Characterizing and Correcting Gradient Errors in Non-Cartesian Imaging: Are Gradient Errors Linear Time-Invariant?

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INTRODUCTION

Non-Cartesian and rapid imaging sequences are more sensitive to scanner imperfections such as gradient delays and eddy currents than conventional Cartesian acquisitions. These imperfections vary between scanners and over time and can be a significant impediment towards successful implementation and eventual adoption of non-Cartesian techniques by scanner manufacturers. Uncorrected differences between the k-space trajectory desired and the trajectory actually acquired lead to misregistration of *k*-space data and reduction in image quality. While early calibration methods required considerable scan time, more recent methods can work more quickly by making certain approximations. We examine a rapid gradient calibration procedure applied to multi-echo 3D radial acquisitions where the calibration runs as part of every scan. After measuring the trajectories traversed for readouts on each of the three physical gradient axes, trajectories for the myriad of projection orientations acquired during the scan are synthesized as linear combinations of the three physical measurements. The ability to do rapid calibration depends on the assumption that gradient errors are linear (with respect to changes in gradient waveform amplitude) and time-invariant (within a single scan). This work examines the validity of these assumptions and shows that the assumption of linearity is reasonable, but that gradient errors can vary over short time periods (due to changes in gradient coil temperature) and thus it is important to use calibration data matched to the scan data.

MATERIALS AND METHODS

The *k*-space trajectory calibration measurement is based on the work of Duyn [1,2] and involves exciting a thin slice a known distance from isocenter, orthogonal to the gradient under test. After excitation, the phase of the excited slice is measured while the readout gradient under test is played. This experiment is repeated with no readout gradient to determine the phase accrual due to off-resonance. The phase difference between the two experiments is proportional to the *k*-space trajectory. In practice, a rapid calibration is run as part of every scan by making a one-dimensional measurement on each physical gradient axis at maximum gradient magnitude, then synthesizing the trajectory for each projection orientation as a linear combination of the three measurements.

All measurements were made on GE Healthcare 1.5 T or 3.0 T TwinSpeed scanners using a four half-echo 3D radial SPGR imaging sequences, with 30° flip angle, ±125 kHz bandwidth, 20-26 cm FOV and 0.8-1.0 mm isotropic resolution. The calibration measured the same trajectory using a GRE sequence with 15° flip and 10 ms TR.

To determine whether trajectory errors vary linearly with gradient magnitude, gradient measurements were repeatedly performed at varied gradient amplitudes and the measured waveforms were compared with a scaled full-magnitude calibration measurement. In addition to the single measurement usually acquired at full gradient strength, additional measurements were made as the gradient strength varied in 10% increments from full strength (100%) down to 10% strength. Subtracting the reduced-strength deviation measurements from scaled version of the full-strength deviation measurement yields the component of the trajectory deviation not corrected by the linear model. To examine the impact of these unmodeled deviations on image quality, images were reconstructed incorporating the additional measurements into the gridding process and compared to conventionally reconstructed images.

The assumption of temporal stability was examined by repeatedly performing calibrations during a gradient-intensive imaging sequence, starting with a "cold" scanner that had been idle for several hours. The effective gradient delays on each axis were calculated and plotted over time. To assess the impact these errors have on image quality, images were reconstructed using "warm" scan data with "cold" calibration data and compared to images reconstructed using "warm" scan data and "warm" calibration data.

RESULTS AND DISCUSSION

Gradient deviations were seen to scale primarily linearly with gradient amplitude, as seen in Figure 1, where deviations are shown as a percentage of programmed gradient strength. *K*-space trajectory estimates based on max amplitude calibration remove almost all error, with the remaining non-linearity causing *k*-space errors typically less than $^1/_{10}$ point, as shown in Figure 2 (note the different axis scaling). The largest errors occur during periods of gradient ramps, likely due to discrete changes in gradient amplifier supply voltages and switching rate that are applied at varying slew rates. Significantly, the remaining errors are small near the center of *k*-space, crucial to eliminating major artifacts.

Figure 3 shows the change in gradient delay time as repeated scanning caused the gradient coil to increase in temperature, with an inset showing the impact on image quality. Gradient delays decreased monotonically as scanning progressed, with timing changes of nearly 1.5 μs from "cold" to "warm".

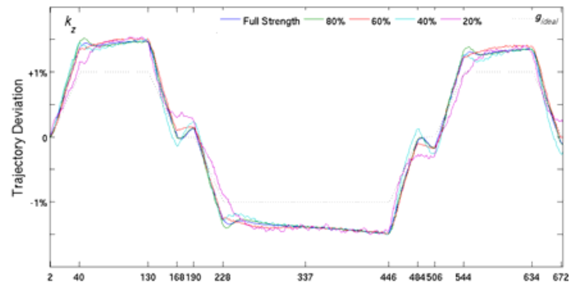

Figure 1: *Performing calibration measurements at various gradient amplitudes shows that trajectory errors vary predominantly linearly with gradient amplitude. The error is dominated by a gradient delay of 1.8 samples, as evidenced by its waveform resembling a scaled version of the gradient waveform.*

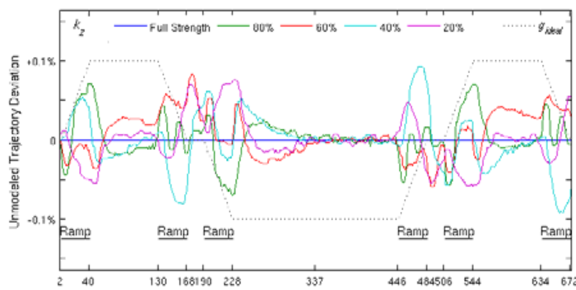

Figure 2: *The difference between the reduced-magnitude measurements and scaled versions of the full-strength deviation measurement is the unmodeled portion of the trajectory error that cannot be corrected using a linear model. Note the ten times larger y-axis scaling – these errors are very small and have a negligible impact on image quality.*

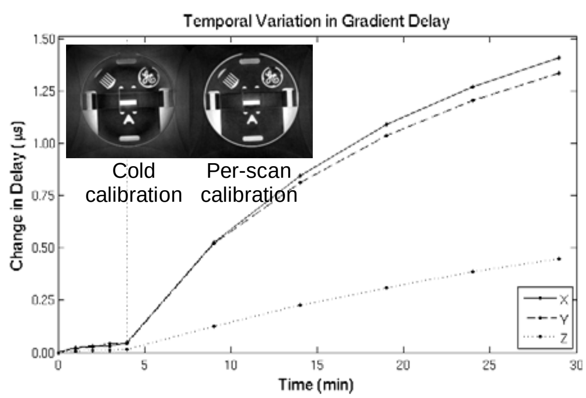

Figure 3: *Gradient timing can change significantly over the course of a single scan session, as shown in this figure plotting the gradient delays as the scanner "warms up" after an idle period. The inset close-up images show the negative consequence of using only a cold calibration instead of a per-scan one. Note the impact on edge detail.*

CONCLUSIONS

Gradient errors can have a significant negative impact on non-Cartesian acquisitions, but a rapid per-scan calibration can substantially correct for the errors, yielding a substantial improvement in image quality. Fortunately, the assumption of linearity is correct, so rapid calibration using only full-strength gradient measurements is possible. The assumption of time-invariance is less correct, but holds reasonably well within a single scan, making per-scan calibration possible and necessary. Calibration and correction will become especially crucial with higher receiver sampling rates, as a given gradient delay will cause a larger k-space sample shift at higher sampling rates.

REFERENCES **1**. Duyn *et al*., JMR 132(1):150 ('98) **2**. Jung *et al*., MRM 57(1):206 ('07)

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