RF pulse design for simultaneous multislice excitation with highly reduced B1 peak amplitude

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INTRODUCTION: Simultaneous multi slice (SMS) excitation is increasingly used to accelerate MR imaging experiments[1,2]. Conventional design approaches, based on a superposition of phase shifted sub-pulses[3] or sinusoidal modulation[1], typically result in a linear scaling of the B1 peak amplitude that easily exceeds RF amplifier constraints. The underlying sub-pulses are often designed based on simplifications of the Bloch equations, e.g. the SLR transform[4]. Using optimal control of the full time-dependent Bloch equations[5] we present its application to the design of low peak-B1 pulses for SMS excitation with an accurate and sharp excitation profile for each slice. Phantom and in-vivo experiments validate numerical Bloch simulations and demonstrate the benefits of using optimized pulses.

THEORY: The optimal control approach consists in minimizing the discrepancy between numerical Bloch simulation and the desired magnetization pattern with an additional cost term to model the power of the RF pulse. A globally convergent trust-region CG-Newton method[6] with exact derivatives via adjoint calculus allows for the efficient computation of optimal pulses.

METHODS: This optimization method is applied to the design of SMS excitation pulses and implemented on a 3T MR scanner (Magnetom Skyra, Siemens Healthcare, Erlangen, Germany). RF pulses for the simultaneous excitation of four, five (not shown) and six equidistant slices are computed in MATLAB and imported into a GRE sequence. To separate aliased slice information in the case of in-vivo imaging, we use the slice-GRAPPA (sG) algorithm[7] with reference scans of 24 phase encoding lines per slice. Since the reconstruction starts to suffer from g-factor problems for more than three slices, we modify the above-described SMS pulses using a CAIPIRINHA-based excitation pattern[8], which alternates two different pulses to achieve phase-shifted magnetization vectors in order to increase the spatial distance of aliased voxels by a factor of FOV/2 for every second slice.

RESULTS AND DISCUSSION: Figure 1 shows the optimized RF pulse for four and six simultaneous slices, each with a linear phase, a flip angle of 25°, a separation of 25mm and a thickness of 5mm. It can be seen that instead of higher amplitudes, the optimization distributes the total RF power more uniformly. Phantom measurements shown in Figure 3 validate the numerical simulations given in Figure 2. Compared to conventional (superposition of single-slice) pulses, the proposed method leads also to a linear increase in total energy with the number of slices, however the peak B1 amplitude stays constant. In particular for six slices, the peak B1 amplitude is reduced by 40% using the optimized pulse, and thus remains within amplifier constraints; by contrast, conventional pulses for more than three slices exceed these constraints (see also Table 1). Figure 4 shows the image reconstruction of a GRE in-vivo experiment using the optimized RF pulses shown in Figure 1. As can be seen in the first column, the pulses lead to the desired excitation pattern in-vivo as well. The second column shows the Cartesian reconstruction of the aliased slices, and the remaining columns show the sG reconstructions, which illustrate the uniform excitation and the applicability of the optimized pulses for in-vivo experiments.

CONCLUSION: Optimal control is a flexible framework for the design of RF pulses with arbitrary slice profiles even in the presence of relaxation effects or large flip angles. The application of optimal control to SMS pulse design reduces peak B1 amplitude, allowing the excitation of a higher number of slices without exceeding amplifier constraints. Furthermore, our approach does not excite magnetization outside the FOV (compared to PINS[9]) and yields, for each slice, the same effective echo-time (compared to a time shifted design[10]) with a linear phase (compared to non-linear phase design[11]). This allows for a simple replacement of standard pulses by optimized pulses in the sequence and is therefore well suited for a wide range of imaging situations in MRI.

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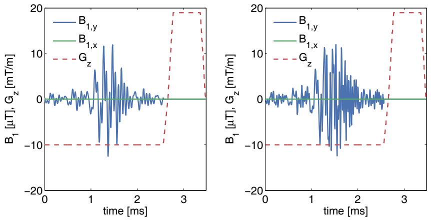

Figure 1: Optimized RF pulse for 4 (left) and 6 (right) simultaneous slices

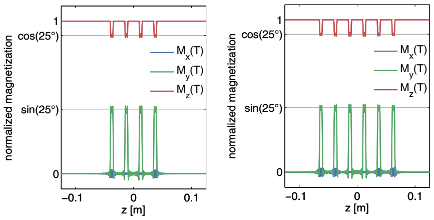

Figure 2: Simulated magnetization (4 and 6 slices)

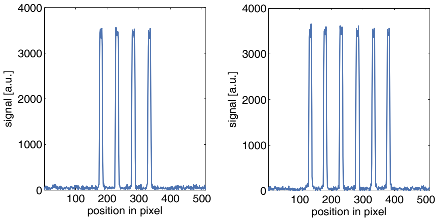

Figure 3: Measured slice profile (4 and 6 slices)

Table 1: Comparison of B1 power and B1 peak of conventional and optimized SMS pulses

	$\|B_{1,y}\|_2^2$ [a.u.]		$\|B_{1,y}\|_\infty$ [μT]	
slices	conv.	opt.	conv.	opt.
4	4.4	4.3	14.0	12.5
5	5.5	5.4	17.5	12.3
6	6.6	6.5	21.0	12.4

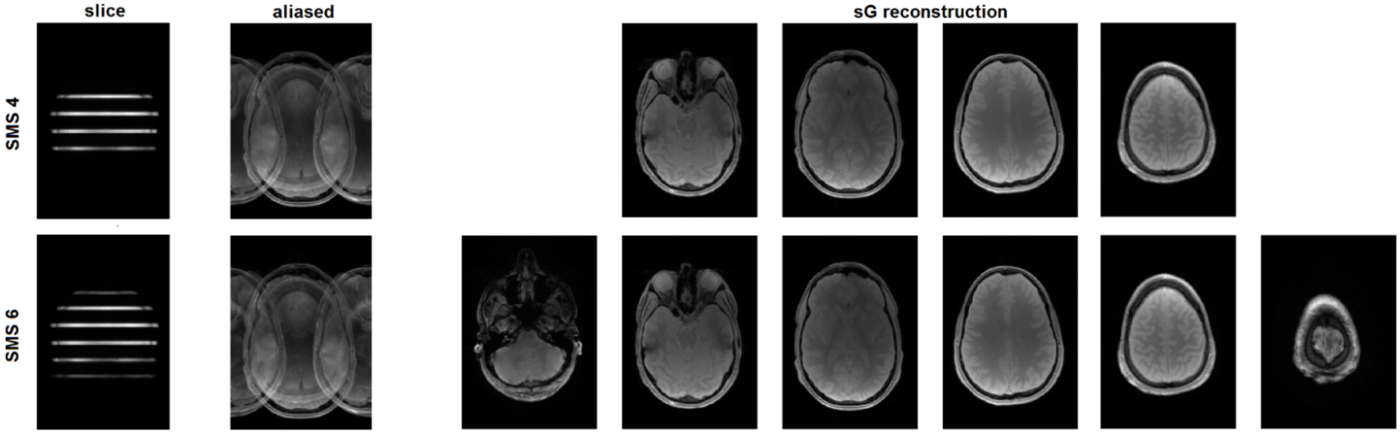

Figure 4: Cartesian and slice-Grappa reconstruction using CAIPIRINHA-based SMS excitation (4 and 6 slices)