Ultra-fast Selective RF Pulse Design for Parallel Transmission using Pre-calculated Base Pulses

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Introduction Parallel transmission in high-field (≥ 3T) MRI can improve the B_1 homogeneity (B_1 shimming) as well as speeding up multidimensional RF pulses (Transmit SENSE). However, the calculation of such pulses [1-3] is still rather complex and takes too long for use in a clinical setting, particularly if RF safety constraints are considered [4-6]. This work presents a novel, simple and efficient approach, named fast-pulse (f-pulse), to calculate selective RF pulses for arbitrary target patterns based on pre-calculated base pulses. These pulses can be precalculated and stored in a data base using an arbitrary pulse design algorithm; they can be optimized for SAR or power, and they are valid for a certain k-space trajectory and TX coil arrangement.

Methods For an N-channel TX system, the excited magnetization μ can be written in matrix notation as $\mu = Ab$ [3], where b is the vector of RF samples, and A the Bloch matrix incorporating the B_1 maps of each coil and the k-space trajectory $k(t)$. The RF pulse b must be found such that $\| \mu - P_{des} \|_2 = min$, with the desired excitation pattern P_{des}. For homogeneous B_1, this is fulfilled if $\mu = P_{des} * PSF$ with * denoting the convolution with the point spread function (PSF) of the RF pulses of the selected k-space trajectory. Consequently, a single voxel is excited by the pulse b_δ representing the PSF (see Eq. 1),

$$PSF(x) = \int_0^T b_\delta(t) e^{ixk(t)} dt \quad \text{(Eq.1)} \qquad b^{\dagger}_{\delta_n}(t) = b_{\delta_n}(t) e^{-i\gamma B_0(n)(t-T)} \quad \text{(Eq.2)} \qquad \min_f \left\{ \| \sum_{m=1}^{M} \sum_{n=1}^{N} ([PSF_n \cdot B_{1m}] f_{mn}) - P_{des} \|_2 \right\} \quad \text{(Eq.3)}$$

where T is the total scan duration. For each base pulse $b_{\delta n}$, being the RF pulse exciting PSF_n at spatial position n, an inverse B_0-field correction is applied at each sampling time t (see Eq. 2), where γ is the gyromagnetic ratio. In Eq. 3, NM individual complex scaling factors f_{mn} for each coil m and base pulse $b_{\delta n}$ are chosen such that the superposition of the individual coil excitations reproduces P_{des}, with N voxels in the actual field of excitation (FOX), M coils, and "·" denoting the element-wise multiplication. Due to the locally restricted excitation of base pulses, Eq. 3 is only solved in a pattern ROI, i.e. non-zero regions of the desired excitation, and other regions are inherently not excited. For R=1, f equals the inverse of the coil sensitivities B_{1m} and is calculated by a single matrix multiplication. For R>1, Eq. 3 needs to be solved. However, the size of the problem is a factor $N(1-1/R^2)+(N-\|ROI\|)$ smaller than the general full-FOX pulse calculation.

For the full pulse calculation, as well as for the base pulse calculation, a SAR optimizing pulse design algorithm (l-pulse) [5] is used, which is based on Lagrange multipliers and was set to minimize the whole body SAR for each base pulse. The performance in terms of normalized root mean square error (NRMSE) of f-pulse and l-pulse is compared for a FOX resolution of 32×32, reduction factors R=1-4, and disc-shaped and kidney-shaped excitation patterns. The required calculation time and peak memory of f-pulse and l-pulse is compared for different FOX resolutions, reduction factors R=1 and R=4, as well as different numbers of TX coil elements (4-32).

The phantom experiments were performed on a whole body 3T MRI system (Achieva, Philips Medical Systems, The Netherlands) extended to eight parallel RF transmit channels [7, 8]. For the B_1 mapping, an inverted AFI (Actual Flip Angle Imaging) technique [9, 10] (480×480×60mm³ FOV, 64×64×3 matrix, flip angle = 50°, $TR_1/TR_2/TE$=20/100/2.3ms, transverse slice) was used. Spiral k-space trajectories were used with a numerical FOX matrix size of 32×32 and 48×48 spatial resolution (pixels) and reduction factors R=1 and R=4, respectively.

Results and Discussion The NRMSE for f-pulse is worse than the NRMSE for l-pulse, but still fairly small (Fig. 1). The calculation time versus the number of voxels in the FOX is depicted in Fig. 2a, and the peak amount of required memory in Fig. 2b. For both R=1 and R=4, f-pulse requires less calculation time and memory than l-pulse. The difference in calculation time rises from one order of magnitude for a FOX resolution of 8×8 to two orders of magnitude for 96×96. Calculation times of about 4 sec. and memory consumption below 3.3 GB are achieved for f-pulse for R=4, even for resolutions of 96×96 voxels, demonstrating promising performance for high-resolution applications.

The results of the performance experiments for an increasing number of coils are depicted in Fig. 3. The calculation time is shown in Fig. 3a as a function of the number of coils, where the two curves for each algorithm represent the R=1 and R=4 for f-pulse and l-pulse, respectively. A clear separation for $M \geq 8$ can be seen for the different algorithms. The peak memory usage depicted in Fig. 3b depends linearly on the number of coils for l-pulse. However, for f-pulse the memory usage is independent of the coil number. The pulse calculation of f-pulse compared with l-pulse is about an order of magnitude faster and requires significantly less memory, which is particularly advantageous for an increasing number of coils.

Fig. 4 depicts the excitation pattern of the pulse acquired in an MR experiment with an excitation matrix of 32×32 voxels and a sampling matrix of 128×128 voxels. Using the described f-pulse algorithm, the calculation time was 0.72 sec for the total pulse. Here, loading of the base pulse from hard disk took 0.26 sec., and calculating the pulse took 0.46 sec. The pre-processing step of calculating the generic base pulses, which has to be performed only once for a given trajectory, took 33 min. for R=1 and decreases with increasing reduction factors.

Conclusion In this study, the technical feasibility of a novel method for RF pulse design for parallel transmission is presented. It proposes to split the RF pulse generation process into a time consuming off-line processing step of generic base pulses and an ultra-fast pulse generation step prior to the scan by integrating experiment-specific information. The method was demonstrated in simulations and phantom experiments on an eight-channel transmit 3T MR system. It is of particular interest for large FOX and TX arrays with a high number of elements, potentially enabling future applications, which are currently prohibited by calculation time. With this method, the use of Transmit SENSE pulses in a clinical setting may be improved.

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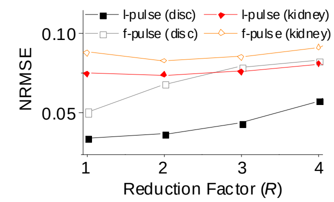

Fig. 1: NRMSE vs. reduction factor. Comparison of NRMSE for different excitation patterns (disc-/kidney-shaped).

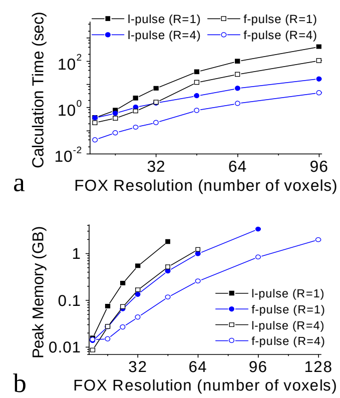

Fig. 2: Time and memory vs. FOX resol. Calculation time (a) and peak-memory usage (b) for RF pulses calculated using l-pulse (black) and f-pulse (blue) for FOX resolutions 8-128, and an NRMSE of 0.1.

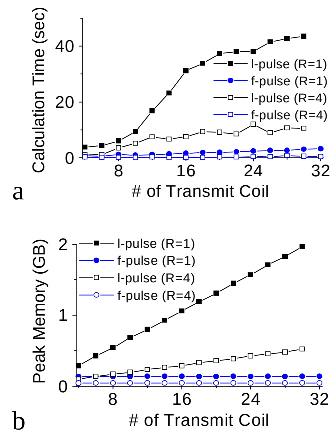

Fig. 3: Time and memory vs. number of TX coils. Calculation time (a) and peak-memory usage (b) for RF pulses calculated using l-pulse (black) and f-pulse (blue), 1-32 Tx coils, and an NRMSE of 0.1.

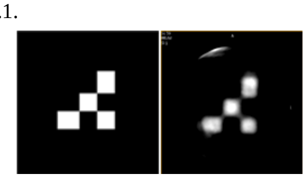

Fig. 4: Experimental verification of f-pulse. Desired excitation (a), and excited pattern (b).