K-SPACE TRAJECTORY ESTIMATION IN SPIRAL IMAGING

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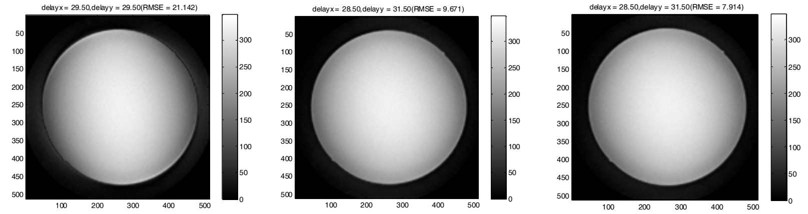
Introduction: For non-2DFT data acquisition, k-space trajectory infidelity due to eddy current effects and other hardware imperfections will blur and distort the reconstructed images. Even with the shielded gradients and eddy current compensation techniques of current scanners, the deviation between the actual k-space trajectory and the requested one remains a major reason for image artifacts in non-Cartesian MRI. The current practice for k-space trajectory correction is to tune the delays on different physical gradients as demonstrated in projection reconstruction [1]. Duyn et al. [2] proposed a technique to measure the k-space trajectory in order to correct for gradient imperfections. However, it is usually not practical to measure the k-space trajectory for each imaging slice. Here we introduce a simple and effective model for eddy current compensation in spiral image reconstruction. The root mean square error (RMSE) and peak error in the reconstructed phantom images using the proposed method are reduced substantially compared to the results achieved by only tuning delays.

Method: First, we collect data on two symmetrical thin slices for coronal, sagittal and transverse views. The B0 eddy currents are then measured using the method proposed by Gurney et al. [3] and deducted from the corresponding phase term. Dividing this corrected signal phase by the slice distance, we get the measured k-space trajectories $k_b(t)$ in each view. Using these measured k-space trajectories, we perform gridding reconstruction to get the benchmark images. To find the delays on different physical gradients, we conduct a 2D search for the minimum RMSE between the images reconstructed using different delays and the benchmark for each view. With the optimum delays on each physical gradient axis, we have the first guess of the k-space trajectory $k_d(t)$. However, the difference between $k_b(t)$ and $k_d(t)$ is still large and the images using this delay model have significant residual error. In order to reduce the deviation between the modeled k-space trajectory and the actual measured k-space trajectory, we introduce an additional eddy current compensation term on each physical gradient axis. In a simple eddy current model [4], the eddy current $g(t)$ can be estimated by the convolution of the slew rate $s(t) = -dG/dt$ of the desired gradient waveform and the system impulse response function $H(t)$, which can be expressed as the sum of a few exponential terms. So we can model the difference $\Delta k(t) = k_b(t)-k_d(t)$ using the convolution model. For each exponential term $e(t) = au(t)e^{-t/b}$ in $H(t)$, if we only consider the first order Taylor expansion, i.e. $e(t) \approx au(t)(1-t/b)$, the convolution can be simplified to three terms $s(t)*e(t) \approx a[-G(t)+G(t)t/b-\int s(\tau)\tau d\tau/b]$. No matter how many exponential terms are in $H(t)$, we can get three parameters by using least squares (LS) to fit the error in the k-space trajectory with respect to the 3 by N vector $\text{cumsum}([G(t_n); G(t_n)t_n; \sum_1^n s(t_m)t_m]^T)^T$ on each physical gradient axis, where cumsum(**A**) is a Matlab (The MathWorks) function that returns a matrix containing the cumulative sums for each column of **A**. After we have these parameters for each physical axis, we can perform the correction on the physical gradients. For an arbitrary slice, we need to know the rotation matrix to map the logical gradients to physical gradients back and forth in eddy current correction and image reconstruction.

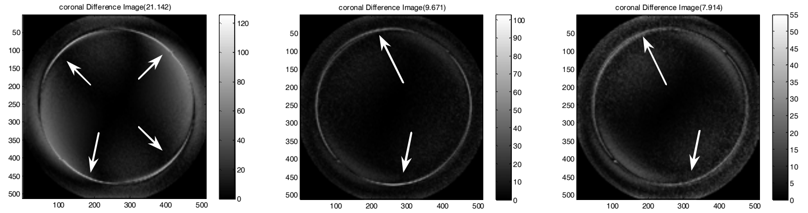
Results and Discussion: We applied our algorithm to two data sets acquired using a gradient-echo spiral scan with field map correction. Figure 1 shows the RMSE (in mm^{-1}) on each interleaf between the resulted k-space trajectory and the measured one using two methods. The results in Fig. 2 were from a calibration dataset acquired more than one month before the results in Fig. 3 on the same Siemens Avanto 1.5 T scanner (Siemens Medical Solutions). The readout for each slice was done with 16 interleaved spirals each of 16.38 ms readout duration. The samples within the first 2 interleaves of the readouts were used to estimate the field map. The reconstructed image matrix was 512 by 512. The delays and additional gradient compensation parameters were estimated on the first dataset and applied to the second dataset. From the difference images in Fig. 2 and Fig. 3, the proposed method yields a more accurate reconstruction with smaller RMSE and peak error. There is little time penalty for using this method after the system calibration.

Conclusion: We proposed a simple and effective eddy current compensation model in order to reduce the deviation between the estimated k-space trajectory and the measured one. The resulting model can be used to generate accurate k-space trajectories for arbitrary slice orientations during image reconstruction.

References: [1] Dana C. Peters et al MRM50: 1-6 (2003); [2] Jeff H. Duyn et al. JMR 132: 150-153 (1998)
[3] Gurney et al. ISMRM 13: 866 (2005); [4] Matt A. Bernstein, et al, "Handbook of MRI Pulse Sequence", 319-323, (2004)



(a) Without correction (c) Delay model (e) Proposed method



(b) RMSE = 21.142 (d) RMSE = 9.671 (f) RMSE =7.914

Fig. 2. Reconstructed images and the corresponding absolute difference to benchmark in the coronal view without correction (a-b) using delay only model (c-d) and the proposed method (d-f)

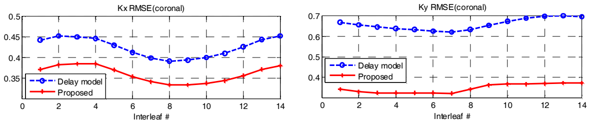
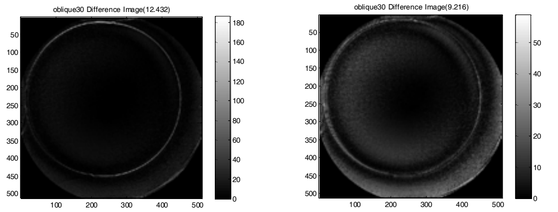


Fig. 1. K-space trajectory RMSE comparison in the coronal view



(a) RMSE = 12.432 (b) RMSE = 9.216

Fig. 3. Absolute difference images on an oblique slice using delay only model (a) and the proposed method (b)