Correction of Excitation Profile in Zero Echo Time (ZTE) Imaging Using Quadratic Phase-Modulated RF Pulse Excitation and Iterative Reconstruction

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Introduction- The zero echo-time (ZTE) imaging method (e.g. WASPI[1] and PETRA[2]) has shown promise for imaging short T2 spins. The unique feature of ZTE imaging is the presence of the spatial encoding gradient during non-selective excitation, resulting in higher image SNR, less T2* blurring and immunity to distortion artifacts known to occur in ramp sampling in ultra-short echo time (UTE) imaging. However, the presence of imaging gradient during excitation causes the hard pulse to become spatially selective, leading to blurring and shadow artifacts near the object's boundaries[3]. In this work, we propose a novel correction method involving quadratic phase-modulated RF pulse excitation and iterative reconstruction. A simple pulse sequence is also developed to measure the RF pulse excitation profile.

Methods- *Signal Model of ZTE Imaging:* In standard MRI, the signal in *k*-space $s(k)$ is the Fourier transform of the spatial magnetization distribution $m(r)$. In order to include the non-uniform excitation effect, an excitation profile is superimposed onto $m(r)$ and $s(k)$ is expressed as: $s(k) = \iiint m(r)p(f)e^{-i2\pi\langle k,r\rangle}\,dr + \varepsilon$ (1) where $p(f)$ is the excitation profile as a function of frequency $f = \gamma\langle G, r\rangle$. In conventional ZTE (see **Fig.1a**), $p(f)$ is the Fourier transform of rectangular hard RF pulse, i.e. *sinc* function. Without correction for the non-uniform excitation profile, the resulting image suffers from blurring artifacts and signal attenuation near the boundary of the imaged object.

Image Reconstruction: Discretize Eq.1 into: $s(k_j) = \sum_{i=1}^{N} m(r)p(G_j, r_i)e^{-i2\pi\langle k_j,r_i\rangle} + \varepsilon_j$ and write into matrix form $s = Am + \varepsilon$ (2), where A is the system matrix. Image reconstruction can be formulated as an optimization problem with total variation regularization: $\hat{m} = \arg\min_m \|Am - s\|_2^2 + \lambda\|Dm\|_1$ (3). The Split-Bregman method was used to solve Eq.3. During each iteration, a Conjugate Gradient algorithm is employed as a subroutine to solve a quadratic optimization problem, in which the matrix-vector multiplication is reduced from (~$O(N^2)$) to ~$O(N\log N)$ by using Radon transform and non-uniform fast Fourier transform (NUFFT).

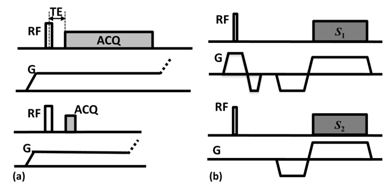

Fig. 1 (a) ZTE sequence and (b) sequence for excitation profile measurement

Quadratic Phase-Modulated Hard RF Pulse: Although the above reconstruction algorithm is able to solve the modeled inverse problem efficiently, the zero crossings of the *sinc* excitation profile would cause the system matrix A to be singular and the inverse problem to be ill conditioned. To eliminate the zero crossings, a quadratic phase is modulated to the RF pulse waveform: $B_1(t) = b_1 e^{i2\pi\beta\left(\frac{t}{\tau}\right)^2},\ |t| \le \frac{\tau}{2}$ (4), where β controls the amount of quadratic phase. The excitation profile can be computed by numerical Bloch equation simulation. To confirm the theoretical excitation profile, we propose a simple pulse sequence for its measurement (see **Fig. 1b**). Suppose the signals acquired by the first and second acquisitions are S_1 and S_2, respectively, the excitation profile $p(f)$ is calculated as: $p = \frac{FT^{-1}(S_1)}{FT^{-1}(S_2)}$ (5). As shown in **Fig. 2**, the quadratic phase-modulated pulse has a flatter excitation profile than hard pulse. More importantly, no zero-crossing point occurs even when the pulse duration is four times that of the dwell time.

Simulations: A 2D Shepp-Logan phantom was used to generate the simulated data with additive Gaussian complex noise. The pulse duration τ was varied from one to four times the dwell time d of 5 µs. Other parameters were: T/R switch dead time = 70 µs, 300 half radial projections, and image matrix size = 128^2. The images were reconstructed with and without the correction algorithm from the simulated noisy *k*-space data.

Experiments: The head of a 40 year-old healthy male volunteer was scanned with PETRA using a 4-channel head coil. Scan parameters were: 1.17 mm isotropic voxel size, matrix size = 256^3, 50,000 half-projections, FA = 5º, TR/TE = 10 ms/85 µs, 5 µs dwell time. Both rectangular and phase-modulated excitation pulses were used for excitation with 20 µs duration. Images from a GRE sequence with the same resolution were used for comparison.

Results- The simulated images with varying pulse durations and constant dwell time are shown in **Fig. 3**. As the pulse duration increases, the excitation bandwidth becomes narrower, resulting in more severe image artifact in the uncorrected image (**Figs. 3a-c**). The corrected images with hard pulse excitation eliminate the artifacts within the main lobe of the sinc-shaped profile, indicated by the red dashed circle. However, residual artifacts are visible in the region outside the circle (**Fig. 3f**). The reconstructed images with phase-modulated pulse excitation in **Figs. 3g-i** effectively correct the artifacts even in the region outside the first zero crossing of the *sinc* function. **Fig. 4** compares *in vivo* ZTE brain images with and without correction. While no residual artifact appears in the regions inside the first zero crossings of the *sinc*-shaped profile indicated by the dashed circles, the noise amplification due to the inversion of a singular system matrix creates artifacts in the corrected images with hard pulse excitation. In contrast, artifacts are eliminated with quadratic-phase pulse excitation yielding image quality comparable to the GRE sequence (**Figs. 4g-h**).

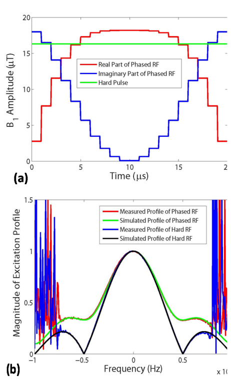

Fig. 2 (a) RF pulse waveforms and (b) their excitation profiles

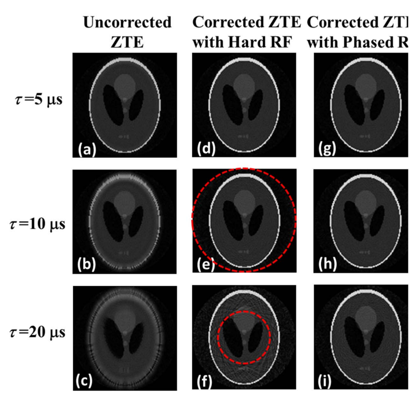

Fig. 3 Simulated 2D phantom images

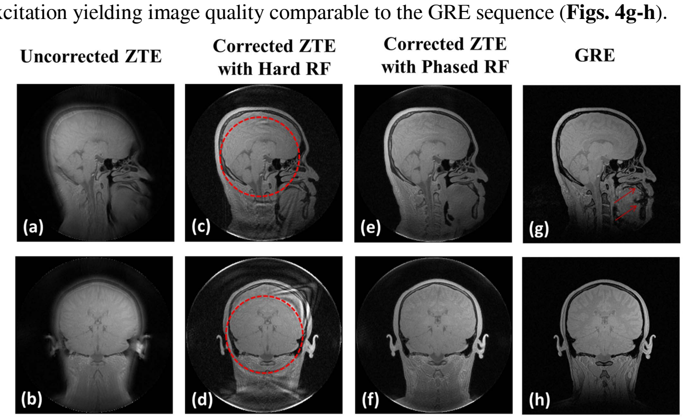

Fig.4 In vivo ZTE brain images

Conclusions- In conclusion, an effective approach integrating quadratic-phase modulated RF excitation and iterative reconstruction for correcting artifacts caused by the heterogeneous excitation in ZTE imaging is presented. The new method has potential to establish ZTE imaging as a routine pulse sequence for visualization and quantification of short-T_2 tissue constituents.

References: 1. Wu Y et al. MRM2007:554-67; 2.Grodzki et al. MRM2012:510-518; 3. Grodzki et al. JMR2012:61-7.

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