Correcting for Gradient Imperfections in Ultra-Short Echo Time Imaging

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Introduction: Unlike Cartesian-based acquisition methods, which are immune to a relatively wide range of imperfections in the applied spatial gradients, radial techniques are susceptible to even very slight delays or miscalibrations in the readout gradients. A delay in one or both of the principal readout gradients induces phase shifts in the resulting projections which are *view-dependent*, leading to image artifacts caused by inconsistent k-space data. If the gradient delays are known, then such problems can be corrected either by applying phase offsets to the projections in image space, or by shifting the data appropriately in k-space prior to gridding. Various strategies have been used to measure such delays [1-2]. However, in the context of ultra-short echo time (UTE) methods, in which data is collected during the up-ramp of the readout gradient, delays are not the only source of gradient imperfection. Indeed, as demonstrated in this study, even when a trapezoidal gradient shape is prescribed, the assumption of a linear ramp-up leading to a flat gradient plateau may be incorrect.

Here we describe a simple, robust technique for mapping the k-space trajectories during ramp-up of the readout gradients in a UTE pulse sequence. Whereas other methods exist for mapping k-space trajectories, particularly for spiral-type acquisitions (see [3]), the present technique has certain advantages in the context of UTE imaging. We require a short, one-time calibration scan involving only a small modification to the main UTE imaging sequence. The shape of the ramp-up portion of the readout gradients is accurately measured, and this measurement is robust with respect to B_0 inhomogeneity.

Methods: All images were acquired on a 3T Siemens scanner (Siemens Tim Trio, Erlangen, Germany) with an 8-channel Tx/Rx knee coil.
***Imaging parameters**:* A 3D variable echo time UTE sequence was used to image the tibia mid-shaft with radial readouts in two dimensions and phase encoding in the third (Z) direction. At the center phase encode step, the delay between end-of-excitation and beginning-of-acquisition was 100 µs. An additional 30 µs delay was applied before beginning the ramp-up of the readout gradient. Ramp time was 150 µs, with a dwell time of 6 µs, and a plateau gradient amplitude of around 20 mT/m. A 480 µs half-sinc pulse (with two gradient polarities) was used for the excitation. In-plane resolution was 0.38 mm, with slice thickness of 4.5 mm over 20 slices, and FOV=180x180 mm^2. With 500 radial views and TR=20 ms, total scan time was 6.6 minutes.
***Calibration scans**:* Two calibration scans were applied, one to map the X-readout gradient and another to map the Y-gradient. For the first calibration scan, the UTE sequence of interest was modified by inserting two dimensions of phase encoding (X and Y encoding) prior to a radial readout in the X direction. In order to accommodate the phase encode tables, it was necessary to increase the echo time from 100 µs to 2.5 ms, but all other sequence parameters matched the main imaging sequence (i.e. excitation pulse specifications, readout gradient shape, dwell time, TR, etc.) With TR=20 ms, 64x64 phase encodes, and two gradient polarities for the half-pulse excitation, total scan time for the X-calibration scan was 164 seconds. A similar calibration scan was applied to map the Y-readout gradient.
Calibration procedure: A 2D FFT was applied along the phase-encode dimensions to yield a 64x64 image for each acquisition point along the ramped readout (see Fig. 1). The 2D k-space location at each readout point was obtained by fitting the phase map for these images to a linear function after phase-unwrapping. Due to macroscopic B_0 inhomogeneity, it was necessary to normalize (relative to the first image in the readout) prior to fitting (see Fig 1). The measured k-space trajectories were used to adjust the locations of the k-space data prior to gridding in the main image reconstruction.

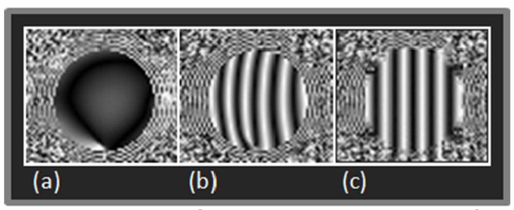

Fig. 1. Phase images of homogeneous phantom obtained from the X-gradient calibration scan at: (a) the first readout point; (b) the 26th readout point; (c) the 26th readout point after B0 inhomogeneity correction.

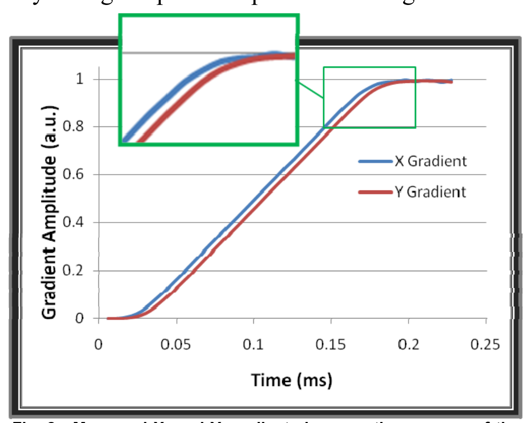

Fig. 2. Measured X- and Y-gradient shape on the up-ramp of the readout gradient. Magnified portion shows the non-trapezoidal shape of the gradient waveform.

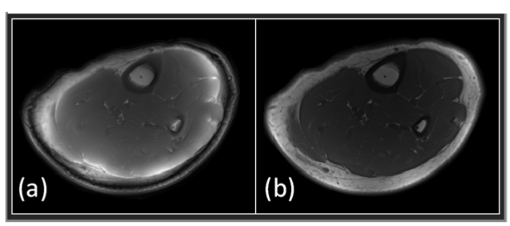

Fig. 3. Reconstructed images of the tibia mid-shaft before (a) and after (b) gradient correction.

Results and Discussion: The measured gradient waveforms, computed as derivatives of the measured k-space trajectories, are shown in Fig. 2, and example images obtained with and without this gradient information are shown in Fig. 3. Artifacts caused by gradient delays are evident in 3a, but are removed after correction in 3b. In addition to the time shift between the X- and Y-readout gradients, Fig. 2 also shows a deviation from a trapezoidal gradient shape, particularly at the beginning and end of the ramp.

Since each point on the measured gradient waveform is obtained using phase data over an entire 2D image, we believe our measurements are highly accurate. The tradeoff, as compared to other techniques, is that only the initial portion of the readout window can be calibrated. This is due to the fact that our calibration sequence has very low resolution as compared with the main imaging sequence (2.8 mm versus 0.38 mm). However, this is not a problem in the present application since we are only interested in correcting data on the initial ramp (i.e. we assume the plateau is perfectly flat).

References: [1] Peters et al, Magn Reson Med 50(1):1-6 (2003); [2] Jung et al, Magn Reson Med 57:206-212 (2007); [3] Tan et al Magn Reson Med 61(6):1396-1404 (2009). **Acknowledgement:** NIH grants RO1 AR50068, K25 EB007646.