Spectrum Optimized Parallel Excitation Pulse Design

Y. Zhu[1], J. E. Piel[1], R. O. Giaquinto[1], R. D. Watkins[1], T. K. Foo[1], A. B. Kerr[2], J. M. Pauly[2], F. Wiesinger[3], M. Vogel[3], and P. Gross[3]

[1]GE Global Research Center, Niskayuna, NY, United States, [2]Stanford University, Stanford, CA, United States, [3]GE Global Research Center, Munich, Germany

Introduction: While symmetry exists between parallel receive (Rx) and parallel transmit (Tx), their practice face different challenges. In sharp contrast with parallel Rx, where k-space coverage is typically carried out in segments, one per TR period, possible segmentation of a parallel excitation pulse over multiple TR periods represents a highly undesired compromise. A stringent constraint on the maximum length of the excitation pulse in one TR, as imposed by such factors as relaxation and off-resonance, thus considerably limits the total coverage of the excitation k-space, and may call for unique approaches to the design of accelerated parallel Tx pulses. A new design method is introduced. It optimizes the spatial spectra of the parallel Tx pulses to ensure excitation profile quality, while accommodating the k-space coverage constraint and possibly further considerations that may include SAR / RF power. Validation results obtained in full-fledged parallel transmit experiments are presented.

Methods and Results: In terms of excitation profile, we note that discontinuities at object boundaries of acquired B_1 maps as well as perturbations to the B_1 mapping process often lead to compromises in aliasing lobe suppression. This problem, to some extent, has a counterpart in parallel Rx MRI, which faces the significant issue of residual aliasing artifact at low spatial resolution (1). The problem, however, can be effectively addressed by incorporating a new *spectrum optimization* idea into the design of parallel Tx pulses. The idea originated from the image space perspective (2,3) that relates the design of parallel Tx pulses to the Fourier transform of spatially weighted versions of the target excitation profile. This perspective leads to the recognition and analysis of a common issue with existing parallel Tx pulse design methods — in the absence of proper measures (explicit or implicit) these methods tend to produce parallel Tx pulses with excessive energy at high spatial frequencies, rendering the pulses sensitive to imperfections in calibrated B_1 maps and causing possible compromises in excitation profile fidelity.

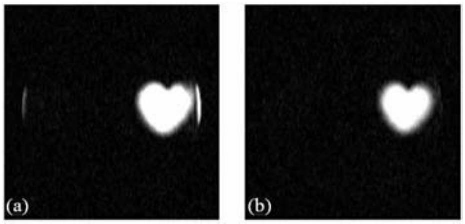

Fig. 1 Results from parallel excitation of a uniform disc phantom at 4x acceleration using (a) the original and (b) the spectrum-optimized designs, both targeting a heart-shaped profile at the same location in the disc.

The spectrum optimization idea could be incorporated into a variety of parallel Tx pulse design methods. Consider, as an example, an image space-based design method (3). The requirement of creating the target profile (i.e., producing a main lobe matching the profile and simultaneously suppressing aliasing lobes) translates into constraints:

$$\mathbf{C}_{all}\,\mathbf{f}_{all} = \mathbf{u}_{all}\,, \qquad [1]$$

which is a system of linear equations that pools all equations of type $\mathbf{C}_{p1,p2}\,\mathbf{f}_{p1,p2}=\mathbf{u}_{p1,p2}$ (3). The entries of matrix $\mathbf{C}_{all}$ and vector $\mathbf{u}_{all}$ are, respectively, properly sampled values of the B_1 maps and the target profile. The entries of vector $\mathbf{f}_{all}$ are values of the image-space periodic patterns, which are directly related to the parallel RF pulse waveforms through Fourier transforms. Let $\mathbf{F}$ be the matrix representation of the Fourier transforms. The new pulse design method achieves spectrum optimization with a constrained optimization:

$$\text{minimize } \|\mathbf{W}\mathbf{F}\mathbf{f}_{all}\| \text{ subject to } \mathbf{C}_{all}\mathbf{f}_{all} = \mathbf{u}_{all} \qquad [2]$$

In Eqn.2, $\mathbf{W}$, a positive (semi)definite matrix, is introduced for tailoring the RF pulses' spatial spectra. With $\mathbf{W}$ set to be a diagonal matrix, for example, a relatively large/small entry on $\mathbf{W}$'s diagonal then penalizes/rewards the inclusion of a corresponding spectral component of a pulse, thus reducing/enhancing the component in the design outcome. For one type of low-pass filtering, where it is simply desired to exclude spectral components above a given spatial frequency, least squares solution to the following is acceptable as an alternative:

$$\mathbf{C}_{all}\mathbf{E}\,\mathbf{a}_{all} = \mathbf{u}_{all}\,, \qquad [3]$$

where product $\mathbf{E}\,\mathbf{a}_{all}$ expresses the image-space periodic patterns with weighted sums of sampled spatial harmonics, and vector $\mathbf{a}_{all}$ collects coefficients of the spatial harmonics.

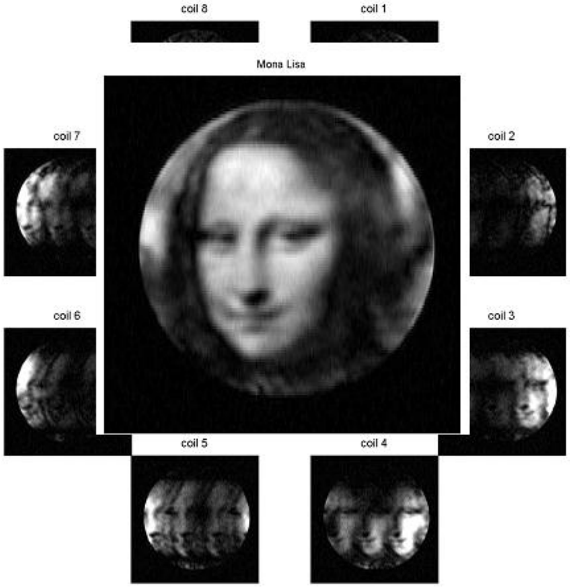

Fig. 2 Results from exciting a uniform disc phantom with a 5.7-msec 2D parallel excitation (center) and with individual channel excitations (perimeter).

The spectrum optimization can be integrated with further optimization based on SAR or RF power considerations (2,3). For example, Eqn.2 can be extended to give:

$$\text{minimize } \mathbf{f}_{all}^{*}\boldsymbol{\Phi}_{all}\mathbf{f}_{all} + \alpha\|\mathbf{W}\mathbf{F}\mathbf{f}_{all}\| \text{ subject to } \mathbf{C}_{all}\mathbf{f}_{all} = \mathbf{u}_{all} \qquad [4]$$

where $\mathbf{f}_{all}^{*}\boldsymbol{\Phi}_{all}\mathbf{f}_{all}$ integrates all $\mathbf{f}_{p1,p2}^{*}\boldsymbol{\Phi}\mathbf{f}_{p1,p2}$'s (3) and tracks total RF power dissipation. By forming a single metric with a weighted sum of two (α is a positive scalar), this formulation effects a balanced optimization of both SAR / RF power and pulse spectra.

The new pulse design method was evaluated in full-fledged parallel Tx experiments, where an eight-channel parallel Tx array (4) was used to excite a uniform disc phantom oriented in the axial plane and a body coil was used for receive. A 2DFT gradient-echo sequence was used to acquire projection images (in z), which mapped magnetization distribution in a 30-cm FOV. A first phantom study compared 4x-accelerated parallel excitation pulses designed with the method of Eqn.1 and the new method incorporating low-pass filtering. Results suggested significant profile improvements with the new method (Fig.1). For example, the residual aliasing lobe effects (Fig.1a), commonly produced by parallel excitation pulses from other conventional design methods too, are well suppressed with the new method.

The improvements offered by the new proposed method is important in ensuring fidelity of parallel excitation profiles, including full FOV (e.g., uniform) as well as local ROI profiles. As a demonstration, a 5.7-msec parallel excitation pulse (4x acceleration; EPI trajectory with peak gradient strength < 1.6 gauss/cm) designed with the new proposed method was evaluated in a study where the target excitation pattern was a low-resolution rendering the *Mona Lisa* by Da Vinci. Accurate excitation profile control over the full FOV, which is required by a satisfactory creation of the chosen target profile, was achieved (Fig.2). The emphasis on *spectrum optimization* in the proposed method improves the robustness of parallel Tx pulses against B_1 map imperfections, including discontinuities in the maps and perturbations due to noise, local errors or minor subject motion.

1. U. Dydak, et al., *MRM* 46:713-722, 2001. 2. Y. Zhu, *MRM* 51:775-784, 2004. 3. Y. Zhu, *14th ISMRM*, p 599, 2006. 4. Y. Zhu, *14th ISMRM*, p 122, 2006.