Transmit-PILS RF pulse design for small-tip-angle parallel excitation

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INTRODUCTION: Several methods exist for the design of small-tip-angle RF pulses in parallel excitation (1-4). These methods either design pulses iteratively, as in Refs (1,3), or non-iteratively, as in Refs (2,4). Iterative design methods are based on the solutions of large systems of equations using gradient-based algorithms (e.g., the Conjugate Gradient algorithm), and can require high computation times. In contrast, current non-iterative pulse design methods require less computation, but are restricted to echo-planar trajectories. We introduce a non-iterative parallel pulse design technique that is applicable to general trajectories, and is the excitation analogue of PILS parallel image reconstruction (5). We demonstrate that the method, dubbed 'transmit-PILS', produces accurate RF pulses with less computation than iterative methods.

METHODS: Transmit-PILS reduces computation compared to iterative methods by dividing parallel pulse design for R coils into R sub-problems that are solved individually using conjugate-phase (CP) pulse design (6). We begin by defining a 'Region-Of-Influence' (ROInf($\mathbf{x}$)) for each coil r that contains most of the energy in that coil's transmit sensitivity. For pulse design using spiral trajectories, we constrain ROInf($\mathbf{x}$) to be a circular binary mask whose diameter is the excitation FOV (XFOV) of the trajectory, while ROInf($\mathbf{x}$) for echo-planar pulse design is a rectangular mask whose width is the XFOV in the blipped (undersampled) direction, and whose height covers the entire FOV. In both cases, for each coil r we center ROInf($\mathbf{x}$) about a centroid defined as:

$$\bar{\boldsymbol{x}}_r \triangleq \sum_{i=1}^{N_s} \boldsymbol{x}_i \left(|s_r(\boldsymbol{x}_i)| \left(\sum_{i=1}^{N_s} |s_r(\boldsymbol{x}_i)| \right)^{-1} \right)^{0.9},$$

where N_s is the number of spatial points over which the sensitivity is defined, $s_r(\mathbf{x})$ is coil r's transmit sensitivity, and 0.9 is a parameter chosen to yield appropriate sensitivity coverage and overlap between ROInf($\mathbf{x}$)'s. Given a desired excitation pattern $d(\mathbf{x})$, we define a coil-specific desired pattern $d_r(\mathbf{x})$ as:

$$d_r(\boldsymbol{x}) \triangleq s_r^{-1}(\boldsymbol{x})\, \mathrm{ROInf}_r(\boldsymbol{x}) \left(\sum_{r'=1}^{R} \mathrm{ROInf}_{r'}(\boldsymbol{x}) \right)^{-1} d(\boldsymbol{x}),$$

where $(s_r(\mathbf{x}))^{-1}$ compensates for coil r's transmit sensitivity pattern, and $\left(\sum_{r'=1}^{R} \mathrm{ROInf}_{r'}(\mathbf{x})\right)^{-1}$ is included to account for overlap between ROInf($\mathbf{x}$)'s. Once $d_r(\mathbf{x})$ has been determined for each coil, we design the pulses using the CP method, i.e., via FFT and reverse-gridding, followed by k-space sampling density compensation.

We verified our method in simulation. Pulses were designed using an 8-channel transmit head array whose transmit sensitivities were obtained by FDTD simulation (7). The desired pattern was a smoothed 10 x 5 cm rectangle, defined on a 64 x 64 grid of FOV = 24 cm. The simulation trajectory was a spiral with resolution 0.75 cm and XFOV = 14 cm, corresponding to a speedup factor of 1.7 and pulse length of 3.9 ms. CP pulse designs used non-uniform fast Fourier transforms (NUFFT's) (8) and sample density compensation (9). For comparison we also designed pulses using the iterative parallel pulse design method of (3). Final excitation error was determined by Bloch simulation of the pulses.

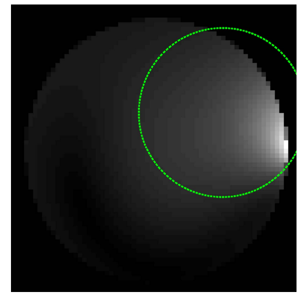

Figure 1. ROInf($\mathbf{x}$) (dashed green line) for a single coil in the array, superimposed on the coil's transmit sensitivity.

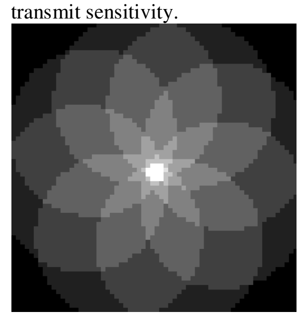

Figure 2. Sum of ROInf($\mathbf{x}$)'s for all coils in the array.

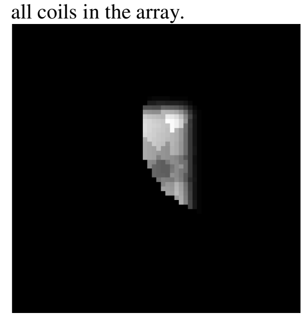

Figure 3. Coil-specific desired pattern $d_r(\mathbf{x})$ for the coil in Fig 1.

RESULTS: Figure 1 shows the ROInf($\mathbf{x}$) superimposed on the transmit sensitivity of a single coil in the array. The region is positioned near the coil, so that it includes the highest energies in the coil's sensitivity. Figure 2 shows the sum of ROInf's for all coils in the array; there is significant overlap near the object's center. Figure 3 shows $d_r(\mathbf{x})$ for the coil of Figure 1, and we can see that the 10 x 5 cm rectangle (Figure 4a) has been multiplied by that coil's region of influence. We also see modulation of the pattern created by division with the overlap term. Figure 4 shows the desired (4a) and excited (4b) transverse magnetization. The NRMSE of the designed pulses is 0.11. CP pulse design required 8 NUFFT operations. In comparison, pulses designed using the iterative method of Ref. (3) required 3 iterations to reach a lower NRMSE of 0.08, at a cost of 48 NUFFT operations.

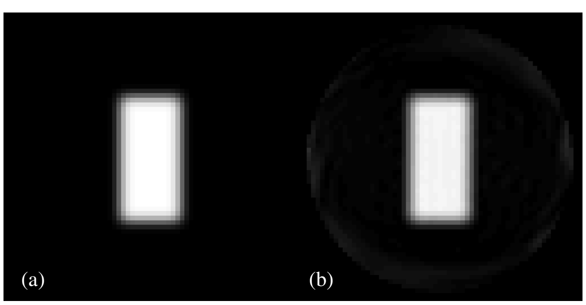

Figure 4. Desired (a) and excited (b) transverse magnetization patterns excited by transmit-PILS pulses. NRMSE between the patterns is 0.11.

CONCLUSION: We have introduced a new pulse design method for parallel excitation that requires less computation than iterative methods, but is not restricted to a certain class of trajectories. Transmit-PILS is particularly effective at low speedup factors, where aliased excitation is effectively suppressed by low transmit sensitivity magnitudes. The method may also be used to initialize a more computationally expensive iterative method.

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