Slice-selective broadband refocusing pulses with B_1 immunity

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Introduction: Broadband refocusing pulses are of great interest for reducing chemical shift displacements, anomalous J modulation, and increasing spectral selectivity. The design of refocusing pulses with broad bandwidth in the presence of limited RF power was accomplished with the Shinnar-Le Roux (SLR) transformation in combination with zero-flipping [1]. Schulte et al. optimized for maximum pulse bandwidth by flipping zeros of the A polynomial, which changes only the pulse shape while retaining its refocusing profile. Besides broad bandwidth, another challenge is insensitivity towards B_1 inhomogeneity. This is required for many applications, such as satisfying the CPMG condition in spin echo sequences when using inhomogeneous RF coils. With optimal control theory (OCT) both challenges can be addressed by tailoring RF pulses to this specific problem. OCT was previously used for designing robust slice-selective broadband RF pulses [2]. Our pulse design aims at refocusing pulses and concentrates on good immunity to B_1 variations and on posing least constraints on the optimization. The OCT pulses are compared to broadband SLR pulses and verified experimentally.

Methods: Optimal control theory enables the design of RF pulses which transform an initial magnetization vector to a target vector (*point-to-point transformation*), or which rotate any magnetization vector around a defined rotation axis by a given angle (*universal rotation*) [3]. The optimization is performed for several discrete values of off-resonance frequencies to achieve the desired slice profile, and for several B_1 deviations to obtain robustness [4]. Point-to-point transformation and universal rotation is combined in one optimization program. The off-resonance values under investigation are divided into four regions: (1) *Pass-band:* In the slice the refocusing pulse performs a universal rotation by 180° around the x-axis. Universal rotation is optimized directly without applying symmetry constraints. (2) *Transition zone:* These off-resonance frequencies are not included in the optimization. (3) *Stop-band:* In order to pose least constraints on the optimization, rotations by any angle around the z-axis are allowed in the stop-band. This is realized by a point-to-point transformation of z-magnetization to z-magnetization. (4) *Undefined zone:* Off-resonance frequencies larger than half the sampling frequency of the acquisition are suppressed by digital filters and need not be included in the optimization.

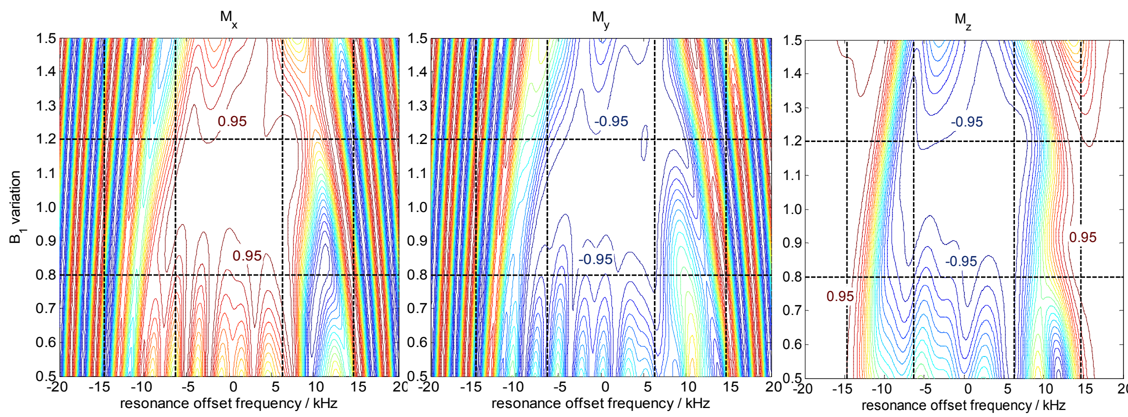


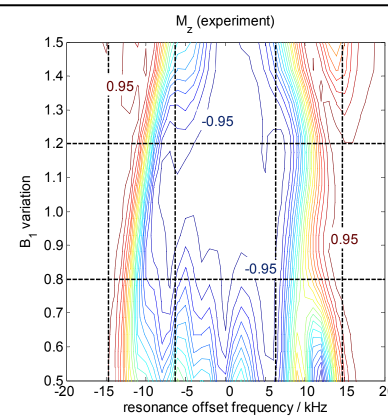
Fig. 1: Normalized magnetization after application of OCT pulse for different off-resonance frequencies and B_1 variations. The pulse is scaled to a maximum B_1 amplitude of 10 kHz, resulting in a bandwidth of 21 kHz. The simulation is executed three times for initial magnetization vectors aligned along the x-, y-, and z-axes to show that the pulse performs as 180° universal rotation around the x-axis. The dashed lines visualize the range of B_1 variations included in the optimization and the transition zone.

A refocusing pulse with immunity to B_1 variations of ±20 % and n = 200 samples is optimized. The design specifications are a time-bandwidth product of T·BW = 7.8, fractional transition width FTW = 0.4, ratio of pulse bandwidth to peak RF amplitude BW/B_{1max} = 2.1. The optimization is initialized with 1000 random pulses and the best result is chosen.

For experimental verification the OCT pulse is scaled to a maximum B_1 amplitude of 10 kHz, resulting in a pulse duration of 370 µs and bandwidth of 21 kHz. The resulting magnetization profile is measured in a water sample on a Bruker 600 MHz / 14 T Avance 3 spectrometer (Bruker BioSpin, Rheinstetten, Germany).

Results: Initializing the optimization with a large number of random pulses results in better pulses than initializing with a single broadband SLR pulse. Simulations (Fig. 1) show that the OCT pulse meets the broadband specifications of the slice profile. It shows good refocusing characteristics for B_1 variations of –10 % to +20 %. In the slice region the pulse rotates y- and z-magnetization by 180°, leaves x-magnetization unchanged, and therefore performs a universal rotation. Experimental results (Fig. 2) correspond well with simulated final z-magnetization.

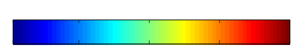
Fig. 2: Experimental verification of the OCT pulse applied at different off-resonance frequencies and B_1 values, each time followed by 90° excitation, and acquisition of a FID signal. For each off-resonance and B_1 value the single peak of the spectrum is integrated and normalized to the maximum value of all integrated spectra. This gives a measure for z-magnetization directly after application of the OCT pulse.

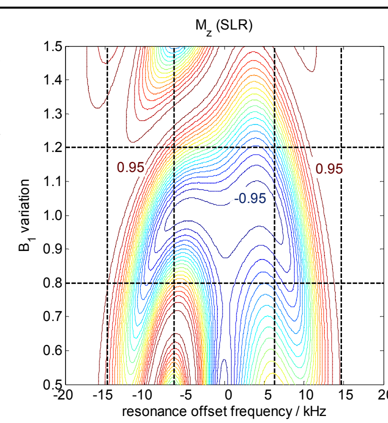


Discussion and Conclusions: Optimal control theory enables the design of robust broadband refocusing pulses. B_1 robustness is successfully included in the pulse design. Comparison with a broadband SLR pulse (Fig. 3) reveals that the OCT pulse reaches a much better immunity to B_1 variations. The refocusing pulse presented here achieves a ratio of pulse bandwidth to peak RF amplitude of 2.1 and immunity against –10 % to +20 % B_1 variations.

Along with the advantages of broader bandwidth comes higher energy deposition (SAR). With OCT broadband RF pulses can be designed for reduced SAR by accepting a trade-off with other pulse specifications, which was not desired for the pulse here.

Fig. 3: Simulated normalized magnetization in z-direction for the phase-modulated broadband SLR pulse. The SLR pulse, taken from [1], was designed for a 172° rotation with identical n, T·BW, FTW, and BW/B_{1max} as the OCT pulse.





References: [1] Schulte RF et al. JMR 190:271 (2008); [2] Matson GB et al. JMR 199:30 (2009); [3] Khaneja N et al. JMR 172:296 (2005); [4] Kobzar K et al. JMR 173:229 (2005)

Acknowledgement: This work was partly funded by BMBF MobiTUM grant # 01EZ0827.