Time-interleaved parallel imaging approach to separation of simultaneously excited slices

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Introduction: Simultaneous excitation of multiple slices helps reduce the time needed to acquire a fixed number of slices [1]. Recently its utility has been demonstrated in improving the temporal resolution of echo-planar functional MRI and for reducing scan time for diffusion spectrum imaging of the whole head [2,3]. Slices that are excited simultaneously by a multi-band excitation can be unaliased by exploiting coil sensitivity differences between these slice locations and calibration data can be acquired from a separate acquisition where each slice is excited separately [4,5]. But this involves additional prescan, and matching of the slice prescription to slice locations excited by the multiband RF pulse. Previously time-interleaved approaches such as tGRAPPA have been proposed for multi-phase scans where different sampling patterns are employed in each temporal phase, and calibration data is collected from neighboring k-space lines of neighboring phases [6]. In this work we will present a multi-band excitation scheme that translates to a similar reconstruction problem, even though the same sampling pattern is employed in each temporal phase.

Theory: If N slices are excited simultaneously with N different excitations, the phase of each slice can be incremented across the excitations such that the slices can be separated by some linear combination of the N signals, for ex. Fourier transform (FT) or inverse Hadamard transform. We propose to acquire data with only one of these N excitation waveforms, and to synthesize the rest N-1 waveform datasets from the first waveform using parallel imaging principles. Calibration data is collected from the previous N phases in each of which a different excitation waveform is employed. For the sake of simplicity, let us discuss the case of two slice excitation only and compare it to conventional tGRAPPA with acceleration factor R=2. The excitation scheme is shown in Figure 1. The phase of the second slice is inverted by the second waveform (Figure 1) so that the individual coil images obtained from these 2 waveforms are $\mathbf{I_1} = f_1 + f_2$ and $\mathbf{I_2} = f_1 - f_2$ respectively, where f_1 and f_2 are images of slices 1 and 2. f_1 and f_2 can be written as $S_1\cdot\rho_1$and $S_2\cdot\rho_2$ where S_1, S_2 are the coil sensitivities at slice locations 1 and 2, and ρ_1, ρ_2 are the "ideal" images of the slices. In a matrix form

$$\begin{pmatrix} S_1 & S_2 \\ S_1 & -S_2 \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} = \begin{pmatrix} I_1 \\ I_2 \end{pmatrix} \quad [1a]$$

For the tGRAPPA analogy with acceleration R = 2, if we denote the set of odd k-space lines 1, 3, 5, … as block 1 and the set of even lines 2, 4, 6, … as block 2, and their corresponding images as B1 and B2 respectively, an equation similar to [1a] can be written

$$\begin{pmatrix} S_1 & S_2 \\ S_1 & -S_2 \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} = \begin{pmatrix} B_1 \\ B_2 \end{pmatrix} \quad [1b]$$

Where S_1 and the ρ_1 represent the coil sensitivity and the "ideal" image respectively, S_2 and ρ_2 are S_1 and ρ_1 shifted by FOV/2 in the phase encode direction. The similarity between [1a] and [1b] shows that k space data of I_1 and I_2 can also be arranged in a block form and reconstructed as in tGRAPPA.

Method: Phantom and in vivo experiments were conducted using an echo-planar sequence incorporated with multiband RF pulse, with a 32 channel head array (Nova Medical, USA) on a GE 3.0 T MR750 scanner (Waukesha, WI). Three slices 30 mm apart were simultaneously excited. In each scan, 12 time frames were acquired. Slice t-ARC, a time-interleaved parallel imaging reconstruction based on ARC [7] was implemented. Once the data corresponding to all the waveforms were synthesized, slices were separated in image space by Fourier transform along the waveform direction.

Figure 1

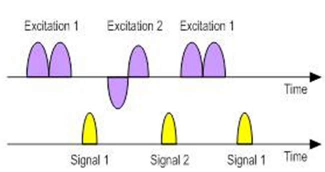
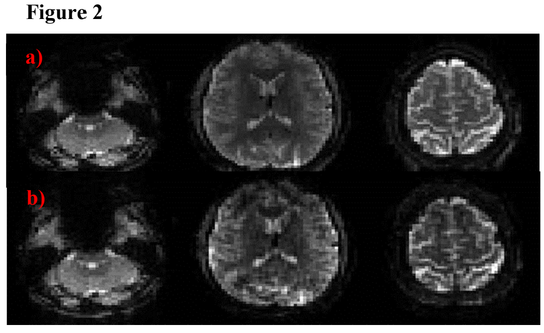


Figure 2



Results and Discussion: Figure 2a) shows three slices that were excited separately by a single-band RF pulse. Figure 2b) shows slice t-ARC results for the same 3 slices excited by the 3 band RF pulse, for the 9th time frame. Calibration data was collated from the first 3 phases. As can be seen, the slices have been unaliased completely. This technique can be combined with in-plane acceleration to further reduce acquisition time or to shorten echo-train length. By using this time-interleaved approach, slices are co-localized between calibration and the accelerated acquisition. In case of a time series acquisition such as functional MRI, there is also the flexibility of re-estimating the reconstruction kernel periodically throughout the scan for a more robust reconstruction and to improve the calibration data by averaging previous time frames. Since the same read-out sampling pattern is employed for all temporal phases, the proposed method should be more robust to EPI phase errors compared to traditional tGRAPPA methods.

References: (1) Breuer F et al, MRM 53: 684-691, 2005 (2) Moeller S et al, MRM 63: 1144-1153, 2009 (3) Feinberg D.A. et al, Plos One, 5(12), 2010 (4) M. Blaimer et al, JMRI 24, 444 (2006) (5) Setsompop K et al, MRM 0?1-15,2011 (6) F. Breuer et al, MRM 53, 981-985 (2005) (7) Beatty P.J, ISMRM 2007 #1749