Consistent non-Cartesian off axis image quality: Removing multiple sources of demodulation phase errors

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INTRODUCTION

Off axis imaging using non-Cartesian sequences suffers degraded image quality relative to on axis imaging. Poorly generated demodulation reference signals on MR receivers force hand tuning of a system delay parameter for off axis imaging. However, even accounting for this delay only partially restores image quality. Eddy currents and anisotropic gradient delays cause deviations in k-space trajectories which in turn make the demodulation reference signal inaccurate. Off axis image quality can be fully restored by correcting for all demodulation phase errors and k-space location errors.

MATERIALS AND METHODS

The phase of the demodulation reference signal for an image centered at d_x, d_y and d_z can be expressed as $\Phi(t) = 2\pi\, [\, k_x(t)\, d_x + k_y(t)\, d_y + k_z(t)\, d_z]$ [Eq. 1]

As phase is the integral of frequency and k-space location is the integral of gradient waveforms, $\Phi(t)$ is commonly generated on commercial scanners by using the theoretical gradient waveforms as inputs to a real-time frequency demodulator. Two source of error are present in $\Phi(t)$:

(i) Incorrect alignment of the gradient coil waveforms and the real-time frequency demodulator cause a shift in $k(t)$ in Eq. 1 and

(ii) The actual gradient waveforms are different than the theoretical waveforms used by the real-time demodulator.

An example of a real-time frequency demodulation reference signal corresponding to a trapezoidal imaging gradient is shown in Fig.1a. Due to an improper system delay, the actual reference signal used for demodulation is illustrated as Fig. 1b and results in a phase error shown by Fig. 1d. Possible eddy currents can change the shape of the trapezoidal gradient, illustrated in Figure 1c. k-space deviations from eddy currents cause additional phase errors, which when summed with the phase errors due to the system delay parameter, are illustrated in Fig. 1e. All these errors can be corrected by modifying the phase of each k-space sample during reconstruction. Under separate research, our group has developed a method to automatically quantify the timing delay τ, the first source of error. A gradient calibration technique [1] was used to determine the actual k-space trajectories, the second source of error. Both measurements were completed in under a second prior to imaging. Using this information, a retrospective phase correction is applied to each k-space sample before the data is regridded during reconstruction. The phase correction is illustrated in Fig. 1d. The corrected raw data is gridded onto the Cartesian space using the actual k-space sampled positions obtained from the gradient calibration technique.

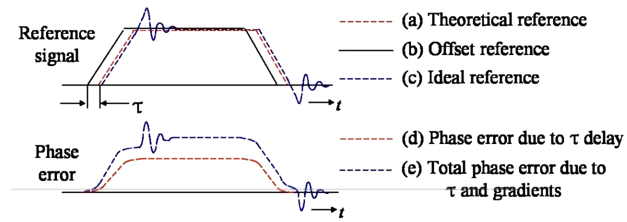

Figure 1. (a) Proper theoretical reference for demodulation. **(b)** Offset reference due to timing error τ. **(c)** Ideal reference considering timing error and k-space deviations. **(d)** Phase errors due to timing error τ **(e)** total phase errors due to delay τ and k-space location errors.

RESULTS AND DISCUSSION

Studies were conducted on a 1.5T Signa EXCITE HD scanner (GE Healthcare, Milwaukee, WI). The automatic measurement technique determined the timing error τ to be 4.3 us greater than the manufacturer recommended delay at a BW of ±125 kHz. k-space deviations due to gradient imperfections were measured to be within ± 1.5 sample points. A phantom was positioned laterally off isocenter by 5 cm and imaged using the dual half-echo VIPR sequence [2]. Using the actual gradient waveforms to correct the sample locations of k-space data works well for on axis imaging, but was surprisingly found to degrade image quality for off axis images (Fig. 2b). Compensating the demodulation phase errors only due to τ (Fig. 1d) caused incomplete correction (Fig. 2c). Excellent results were obtained when the k-space data was compensated for all demodulation phase errors and regridded using the actual k-space sample locations (Fig. 2d). Since the phantom was shifted laterally, it should ideally result in a linear phase across the k-space along k_x. Fig. 3 shows the phase of k-space data before and after correction. The corrected phase data has a linear phase characteristic which is consistent with a lateral spatial shift.

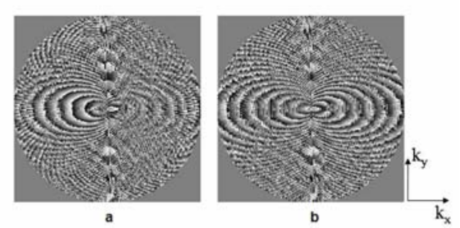

Figure 3. (a) k-space phase before correction, corresponding to Fig. 2a. **(b)** k-space phase after correction, corresponding to Fig. 2d.

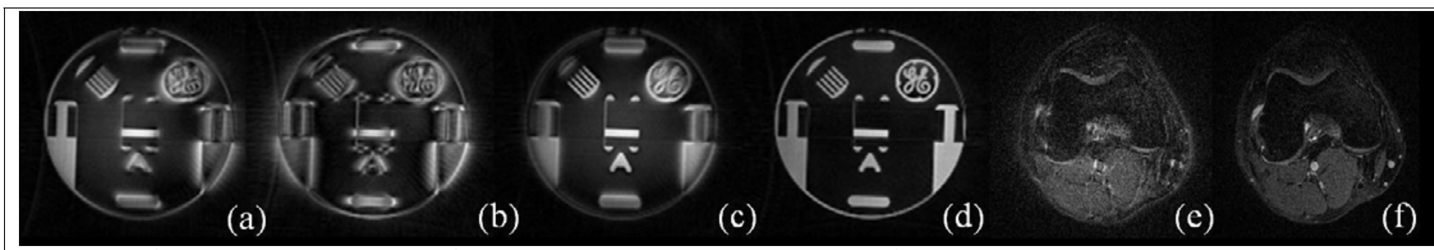

Figure 2. (a) Off axis uncorrected image. **(b)** Sole correction for k-space location errors. **(c)** Correcting phase errors only due to the timing delay in the demodulation reference signal gives partial correction. **(d)** Correcting both sources of error gives the best image quality. **(e)** & **(f)** In vivo equivalent of (a) and (d) using same parameters, with off axis distance of 6 cm, using a single channel extremity coil.

CONCLUSIONS

Removing phase errors due to timing offsets only partially restores off axis image quality. Demodulation phase errors due to deviated k-space sample locations must be compensated to fully restore image quality. While implemented for radial imaging, the method applies to all non-Cartesian trajectories.

REFERENCES

1. Duyn J, et al., JMR, **132**, 150, 1998. **2.** Lu A, et al., MRM, **53**, 692, 2005.

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