to correct it. Note the shifts do not need to be converted into timing delays, because they will be used only to shift the k-space coordinates before a reconstruction is performed.

RESULTS: Figure 1 shows an example fit to the magnitude of the Fourier coefficients. Figure 2 shows the effect of correcting for gradient delays on reconstructed image quality. The detected shifts in this example were $\boldsymbol{\delta} = (-0.0094, -0.0099, -0.0060)$ in units of inverse field of view.

DISCUSSION: One common method to correct gradient delays in radial acquisitions with a linearly increasing angular orientation acquires that the readout gradient polarity alternates between profiles. This ensures that the neighbors of every profile are acquired with the opposite polarity. The gradient delay then appears as twice the difference between the center profile and the mean of the neighbors. Unfortunately, in golden angle radial imaging, neighbors are not guaranteed to have opposite polarity and are typically acquired at very different times due to the order in which k-space is filled in. Thus conventional methods of gradient delay correction cannot be used. Before now, golden angle acquisitions were limited to those that did not challenge gradient hardware.

CONCLUSION: We have presented a model for the delay imparted to a radial sampling trajectory parallel to the readout direction based on timing delays in the three physical gradient channel axes can be used to correct these delays with the need for additional measurements. No alternating profile directions are required so this technique is compatible with golden angle radial imaging.

REFERENCES: [1] P. Anderson, *J Elec Imag*, **2(2)**: 147-54, 1993,
ACKNOWLEDGEMENTS: NCI R25CA092043

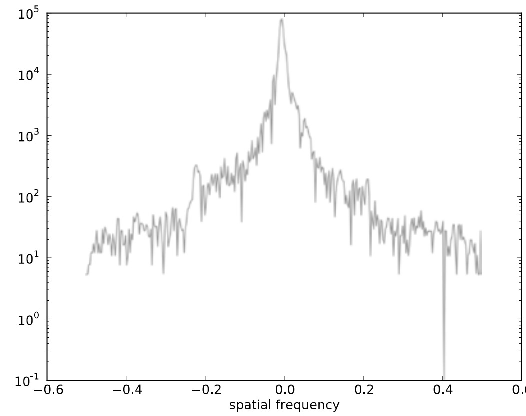

Figure 1: Fit of the Cauchy distribution to the magnitude of the Fourier coefficients from a single 3D radial golden angle profile. The peak center estimates the offset parallel to the readout direction.

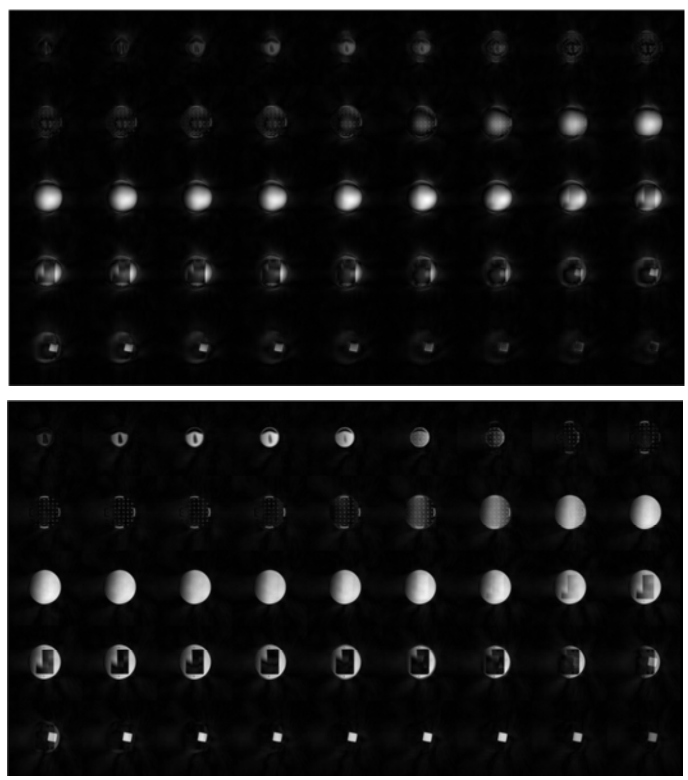

Figure 2: Example images of a picture image quality test (PIQT) phantom acquired at 7T using a 3D golden angle radial "koosh ball" pattern. The top panel shows the effect of a small gradient delay on the reconstructed image quality. The bottom panel shows the improvement after correction. The right-to-left intensity variation is due to the sagittal orientation of the phantom in a 16-channel head coil.