Simultaneous multislice refocusing by time-optimal control

Armin Rund[1,2], Christoph Stefan Aigner[3], Karl Kunisch[1], and Rudolf Stollberger[2,3]

[1]*Institute for Mathematics and Scientific Computing, University of Graz, Graz, Austria,* [2]*BioTechMed Graz, Graz, Austria,* [3]*Institute of Medical Engineering, Graz University of Technology, Graz, Austria*

Synopsis

We demonstrate the design of minimum duration SMS refocusing pulses and slice selective gradient shapes with specific hardware constraints such as peak B1, peak slew rate and peak amplitude of the slice gradient. The proposed bi-level time-optimal control method works with a detailed description of the slice profile accuracy by inequality constraints, and allows the use of fine spatial and temporal grids. The optimized results are validated on a 3T scanner with phantom and in vivo measurements demonstrating the practical realizability of the presented approach.

Purpose

Simultaneous Multislice Imaging (SMS) is an emerging field to reduce the overall scan duration by acquiring multiple slices and using coil sensitivity differences to disentangle the individual slice information. Contrary to in-slice parallel imaging techniques, the signal to noise ratio of SMS Imaging does not decrease with the multiband (MB) acceleration factor. However, for large MB acceleration factors or a high time-bandwidth product (TBP), SMS refocusing pulses typically possess a high B1 peak and B1 power, and/or a very long pulse duration[1]. Hardware and safety limitations then limit the achievable MB factors especially for high flip angles. Recently, different design approaches were proposed to reduce B1 peak only[2-4], or both B1 peak and B1 power[5,6]. Further progress regarding the design of short SMS refocusing pulses with specific hardware constraints was made in the last ISMRM challenge[7]. The method below was developed and applied in the SMS design subchallenge for computing pulses with minimum duration that fulfill the technical restrictions.

Theory

To design RF pulse and slice selective gradient shape of minimum duration we introduce a bi-level method for time-optimal control of the Bloch equation in the spin domain. We include inequality constraints for the slice profile accuracy (for magnitude b and phase φ) and MR hardware limitations (peak B1, peak gradient and peak slew rate). The bi-level time-optimal control approach consists of an upper level problem where the pulse duration T is iteratively reduced and a lower level problem to minimize the penalized objective with a large even integer p, parameters μ_* and maximum errors e_*

$$\min T + \mu_{\text{in}} \sum_{\text{inslice}} \left(\frac{1-|b(z,T)|^2}{e_{\text{in}}} \right)^p + \mu_{\text{out}} \sum_{\text{outslice}} \left(\frac{|b(z,T)|^2}{e_{\text{out}}} \right)^p + \mu_{\text{ph}} \sum_{\text{slices}} \sum_{\text{inslice}} \left(\frac{\varphi - \bar{\varphi}}{e_{\text{ph}}} \right)^p + \mu_{\text{rf}} \sum_{\text{time}} |B_1(t)|_2^2 + \mu_{\text{g}} \sum_{\text{time}} \left(\frac{G_{\text{s}}(t)}{G_{\text{s,max}}} \right)^p$$

This minimizes the overall pulse duration T and the errors of the refocusing profile (with ideal crushers) at each spatial position z with cost terms for the power of the RF pulse $B_1(t)$ and the peak amplitude of the slice selective gradient $G_{\text{s}}(t)$ over time t. Pointwise hard constraints on the controls $|B_1|_\infty \leq B_{1,\max}$ and $|\dot{G}_{\text{s}}|_\infty \leq \dot{G}_{\text{s,max}}$ are added. The lower level problem for a fixed T is solved with a constrained design method from our preceding work. Its kernel is a trust-region semismooth quasi-Newton method with exact derivatives via adjoint calculus.

Methods

The proposed time-optimal control method is implemented in MATLAB (The MathWorks, Inc, Natick, USA) and applied to the test set of 31 examples given by the ISMRM challenge7. We give results for a representative turbo spin echo case (MB=5, TBP=4, slice thickness = 2mm). The iterative optimization is started from a PINS5-based RF and slice selective gradient shape. The constraints are a peak B1 of 18μT, a peak slew rate of 200mT/m/ms, and a maximum refocusing error of 2%. The optimized refocusing pulse is implemented on a 3T MR scanner (Magnetom Skyra, Siemens Healthcare, Erlangen, Germany) using a crushed spin echo sequence and a conventional SLR 90 MB excitation pulse. To validate the Bloch simulations, we acquired a high-resolution phantom scan (TR/TE=114/15ms, FOV=200x200mm, matrix=960×960) and an in vivo scan (TR/TE=200/15ms, FOV=250x250mm, matrix=512×512) with the readout in slice-direction.

Results and Discussion

Figure 1a shows the computed time-optimal RF pulse, slew rate and slice selective gradient. The constraints of RF and slew rate are active at almost every time point resulting in a bang-bang shape. The simulated refocusing profile (assuming ideal crushers) is given for the full FOV and in detail for one slice. Due to a large $p \gg 2$ in the penalization, the error forms an equiripple distribution. Figure 2 compares the optimized pulse to a conventional superposed SMS pulse. The overall pulse duration could be reduced by roughly 90%, from 24.3ms to 2.41ms, while still fulfilling all given constraints on the refocusing profile and the hardware limitations. Figure 3 shows the refocusing profile for a B0 offset range of ±200Hz for the optimized RF pulse shown in Figure 1. Despite a time varying slice selective gradient shape, the short pulse duration leads to a minor slice profile degradation. Figure 4 shows the reconstructed phantom and in vivo measurements using the optimized pulse for a restricted gradient raster time of 10μs (which results in a pulse duration of 3.3ms). We observe sharp refocusing profiles that are in accordance with the simulations.

Conclusion

The presented approach designs minimum duration RF pulse and slice selective gradient shape in the presence of physical and technical constraints, that can be customized to a broad range of applications. This guarantees practical applicability and allows the optimized pulses to be integrated in existing EPI or TSE sequences. Thereby, the shorter pulse duration can be used to decrease the echo-spacing or effective echo time.

Acknowledgements

supported by SFB F3209-18

References

1) Barth M, Breuer F, Koopmans PJ, Norris DG and Poser BA. Simultaneous multislice (SMS) imaging techniques. Magn. Reson. Med. 75(1): 63–81, 2016

2) Wong EC. Optimized phase schedules for minimizing peak RF power in simultaneous multi-slice RF excitation pulses. In Proceedings of the 20th Annual Meeting of the ISMRM, Abstract 2209, Melbourne, Australia, 2012

3) Auerbach EJ, Xu J, Yacoub E, Moeller S and Ugurbil K. Multiband accelerated spin-echo echo planar imaging with reduced peak RF power using time-shifted RF pulses. Magn. Reson. Med. 69(5): 1261–1267, 2013

4) Sharma A, Lustig M and Grissom WA. Root-flipped multiband refocusing pulses. Magn. Reson. Med. 75(1):227-237, 2015

5) Norris DG, Koopmans PJ, Boyacioglu R and Barth M. Power Independent of Number of Slices (PINS) radiofrequency pulses for low-power simultaneous multislice excitation. Magn. Reson. Med. 66(5):1234–1240, 2011

6) Eichner C, Wald LL, Setsompop K. A low power radiofrequency pulse for simultaneous multislice excitation and refocusing. Magn. Reson. Med. 72(4): 949–958, 2014

7) Grissom WA, Setsompop K, Hurley SA, Tsao J, Velikina JV and Samsonov AA. Advancing RF pulse design using an open-competition format: Report from the 2015 ISMRM challenge. Magn. Reson. Med., 2016

Figures

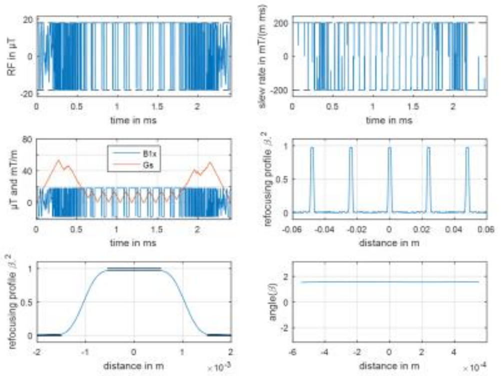

Figure 1: Time-optimal RF and slice selective gradient shapes and Bloch simulations

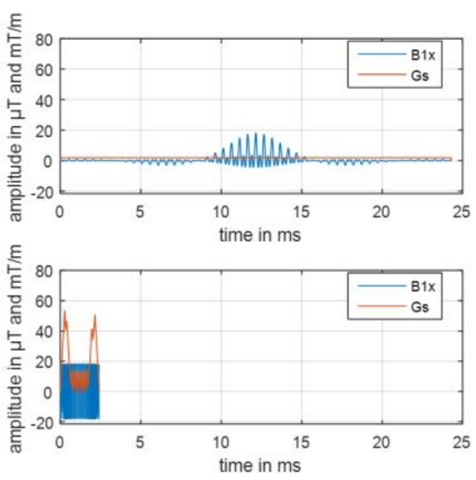

Figure 2: Comparison of the overall pulse duration of a conventional SMS pulse using superposition (top) vs the time-optimal pulse and gradient pair shown in Figure 1 (bottom)

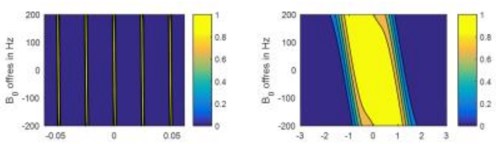

Figure 3: B0 influences on the refocusing profile. left: whole FOV, right: central slice (zoom)

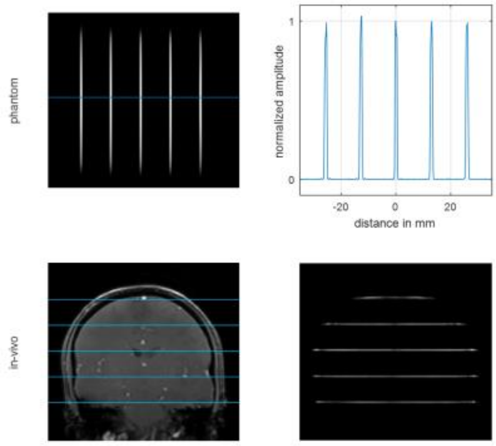

Figure 4: Reconstructed phantom and in vivo measurements