RF pulse design for low SAR simultaneous multislice (SMS) excitation using optimal control

Christoph Stefan Aigner[1], Christian Clason[2], Armin Rund[2], and Rudolf Stollberger[1]

[1]*Institute of Medical Engineering, Graz University of Technology, Graz, Austria,* [2]*Institute for Mathematics and Scientific Computing, University of Graz, Graz, Austria*

INTRODUCTION

Simultaneous multislice (SMS) excitation is increasingly used to accelerate imaging experiments[1-3]. Conventional design approaches result in a quadratic or linear increase in SAR[4] and are sensitive to flip angle variations[4]. The slice dependent SAR increase can be addressed by the Power Independent of Number of Slices technique[4], which was extended to the kT-PINS method[5] to account for B_1 inhomogeneities; however, this method requires specialized gradient sequences. On the other hand, it has been demonstrated that optimal control is a powerful tool for the design of flexible and robust RF pulses. We therefore propose to apply an optimal control approach based on the full time-dependent Bloch equation, including relaxation and field inhomogeneity effects, for computing optimized SMS excitation pulses.

METHODS

Optimization: The optimal control approach consists in minimizing the discrepancy between the numerical solution of the full time-dependent Bloch equation corresponding to the RF pulse at read-out time and a prescribed, arbitrary, slice profile (in the form of a magnetization vector for each slice coordinate) together with a cost term modeling the SAR of the pulse. The minimizing pulse can be computed using a globally convergent trust-region Newton method[6] with a matrix-free iterative solution of the Newton step involving adjoint consistent numerical simulation of the Bloch equation.

Implementation: This approach was applied to compute RF pulses for a simultaneous excitation of two and three rectangular slice profiles using a standard slice selective gradient, considering a z-range of 400mm with a spatial resolution of 0.08mm and a thickness of 4mm for each slice. The pulses were designed for a total excitation time T=2,56ms and consisted of 256 samples every 10µs. For each slice, a flip angle of 45° was specified.

Validation: The numerical results were verified by experimental measurements using the optimized RF pulses in a modified gradient echo sequence on a 3T MR scanner (Magnetom Skyra, Siemens Healthcare, Erlangen, Germany) with the readout gradient along the z-axis. The body coil was used to transmit the RF pulse and receive the MR signal of a homogeneous cylinder phantom with diameter of 140mm, a length of 400mm and relaxation times T1≅102ms, T2≅81ms and T2*≅70ms. The same parameters and slice selection gradient were used in the numerical optimization. For the imaging experiments, we used an echo time TE=5ms, a repetition time TR=100ms, a matrix size of 256x256 and a field of view of 300x300.

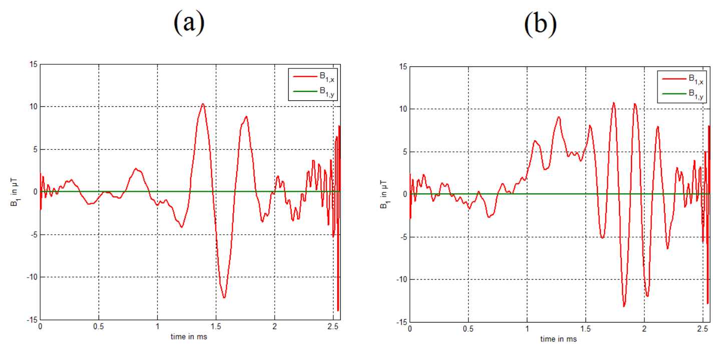

Figure 1: Optimized RF-pulse for two (a) and three (b) rectangular slice profiles

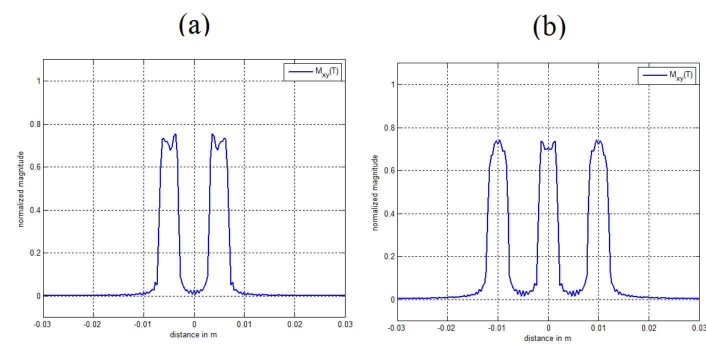

Figure 2: Simulated magnetization pattern of 1a and 1b.

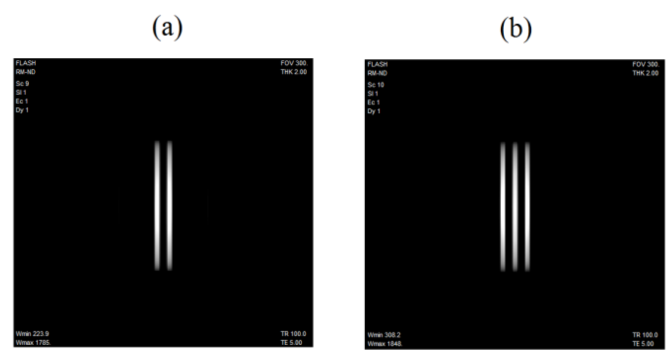

Figure 3: Reconstructed images of GRE experiment using the optimized pulses 1a and 1b respectively.

RESULTS AND DISCUSSION

Figure 1 shows the optimized RF pulses (B1,x, B1,y) for the two-slice (Figure 1a) and three-slice (Figure 1b) target profiles. The corresponding simulated slice profiles are given in Figure 2a and Figure 2b, respectively. It can be seen that the slices have a correct flip angle and a sharp transition profile, without requiring high SAR.

These results are validated by the implementation of the computed pulses in gradient echo sequence on the above mentioned 3T MR scanner for the imaging of a homogeneous phantom with frequency encoding in z-direction. The reconstructed images, given in Figure 3, demonstrate the ability to excite multiple homogeneous slices.

ACKNOWLEDGEMENT

This work is funded and supported by the Austrian Science Fund (FWF) in the context of project "SFB F3209- 8" (Mathematical Optimization and Applications in Biomedical Sciences).

REFERENCES

1. Larkman DJ et al. Use of multicoil arrays for separation of signal from multiple slices simultaneously excited. JMR 2001; 13: 313-7
2. Nunes RG et al. Simultaneous slice excitation and reconstruction for single shot EPI. Proc. ISMRM 14. 2006; 293
3. Feinberg DA et al. Ultra-fast MRI of the human brain with simultaneous multi-slice imaging. JMR 2013; 229: 90- 100
4. Norris DG et al. Power Independent of Number of Slices (PINS) radiofrequency pulses for low-power simultaneous multislice excitation.Magn Reson Med. 2011; 66:1234-40
5. Sharma A et al. kT-PINS RF Pulses for Low-Power Field Inhomogeneity-Compensated Multislice Excitation. Proc. ISMRM 21. 2013; 73
6. Steihaug. Conjugate gradient method and trust regions in large scale optimization. SINUM 1983; 20: 626-637