Parallel Transmission Three-Dimensional Tailored RF (PTX 3DTRF) Pulse Design for Simultaneously Recovering Multi-slice Signal Loss at 7T

Hai Zheng[1], Tiejun Zhao[2], Yongxian Qian[3], Claudiu Schirda[3], Tamer Ibrahim[1,3], and Fernando Boada[1,3]
[1]*Bioengineering, University of Pittsburgh, Pittsburgh, Pennsylvania, United States,* [2]*Siemens Medical Solutions USA, Pittsburgh, Pennsylvania, United States,*
[3]*Radiology, University of Pittsburgh, Pittsburgh, Pennsylvania, United States*

Introduction: In recent years, ultra high magnetic field (UHF) MRI has been used to depict fine anatomy previously unattainable at lower field strengths. Unfortunately, other previously established MRI applications, such as fMRI, have not fared as well due to the confounding effects from increased through-plane susceptibility-induced (SI) signal loss and/or increased physiological "noise". SI artifacts manifest as geometrical distortions and/or signal loss near important functional areas of the brain such as the orbital frontal and inferior temporal cortices [1], and severely hinder the effectiveness of UHF fMRI studies. Several approaches have been proposed to recover the susceptibility-induced signal loss. The original three-dimensional tailored RF (3DTRF) [2] and its derivative methods [3,4] proved very effective, albeit at the expense of unpractical RF pulse lengths. The introduction of parallel transmission (PTX) has provided an effective means to shorten RF pulse length without sacrificing the excitation performance [5,6] in many single-slice studies. In this study, we demonstrate a fast and robust approach for multi-slice signal recovery during whole-brain fMRI at UHF.

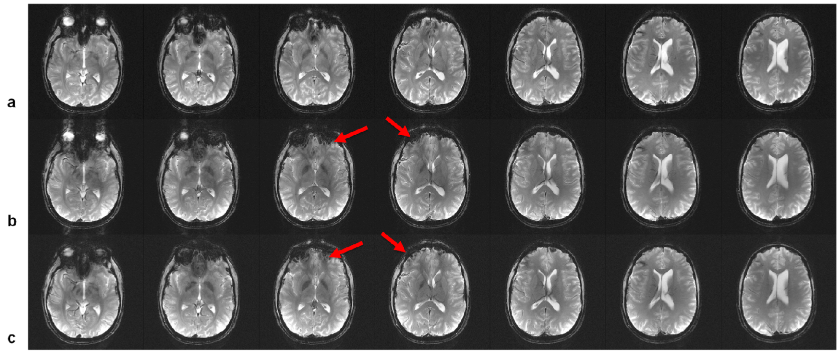

Figure 1 Multi-slice excitation with GRE sequence on one subject using (a) SINC pulses, (b) regular method and (c) time-interpolation method.

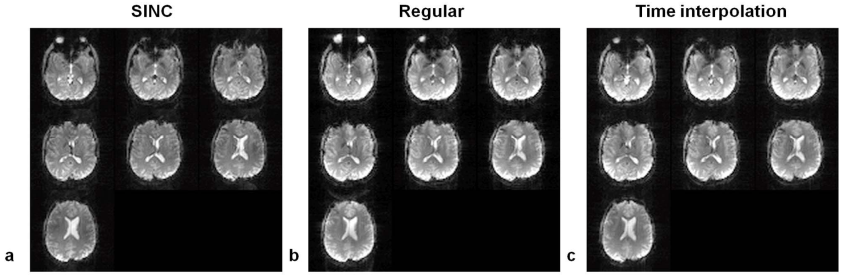

Figure 2 Multi-slice excitation with EPI sequence on one subject using (a) SINC pulses, (b) regular method and (c) time-interpolation method.

Method: The 3DTRF pulse design method recovers SI signal loss via pre-compensation of the through-plane phase variation during the RF pulse excitation. We use the derivations in Ref. [3] to calculate the pre-compensation phase, which is the negative of the phase variation due to an inhomogeneous main magnetic field with frequency offset Δf. Assuming the slice location z_0 is excited with echo time of T_E, the through-plane differential phase variation that is responsible for signal loss at in-plane location (x,y) can be described as the follows,

$$\phi(x,y,z;z_0) = -2\pi\cdot T_E\cdot[\Delta f(x,y,z) - \overline{\Delta f}(x,y;z_0)] \qquad (1)$$

$$D_{comp}(\mathbf{r},z_0) = D_{orig}(\mathbf{r},z_0)\cdot p(z-z_0)\cdot \exp(-i\cdot\phi(\mathbf{r},z_0)) \quad (2)$$

where $\overline{\Delta f}$ is the mean frequency offset of field maps for multiple slices; p(z) is the slice profile; D_{orig} and D_{comp} are the original and precompensated desired patterns at each slice, respectively. The dephasing phase patterns are, as customary, calculated from main magnetic field maps.

The multi-slice RF pulse design for signal recovery is an extension of the previously introduced formulation in combination with PTX. To control the excitation at a set of N different slices, we extend the set of equations in Ref [5] and concatenate the desired patterns $D_{precom}\{D_{Slice1},\ldots,D_{SliceN}\}$ in Eq. (2). Using this notation, we can formulate the following concatenated equation for multi-slice signal recovery,

$$\begin{bmatrix}[D_{slice1}]\\ [D_{slice2}]\\ \vdots\\ [D_{sliceN}]\end{bmatrix}_{z_n} = \begin{bmatrix}[S_{slice1}A_{slice1}]\\ [S_{slice2}A_{slice2}]\\ \vdots\\ [S_{sliceN}A_{sliceN}]\end{bmatrix}_{z_n} \times B_{1,z_n} \qquad (3)$$

where z_n (n=1,…,N) is the location of the slice-selective peak, B_1^+ is the spatial maps of the B_1 field for all slices $S_{total}\{S_{Slice1},\ldots,S_{SliceN}\}$ and $A_{total}\{A_{Slice1},\ldots,A_{SliceN}\}$ is the encoding matrix. The RF pulses required for signal recovery at slice location of z_n can then be efficiently solved via Conjugate Gradient optimization. This process is repeated for each location by shifting the location of excited peak (z_n) from slice 1 to slice N. In other words, the slice selection profile $p(z-z_0)$ is modified according to the location of the excited peak. Because the concatenated matrix on the right side of Eq. (3) does not change with the excitation profile, fast parallel computation can be implemented via the use of multiple CPUs. All human brain studies (N=5) were performed on a 7T whole body scanner equipped with a PTX extension (Siemens AG, Erlangen, Germany). Multi-slice B_1^+ maps were acquired with a novel fast B_1^+ mapping method introduced by Zhao *et al* [7]. To demonstrate the potentiality of the proposed multi-slice signal recovery method, the technique was employed with a flyback fashioned five-rung fast-kz trajectory to obtain RF pulses that uniformly excite Gaussian-shaped slice profiles with the full width half maximum (FWHM) of 5mm and flip angle=15° (TE=16ms). In our pulse design, we have two schemes of PTX 3DTRF method in terms of the gradient dwell time (GDT): the regular method with GDT of 10us and the time-interpolation method with GDT of 5us. RF design was implemented in Matlab R2011a on a Linux PC computing platform running two 2.33GHz quad-core Intel Xeon processors. For the regular method, 5mins were required to calculate the RF pulses for 7 slices using high-resolution B_1^+ and field maps from 21 slices. The corresponding computational time for the time-interpolation method was 7mins due to its higher sampling rate. The resulting RF pulse durations were 8.52ms and 6.13ms, respectively.

Results and Discussion: For the excitation of routinely used SINC pulses (Fig. 1a), significant signal loss can be observed at multiple slice locations. With the use of PTX 3DTRF(Figs. 1b and 1c), signal loss is simultaneously and precisely recovered at different regions across multiple slice locations. The improvement in signal recovery is more evident with the use of time-interpolation method due to its shorter pulse duration. Remarkably, PTX 3DTRF pulses can be effective in recovering signal loss at global regions not only orbital-frontal lobe regions, where the solid arrows are indicated. When EPI sequence is employed in Figure 2, visual inspection of multiple slices indicates that both regular and time-interpolation methods of PTX 3DTRF have successfully recovered the signal loss. Moreover, from the results on subjects with severe field inhomogeneities (not shown), time-interpolation method proves to be more effective and robustness at the regions of large frequency offsets albeit at the expense of increased computational demand.

Conclusions: We have successfully presented a novel excitation strategy to recover the susceptibility-induced signal loss at multiple slice locations via through-plane phase precompensation and parallel transmission at ultra high field. This is the first demonstration the 3DTRF method in conjunction with parallel transmission technique can be effective to recover the signal loss at ultra high field. This is also the first time to prove the through-plane phase precompensation method to globally and precisely recover the signal loss of different regions at multiple slice locations. Robustness and reproducibility are proved by scanning multiple subjects (N=5) and multiple times on one subject (two of the five subjects were scanned twice, respectively). Further investigation will focus on proving the PTX 3DTRF pulses are beneficial for increasing the BOLD contrast and sensitivity to brain activations during fMRI experiments.

Reference: [1] Lipschutz et al., Neuroimage 2001;13:392-398. [2] Stenger et al., MRM 2000;44:525-531. [3] Yip et al., MRM 2006;56:1050-1059. [4] Yip et al., MRM 2009;61:1137-1147. [5] Grissom et al.,MRM 2006;56:620-629. [6] Zheng et al., MRM 2011;66:687-696. [7] Zhao et al., ISMRM 2011 (Abstract 2925).