Application of time-optimal Simultaneous Multi-Slice refocusing to TSE/RARE

Christoph Stefan Aigner[1], Armin Rund[2,3], Berkin Bilgic[4,5], Borjan Gagoski[6], Kawin Setsompop[4,5], Karl Kunisch[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, [3]BioTechMed Graz, Graz, Austria, [4]Massachusetts General Hospital, Martinos Center for Biomedical Imaging, Charlestown, MA, United States, [5]Harvard Medical School, Boston, MA, United States, [6]Department of Radiology, Boston Children's Hospital, Boston, MA, United States

Synopsis

RF pulses for Simultaneous Multi-Slice imaging (SMS) are still limited by hardware and safety requirements leading to lengthy pulse durations. In this work we apply a bi-level time-optimal control method to design a minimum time SMS refocusing pulse for a multiband factor of 15 with 1mm slice thickness resulting in a refocusing duration of 4.58ms, which is 1.7x shorter than the state of the art MultiPINS pulse. The optimized RF pulse and the corresponding shaped slice selective gradient are tested in-vivo in a T2-TSE SMS wave-CAIPI scan of the whole head in 70s.

Purpose

Simultaneous Multi Slice (SMS) imaging is increasingly used for EPI and TSE based imagings to reduce the overall acquisition time[1]. However, the application of SMS sequences is still limited by the high specific absorption rate (SAR) of SMS RF pulses, leading to the use of lengthy RF pulses. While conventional Multiband (MB) pulses[2] exhibit a linear scaling of peak B1 and SAR with MB acceleration factor, the power independent number of slices (PINS) approach[3] allows for a MB factor independent peak B1 and SAR behavior at the cost of bandwidth. Recently, MultiPINS[4], a combination of conventional MB and PINS pulses, was also proposed to further reduce peak B1 and SAR. In this work, we improve RF and slice selective gradient shapes of SMS pulses further by iterative mathematical optimization. We apply a time-optimal control pulse design that was developed during the ISMRM challenge 2015[5] in order to design SMS refocusing pulses for a large MB factor with strict SAR and scanner hardware constraints. The optimized pulse was demonstrated in phantom and in in-vivo for a 1mm isotropic T2-TSE SMS wave-CAIPI[6] scan at MB-15, where refocusing pulse duration was reduced by 1.75-fold over MultiPINS design to just 4.58ms.

Theory

The time-optimal control approach is based on a bi-level method that iteratively reduces the overall pulse duration while optimizing the RF and slew rate amplitude of the slice selective gradient. The method works with prescribed constraints on the slice profile accuracy (magnitude and phase), peak and global B1, maximum gradient amplitude and slew rate. A customized trust-region semi-smooth quasi-Newton method with exact derivatives via adjoint calculus adapts B1 and slew rate in the lower level problem to fulfill the constraints.

Methods

The optimization method is applied to the design of SMS refocusing pulses at MB-15, slice thickness/gap of 1mm/17mm, and a time-bandwidth product of 2.37 using a PINS initial guess. The time-optimal RF pulse and the shape of the slice selective gradient (peak gradient amplitude of 35mT/m) are computed in MATLAB (The MathWorks, Inc, Natick, USA) and imported into the TSE sequence[6]. To maximize the spatial distance of aliased voxels and reduce g-factor, a Wave-CAIPI encoding scheme[6] is used. To ensure the CPMG condition we set the global mean phase of the refocusing pulse to be –pi/2 to be use with standard SLR 90 MB pulse. Measurements are performed on a 3T MR Scanner (Magnetom Trio, Siemens Healthcare, Erlangen, Germany). Imaging parameters were, Tacq=70sec, FOV=256x192x255, 1mm isotropic voxels, TR/TE=4000/100ms, BW=130Hz/pixel, Turbo Factor=12, MB Factor=15. Wave gradients were played during the readout to create a corkscrew trajectory due to Gmax=6mT/m, Smax=50mT/m/s, 7 sinusoidal cycles. Coil sensitivities used in generalized SENSE[7] reconstruction were estimated using ESPIRiT[8] from a 3D-GRE acquisition at 2mm isotropic resolution.

Results and Discussion

Figure 1 shows the RF and slice selective gradient shapes together with the simulated refocusing profiles (assuming perfect crusher gradients) of a MultiPINS pulse (using a mixing ratio of 50%) and the time-optimal control pulse pair. It can be seen that the overall pulse duration is shortened from 8ms to just 4.58ms through a modulation of the slice selective gradient shape. This distributes the B1 power more uniformly. The optimized controls and Bloch simulations are shown in detail in Figure 2. The peak B1 is slightly increased compared to the MultiPINS pulse. It touches the allowed amplitude constraint only in one point. In contrast, the slew rate jumps from the upper to the lower bound of ±180T/ms, which is a typical behavior of time-optimal controls. The strict SAR and B1 amplitude constraints prevent a further reduction in time. The simulated refocusing profile and the in slice-phase are given for the whole field of view and in detail for the central slice. Both, the magnitude and phase constraints are not exceeded anywhere in space. Figure 3 compares the B0 influences of the optimized pulse showing just minor degradation of the refocusing profile in a B0 range of ±200 Hz. The Wave-CAIPI reconstruction of the optimized RF pulse is shown in Figure 4 for a phantom and in-vivo in Figure 5.

Conclusion

The application of the time-optimal control approach allows for optimization of RF pulse and slice selective gradient in the presence of hard constraints given by actual scanner hardware and safety measures such as the B1 power. This assures a simple replacement of existing pulses and is well suited to further decrease the echo spacing in TSE/RARE sequences. The combination of optimized pulses for large MB factors with a Wave-CAIPI reconstruction allows for fast acquisition of whole head 3D-TSE/RARE imaging in 70s.

Acknowledgements

supported by SFB F3209-18, R01EB020613 and P41EB015896

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) Müller S. Multifrequency selective RF pulses for multislice MR imaging. Magn. Reson. Med. 6(3):364–371, 1988

3) 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

4) 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

5) 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

6) Gagoski BA, Bilgic B, Eichner C, Bhat H, Grant PE, Wald LL and Setsompop K. RARE/turbo spin echo imaging with simultaneous multislice Wave-CAIPI. Magn. Reson. Med. 73(3): 929–938, 2015

7) Pruessmann KP, Weiger M, Scheidegger MB and Boesiger P. SENSE: Sensitivity encoding for fast MRI. Magn. Reson. Med. 42(5): 952–962, 1999

8) Uecker M, Lai P, Murphy MJ, Virtue P, Elad M, Pauly JM, Vasanawala SS and Lustig M. ESPIRiT—an eigenvalue approach to autocalibrating parallel MRI: Where SENSE meets GRAPPA. Magn. Reson. Med. 71(3): 990–1001, 2014

Figures

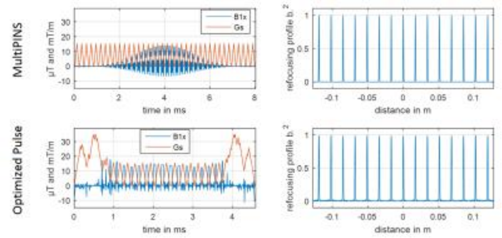

Figure 1: Comparison of the a MultiPINS and time-optimal SMS refocusing pulse: RF pulse, slice-selective gradient and pulse duration (left) and the simulated refocusing profiles (right)

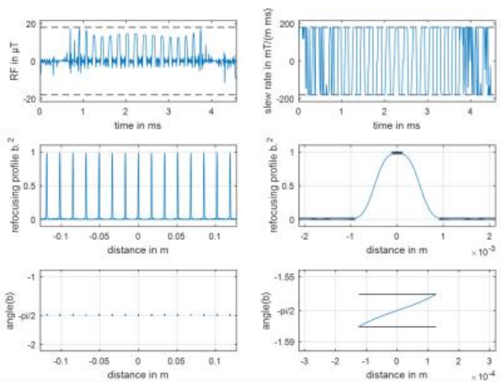

Figure 2: Time-optimal RF and slice selective gradient slew rate (1st row), refocusing profile with zoom (2nd row), and in slice phase with zoom (3rd row)

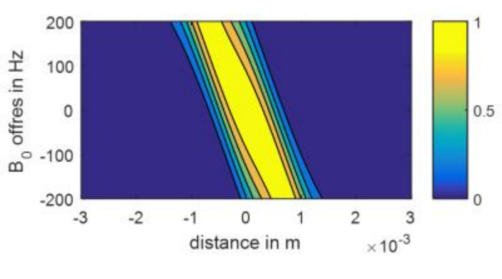

Figure 3: B_0 influences on the refocusing profile of the central slice

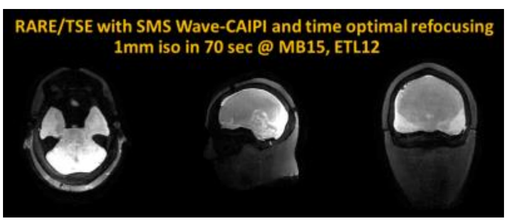

Figure 4: Phantom RARE/TSE measurement

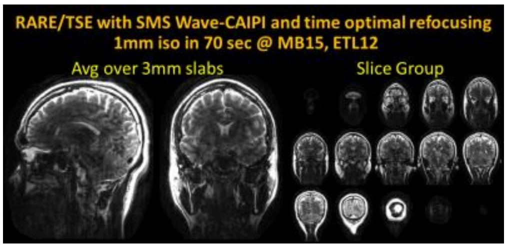

Figure 5: In-vivo RARE/TSE measurement