K-space Trajectory Errors: Dependence of View Ordering for ECG-gated Radial TrueFISP Acquisitions

K. J. Barkauskas[1], C. M. Hillenbrand[2], J. S. Lewin[2], J. L. Duerk[2]

[1]Biomedical Engineering, Case Western Reserve University, Cleveland, OH, United States, [2]Radiology, MRI, University Hospitals of Cleveland, Cleveland, OH, United States

Introduction:

Two methods to correct for trajectory errors have been proposed: gradient delay compensation[1,2] and reconstruction based on a measured trajectory[3,4]. In gradient delay compensation, echo shifts in K-space along each projection direction are used to extract an estimate of waveform delays of the physical gradient system, which are then used to trim the gradient areas for each projection angle. In cardiovascular MRI applications, data is usually acquired with a rapid acquisition and ECG-gating to achieve the desired temporal resolution. The impact of cardiac sequence parameters and view ordering on radial trajectory errors has yet to be described. The purpose of this work is to establish if gradient delay compensation alone would be sufficient to correct trajectory errors in ECG gated TrueFISP acquisitions with sequential or interleaved view ordering.

Methods:

An ECG-gated, segmented (i.e. total of all views acquired over multiple heartbeats) Radial TrueFISP acquisition was modified to allow sequential and interleaved view ordering. Data was acquired on a Siemens 1.5T Sonata imager (Siemens Medical Solution, Malvern, PA) and the following parameters: FOV 300mm, 6mm slice thickness, TE 2.19ms, 1 average, flip angle 70°, 256^2 final image matrix, 512 samples per view (including 2x oversampling), 180 projections, bandwidth 558 Hz/pixel. The simulated ECG timing parameters were: RR interval 1000ms, acquisition window 225ms, 10 segments per full K-space acquisition, TR 53.3ms, 5 phases per cardiac cycle. A quadrature head coil was used in phantom trials to eliminate confounding factors associated with coil phase variations over the FOV common to multi-element body/cardiac coil designs. A repeating "dummy" pulse was played during non-imaging portions of the RR interval to maintain the steady state. The imaging experiment was conducted in a spherical water phantom at isocenter and repeated for both the sequential and interleaved view ordering along the transverse plane with no slice offsets in any direction. Images were reconstructed with a convolution regridding algorithm provided by Siemens.

An algorithm for echo alignment in temperature imaging[5] was used to detect echo shift along each projection to the nearest $1/256^{th}$ of a sample. The shift was multiplied by the ADC dwell time (3.5 µs) to compute the time delay of the echo. The measured time delays along each projection, td(θ), were fit in the least squared error sense to the following model[2] using the Matlab (The MathWorks, Nattick MA) function lsqcurvefit: $td_{model}(\theta) = t_x{*}\cos^2(\theta) + t_y{*}\sin^2(\theta)$, where θ is the projection angle, and t_x and t_y are the time delays along the physical x- and y-gradient axis, respectively. The model and measured time delay patterns were compared and presented with their respective reconstructed images.

Results:

Time delays (in µs) were plotted against projection angle for cardiac phase 1 and 2 for both the sequential (Fig 1a,b) and interleaved ordering (Fig 1c,d). There is a discrepancy between the model and measured delay at 90° and 180° for the sequential ordering (Fig 1a,b). The pattern of phase 1 of the interleaved ordering (Fig 1c) resembles that obtained with the sequential ordering (Fig 1a,b). The measured echo shift pattern of phase 2 of the interleaved ordering (Fig 1d) does not vary smoothly with projection angle, and the pattern persists through latter phases of the data set (not shown). By reducing the time allotted to "dummy" pulses to zero, phase 1 of the current heartbeat is corrupted by the last phase of the preceding heartbeat with interleaved ordering (data not shown). The reconstructed images are shown below their corresponding echo shift plots (Fig 1e-h; with scale inversion to better highlight artifacts). Phase 2 of the interleaved view ordering data (Fig 1h) set shows an increase in streak artifact relative to the other images. The time delay model parameters for the transverse plane are shown in Table 1. The model gradient delay parameters for phase 2-5 of the interleaved data set (shaded) are consistent but yield a poor fit to the data.

Discussion & Conclusions:

Although stable for several imaging parameters[2], sources other than gradient delay contribute to echo shift when using ECG-gated Radial TrueFISP, imaging parameters that are typical of cardiac sequences and different view ordering schemes. With respect to interleaved view ordering, cardiac phase 1 is preceded by a series of "dummy" pulses; phase 2 is preceded by a block of views with 18° angular increment in projection angle between consecutive views. This yields twice the echo shift amplitude in phase 2 (Fig 1c) relative to phase 1 (Fig 1d) and the observed fluctuations in the echo shift pattern. Despite active gradient shielding, it is believed that long and short term eddy currents induced by the transition between segments in interleaved radial acquisitions prevent successful use of a gradient delay model in correcting radial K-space trajectory errors. We conclude that a measured trajectory, along with gradient delay correction, will be necessary for radial acquisitions including those using interleaved segmented ordering schemes commonly used in cardiac MRI.

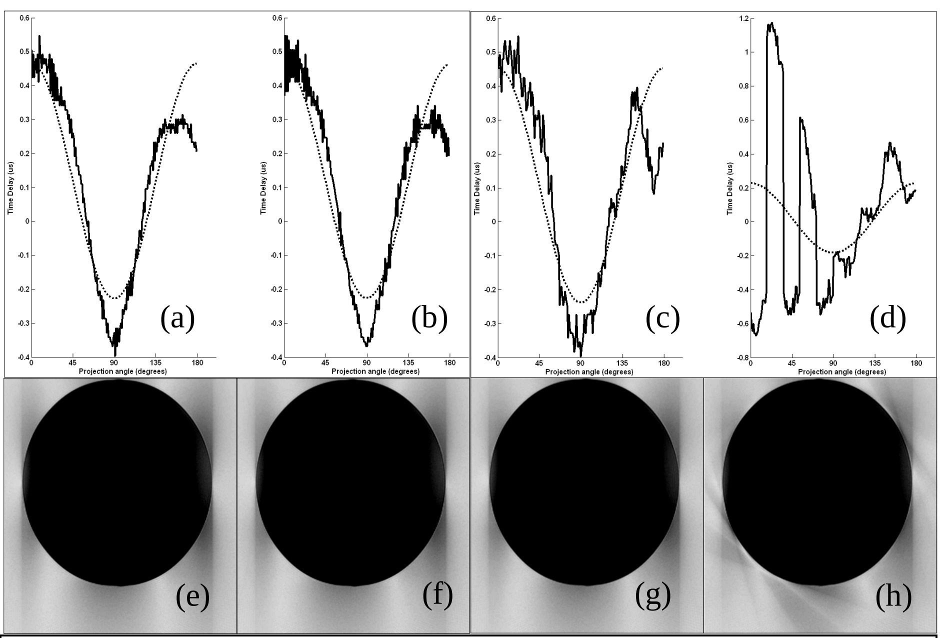

Figure 1a-d: Measured (solid) and model (dotted) time delay (µs) vs. projection angle for phase 1 and 2 of the sequential (a,b) and interleaved (c,d) ordering.
Figure 1e-f: Images from phase 1 and 2 of the sequential (e,f) and interleaved (g,h) ordering (inverse colormap, and windowed/leveled to reveal streak artifacts).

References:

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Table 1: Model delays (in µs) along physical gradients for transverse plane

	S	S	I	I
Phase	t_x	t_y	t_x	t_y
1	0.47	-0.23	0.45	-0.24
2	0.46	-0.23	0.23	-0.18
3	0.46	-0.23	0.24	-0.19
4	0.46	-0.23	0.25	-0.19
5	0.46	-0.23	0.24	-0.19

S: Sequential view ordering
I: Interleaved view ordering