Robust estimation of true k-space center position for radial center-out trajectories

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Target Audience – Researchers working with radial center-out trajectories such as with UTE imaging.

Purpose – Radial center-out trajectories are becoming increasingly important not only for fast real-time MRI but especially for *ultra-short echo time* (UTE) imaging[1]. However, starting the readout directly in the k-space center makes data acquisition extremely sensitive to even smallest imperfections in the gradient and sampling hardware. Especially on clinical systems, which are often not optimized for center-out acquisition, implementation of UTE sequences can be a challenging problem. In this work, we describe a template scan from which an estimation of any delay between data sampling and gradient activity is possible. For improved reliability we propose to analyze k-space phase information of the template scan directly.

Methods – Besides well-known spatially varying gradient delays[2], additional hardware imperfections such as digital filtering artifacts during the first readout points or an unpredictable jitter between the data sampling and the gradient grids can compromise radial center-out readouts. Because k-space center is sampled during the ramp-up of the gradients even small errors do have a significant impact on the final image quality. To avoid digital filter artifacts and to shorten the effective dead time of the ADC, the sampling hardware is switched on (ADC start) immediately after the RF pulse. At the end of the dead time interval the readout gradients are switched on and all data points acquired up to this time point are discarded. However, due to jitter, gradient delays and eddy currents, the actual start of the gradient ramp up occurs a time delay Δt later than expected (Fig. 1a, black solid vs. dashed line), which has to be corrected during image reconstruction. However, the actual time delay Δt depends on a wide range of measurement parameters and is therefore difficult to predict.

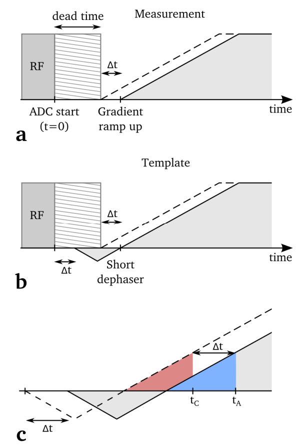

Fig. 1. ADC, RF and gradient timings for measurement (a) and template (b). An enlarged view of the dephaser timing is given in (c).

To estimate the delay Δt we implemented a template scan which measures 360 radial spokes with evenly spaced rotation angles in each of the imaging planes, *x-y*, *x-z* and *y-z*. For a 2D acquisition a set of rotated spokes in the imaging slice would be used. During the dead time of the ADC an additional short dephaser is played out, ensuring that the readout gradient of the template scan is crossing the k-space center (Fig. 1b). With the gradient area of the dephaser known, the exact time t_C when the readout gradient has compensated the dephaser (Fig. 1c, red area) can be calculated from the gradient parameters. However, the dephaser of the template is affected by the same delay Δt as the readout gradient. By extracting the actual time t_A of the k-space center crossing (Fig. 1c, blue area) the delay can be calculated $\Delta t = t_A - t_C$.

To estimate t_A we analyzed the k-space phase of all measured template spokes (Fig. 2b). Contrary to the magnitude (Fig. 2a), k-space phase has no broad maxima but rather forms a distinct fixed point at the center of k-space. To estimate the position of this phase node we calculated the deviation of all spokes from the mean phase. The point where the sum over all deviations is minimal gives an estimate of the phase node position on the sampling grid. To achieve sub-dwell time accuracy we performed a linear fit over the phase data of each spoke next to the sampling point which was found to be nearest to the phase node (Fig. 2c). From these linear functions the searched time point is calculated for which the deviation of all fit functions $\varphi_k = m_k \cdot t + n_k$ from the mean fit equation $\overline{\varphi} = \overline{m} \cdot t + \overline{n}$ is minimized. This problem can be solved analytically by finding the minimum of the sum over the squared differences: $0 = \frac{\partial}{\partial t} \sum_k (\overline{\varphi} - \varphi_k)^2$. The result is the true time t_A where the readout gradient has compensated the dephaser:

$$t_A = -\frac{\sum_k (\overline{m} - m_k) \cdot (\overline{n} - n_k)}{\sum_k (\overline{m} - m_k)^2} .$$

With known t_A the time delay Δt can be calculated and used for correcting the actual measurement data, which is acquired without the additional dephaser.

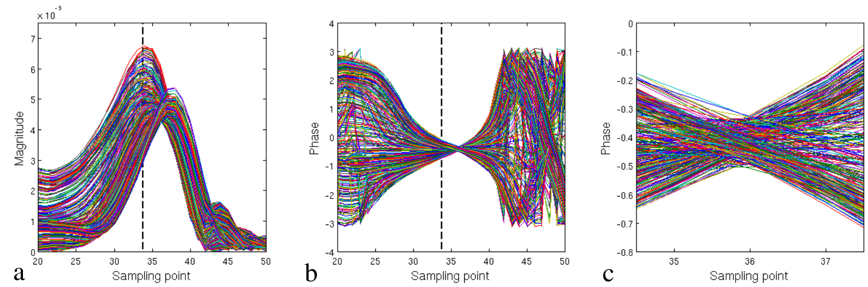

Fig. 2. Magnitude and phase of the template data for 360 spokes from the *x-y* plane. While the magnitude data has no clear center (a), the phase forms a fixed point at the true k-space center position (b). The dashed black line delineates the expected position of the k-space center. An enlarged portion of (b) is shown in (c).

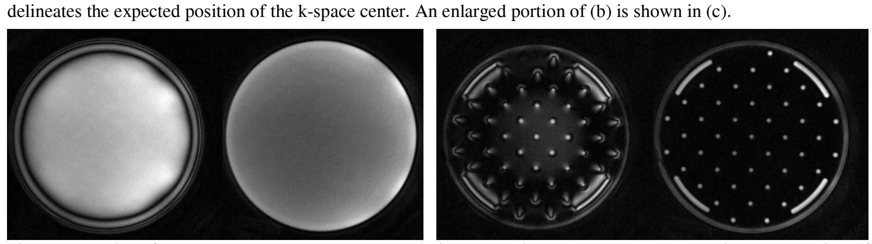

Fig. 3. Two slides from a structure phantom measured with a 3D spikey ball UTE sequence without correction of delays and with a correction calculated from the phase knot of the template data (left and right, respectively).

Phantom measurements were performed on a clinical 3T system (Siemens Trio, Erlangen, Germany) using 3D “spikey ball” center-out acquisition. Acquisition parameters were: 160 x 160 x 160 acquisition matrix size, 3.05 µs dwell time, 3.4 ms repetition time, 70 µs echo time, 10° flip angle with a total of 20,280 measured spokes. Image reconstruction was performed by state-of-the-art 3D gridding using iterative grid weights estimation[3].

Results – From the template data, a delay Δt of 9.08 µs was calculated between the expected time of k-space center crossing and the actual time of the crossing. With the given dwell time, this delay corresponds to approximately three sampling points. Without correcting for the time delay, reconstructed images are severely degraded (Fig. 3), whereas with correction of the calculated delay the images are free of artifacts.

Discussion & Conclusion – Exact correction of delays between data sampling and onset of gradient activity is crucial for radial center-out acquisition. By analyzing the phase node, which forms in the vicinity of the true k-space center, the proposed method is highly accurate, allowing for sub-dwell time precision using simple linear fitting. Since different parameters could lead to different delays Δt, it is important to use the same parameters (FoV, BW, matrix, oversampling,..) for the template scan as for the actual measurement. The gradient integral of the dephaser should be small compared to the readout gradient to ensure that the k-space center crossing is sampled during ramp up of the readout gradient with low gradient amplitude. We implemented the template scan for a spikey ball 3D UTE sequence; however, application to 2D real time imaging sequences[4] should also be possible.

References [1] Waldman A et al., Neuroradiology, 2012 [2] Peters DC et al., MRM, 2003 [3] Zwart NR et al., MRM, 2012 [4] Uecker M, NRM Biomed, 2010