

## Multi-frequency Parallel Transmit for Multi-Slice Scan Acceleration

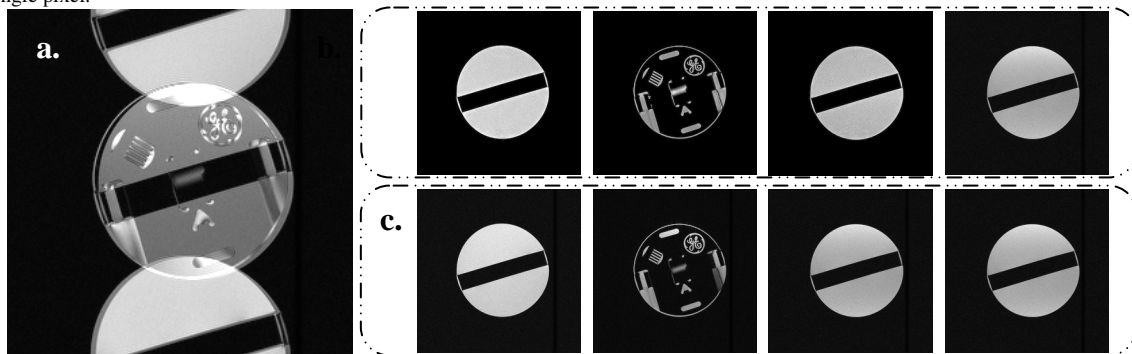
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**INTRODUCTION:** The large majority of current applications for parallel transmit systems in MRI have focused on their capabilities to address the problem of  $B_1$  inhomogeneity. Here we demonstrate a novel application of parallel transmit for scan time acceleration. A typical parallel transmit system consists of multiple independently controlled RF amplifiers, each driving individual or multiple RF coils. Here, the multiple transmit channels are used to produce RF simultaneously at multiple carrier frequencies. In combination with a spatial encoding gradient, RF at each carrier frequency is used to select an individual slice in the sample. This results in multiple slices being simultaneously excited. Signal from the multiple slices can then be simultaneously acquired, and each slice reconstructed from the aliased image by a variety of methods (1,2).

**METHODS:** Multi-slice excitation was carried out on a GE Signa Excite HD 3T system equipped with 8-channel parallel transmit connected to a 16-rung whole-body TEM array. Signal reception was carried out with an 8-channel receive coil torso array (USA Instruments). The eight RF channels were used to transmit identical, slice-selective low flip angle SLR pulses simultaneously at four carrier frequencies with 10 kHz separation. These excited four 5 mm thick sagittal slices with 3.5 cm separation, in an otherwise typical gradient echo sequence. Two RF transmit channels were assigned to each slice based on the proximity of the coil rungs to the slice, to minimize  $B_1$  inhomogeneity as well as RF power. An optimal RF phase shim was calculated for the two transmit channels assigned to each slice. The RF phases were optimized such that the two channels selecting each slice would produce a uniform  $B_1$  field, and a uniform excitation phase for all slices. The uniform excitation phase between slices is necessary so the magnetization excited in all four slices adds coherently. The transmit RF phase shim and coil sensitivity profiles for the 8-channel receive array were calculated from a set of two gradient echo images acquired for each of the four slices with each of the two RF channels per slice transmitting individually.

Signal from the four slices was acquired simultaneously, with all four slices aliasing into one image. The four slices were then reconstructed by SENSE from the eight receive coils. The total complex signal acquired in coil  $m$  in a single image pixel ( $S_m$ ) is given by:  $C_{m,1}X_1 + C_{m,2}X_2 + \dots + C_{m,N}X_N = S_m$ , where  $C_{m,n}$  is the complex receive sensitivity of coil  $m$  to slice  $n$ , and  $X_n$  is the complex signal from each slice. The signal coming from each of the  $N$  slices can be reconstructed by  $\mathbf{X} = \mathbf{C}^{-1} \cdot \mathbf{S}$  (2,3). Every other slice was shifted by FOV/2 in the phase-encoding direction by alternating the phase of the RF pulses for those two slices by  $\pi$  on every other excitation (4). The FOV shift gives a larger difference in the receive coil sensitivities for the locations in adjacent slices that alias into a single pixel.



**Figure 1:** (a.) Aliased four-slice gradient echo image, pre-SENSE reconstruction (TR = 50 ms, TE = 12 ms, FOV = 20 x 20 cm, in plane resolution = 256x256, slice thickness = 0.5cm, inter-slice distance = 3.5 cm, inter-slice RF excitation frequency = 10 kHz). (b.) The four SENSE-reconstructed slices. (c.) Individually acquired gradient-echo images of the four slices, where each slice is excited with two transmit channels as in the multi-frequency accelerated scan.

**RESULTS AND DISCUSSION:** Simultaneous excitation of multiple slices has been demonstrated previously with a single RF channel, however significant advantages are gained by transmitting with a parallel transmit system. At low flip angles, or with sufficient distance between frequency bands, a multi-banded RF excitation can be produced by linearly adding two or more single-banded RF pulses. Under the linear conditions of low flip angle and/or sufficient distance between frequency bands, this multi-frequency RF pulse will have the base pulse shape, modulated by the frequency difference between excitation bands. This requires the amplifier to produce a very highly time-varying RF pulse shape. Typical proton RF amplifiers for clinical field strengths have a constant gain over a range of tens of kHz in producing a pulse shape (20 kHz for the 8kW Analogic amplifiers used in this work). Compounding the problem, a multi-frequency pulse selecting  $N$  slices would need approximately  $N$  times the  $B_1$  power of a single slice. Single channel multi-frequency excitation operates in a limited enough frequency range that the frequency bands do not add linearly, giving unwanted signal excitation between slices (5). RF pulses for a single channel are thus typically designed by SLR optimization for the desired multi-slice profile.

A parallel transmit system significantly simplifies multi-frequency RF pulse design. In any multi-frequency excitation- either by single or multiple channels, the farther apart the frequency bands, the closer the frequency response of the composite RF pulse gets to the linear addition of the frequency responses of the single-band pulses. The range of the RF pulse frequencies are determined here by the carrier frequency ranges of the RF amplifiers- in the range of hundreds rather than tens of kHz (720 kHz for the 8kW Analogic amplifiers used in this work). A multi-band excitation can be produced easily with a parallel transmit system by transmitting an identical pulse shape on each channel or combinations of channels at multiple carrier frequencies. The larger frequency range gives clean slice excitation without any further RF pulse optimization.

Multi-slice parallel transmit can be used to reduce SAR as well as scan time. Single coils, or subsets of coils in a parallel transmit system can be used to locally excite individual volumes. Here the channels assigned to excite each slice were chosen to minimize the total RF power for the four-slice excitation. Furthermore, multi-slice excitation can be used to reduce SAR in spin echo and a variety of other sequences as well- each refocusing/inversion/chemical shift selective, etc. pulse would act on multiple slices at once.

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