Anisotropic Gradient Time Delay Correction for Oblique Radial Readouts Used in Ultrashort TE (UTE) Imaging

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Introduction: Center-out, ramp sampled, radial k-space trajectories are used in Ultrashort TE (UTE) imaging to minimize the time between the end of the RF excitation and the beginning of data acquisition. Data acquisition commences at the beginning of the readout gradient ramp and continues to the end of the "flattop." The gradient amplitude and slew rate are determined by the sampling bandwidth, field of view and the maximum dB/dt limit imposed by the hardware or by physiological stimulation. However, time delays on the three physical gradient axes can differ by up to several microseconds. With high slew-rates and high resolution imaging, artifacts can be seen with errors in the timing of less than 0.25μsec. Gridding is typically used for image reconstruction and if the actual trajectory is known, image quality can be maintained despite small errors in the gradients. Fig. 1 compares the k-space trajectories of an ideal k-space trajectory compared to a trajectory with a difference of 2 μsec between the X and Y gradients.

Theory: We can think of a logical set of gradients ($L_x(t)$, $L_y(t)$ and $L_z(t)$) as being the coordinate system of the patient. The gridded reconstruction must be performed in this coordinate space. There is also a set of physical gradients ($P_x(t)$, $P_y(t)$ and $P_z(t)$) that is the source of the inherent, anisotropic delays. The delays can be expressed by the following expressions: $P_x(t-t_x)$, $P_y(t-t_y)$ and $P_z(t-t_z)$ where the delays on the physical gradients are denoted by t_x, t_y and t_z. We first express the physical gradients in terms of the rotation matrix applied to the logical gradients. We then apply the delays to each of the physical axes as expressed by the logical coordinates. Then we apply the inverse of the rotation matrix to the delayed physical co-ordinates and give these to the gridding reconconstruction program.

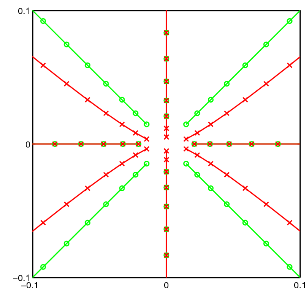

Figure 1: The origin of k-space in the presence of a 2 μsec delay on the y gradient relative to the x channel, shown in red compared to the ideal in green. Note the slight curvature of the red trajectory.

Results and Discussion: Oblique images of a phantom with sharp edges were acquired and reconstructed with a gridding routine. In the image in Fig. 2a), the average gradient delay was applied to all gradient waveforms resulting in signal pileup near the edges of the phantom. In the image in Fig. 2b), the physical delays were mapped back to the logical (patient) coordinate system as described above resulting in sharpening of the edges of the phantom. The physical gradient delays can be found by measuring the gradient trajectories of the readout gradients applied on each of the gradient axes. Duyn's method [1] or self-encoding [2] may be used for measuring the trajectories but we chose self-encoding in a MnCl doped phantom because the SNR of the trajectory measurement is constant regardless of position and extent of k-space. The initial ramp portion of the gradient waveform results in a parabolic k-space trajectory that we fit, numerically with the delay time as one of the fit parameters. The three, fitted, physical delay times were then used by the radial imaging recon. We also compared measuring the all rays (256^2 matrix -> 804 rays) with measuring just full scale positive and negative rays on the three principle axes (six rays total) and using linearity to generate the intermediate rays. Gradient fidelity and linearity were such that all three methods produced images indistinguishable to the eye.

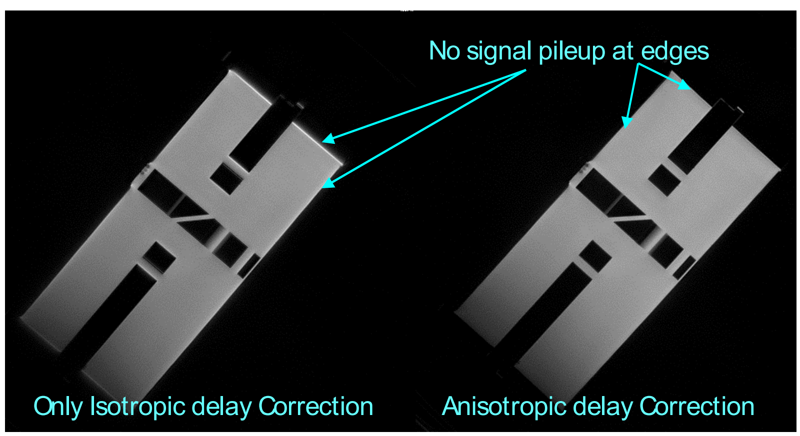

Figure 2. Oblique images reconstructed a) without considering the anisotropy of the physical gradients and b) by mapping the correct physical gradient delays back to the logical (patient) co-ordinate system. By knowing the three gradient delay parameters, images in all planes can be reconstructed.

Conclusion: Measurement of gradients with self-encoding yields very high signal to noise trajectories independent of the extent covered in k-space. Measuring all 804 radial rays is very time consuming and added no image quality improvement over measuring full positive and negative trapezoidal waveforms on just the three principal axes. Both these measurements would have to be repeated should the slew rate or gradient amplitude be changed. Fitting the delay of the three physical gradients and applying these to all possible radial readout waveforms is sufficient. By mapping from logical to physical gradient axes, applying the physical delays and mapping back to the logical frame allows a small number of calibrations to work with any radial trajectory in any imaging plane.

References: Duyn, et al.; J.Magn.Reson; v132:150-153 (1998), Alley et al.; Magn.Reson.Med 39:581-587 (1998)