OPTIMAL CONTROL SINGLET STATE STORAGE FOR CLINICAL MR SYSTEMS

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Introduction: The use of hyperpolarized compounds has so far been limited by the T_1 decay of the magnetization. Recently the novel method magnetization-to-singlet order (M2S) and singlet order-to-magnetization (S2M), has been shown applicable on pre-clinical systems [1] to extend the hyperpolarized life time several orders of magnitude. However, several limitations are imposed by clinical MRI systems with typical hardware constraints such as low maximum B_1 amplitude and lower static magnetic field B_0. The large B_1 and B_0 inhomogenties combined with T_2 relaxation impose severe limitations on the efficiency of the method.

Aim: Here we show in simulations that by optimal control (OC) theory it is possible to create pulses which transfer magnetization to and from the singlet state with much less sensitivity to hardware constraints typically encountered in clinical MRI systems. The open source software SIMPSON was used [2],[3]. Selecting the transfer from the initial magnetization I_z to the singlet state S_0 and from the singlet state S_0 to observable magnetization I_x.

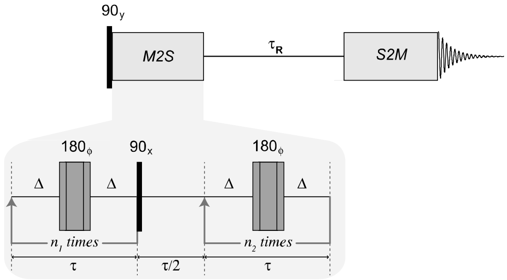

Figure 1: The M2S and S2M pulse sequence, consists of J-syncronized echo trains N_1 and N_2, where $N_1 = 2\ N_2$. The S2M is teh mirror image of the M2S.

Methods: The simulated environment involved a spin system of two strongly coupled nearly equivalent ^{13}C nuclei with a chemical shift of 4.16 Hz and scalar J copuling of J = 178.8 positioned in a field of 3 T and a equipped with a typical coil system for ^{13}C yielding a RF field strength of 400 Hz.

Results: A simulation of the analytical derived M2S with $\tau = 1/\left(2\sqrt{\Delta v_{cs}^2 + J^2}\right) - T_{180}$, T_{180} being the refocusing pulse length, shows an efficiency below 67% with an RF field of 400 Hz, and a total pulse length τ_p of 464 ms (figure 1, right) found by optimizing the number of echoes N_2 and $N_1 = 2N_2$, (figure 1, left). Two OC derived M2S (OC-M2S) pulses $\tau_P = 200$ ms (figure 1, middel left) and $\tau_P = 300$ ms (figure 1, middel right), with a max RF strength of 400 Hz, showing > 83% and optimum transfer respectively for a broad range of B_1 and B_0 fields, a 57% and 35% reduction in pulse length, reducing the limiting T_2 relaxation during the pulses, in addition the efficiency being improved by 35% compared to the M2S sequence.

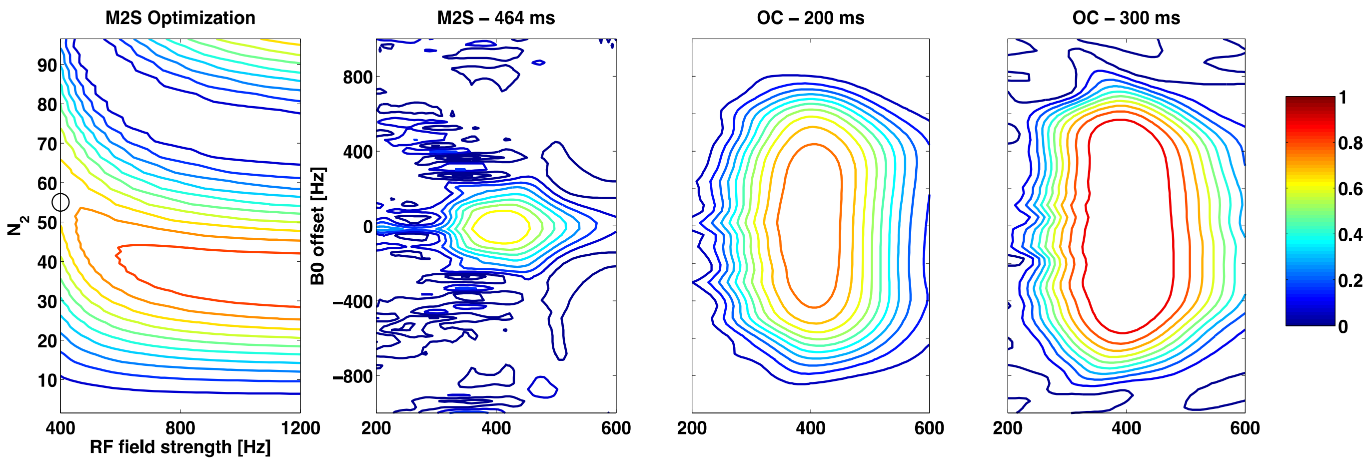

Figure 2: SIMPSON simulations of the optimization, with number of echo's N_2, $N_1 = 2\ N_2$ as a function of RF field strength, showing a reduced efficiency for low RF field strength. An optimized M2S (circle in the M2S optimzation simulation) at RF strength of 400 Hz with duration 464 ms, showing the reduced efficiency together with a narrow B_0 offset range and OC equvialents with RF strength of 400 Hz, and pulse duration 200 ms and 300 ms respecitlvey and 2048 elements, shwing increased effciency for shorter pulse durations than the optimum found for M2S.

Conclusions:
It is evident that the OC method finds a solution for the desired transfer to the singlet state. The OC shape requires little prior knowledge and is easily implemented on MRI systems. The improvements enhance the effeciency significantly hardware specification typical for clinical MR systems It is shown that both reduced pulse lengths and increased B_1 and B_0 inhomogeneity robustness can be achieved.

References:

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3. Tošner Z, Vosegaard T, Kehlet C, Khaneja N, Glaser SJ, Nielsen NC. Optimal control in NMR spectroscopy: Numerical implementation in SIMPSON. *J Magn Reson* 2009 Apr 1;**197**(2):120-34.