Application of Strongly Modulated Pulses in Triple Quantum Filtering in Animal Sodium MRI *in vivo*

A. Shymanskaya, W.A. Worthoff, C.-H. Choi, J. Felder, N.J. Shah

This work is of interest to researches working with optimal control algorithms and those who have an interest in the physics of quadrupolar interaction in sodium MR imaging.

<u>Purpose</u>: Strongly modulated RF pulses (SMPs) can be used to control transfer between states of the nuclear spin ensemble. The Krotov algorithm[1] and unified framework of concurrent and sequential optimal control algorithms[2] were used to generate an SMP, which replaced the first rectangular RF pulse in an enhanced SISTINA sequence[3,4] in order to improve *in vivo* animal measurements. A comparison in performance of these algorithms in creation of programmed transfer between states that depend on the environment of the nuclei was performed.

<u>Methods</u>: The enhanced SISTINA sequence[3,4] (Fig. 1) provides simultaneous measurement of single-quantum (SQ-) and triple-quantum (TQ-) weighted images. Multiple coherences develop depending on the restrictions present in sodium nuclei environment. The dynamics during the RF pulse are determined by the sum of Hamiltonians describing the interaction of nuclear ensemble with the RF field and with the nuclei environment. The control element in both optimisation routines[1,2,7,8] is the complex amplitude of the RF pulse. Two types of SMPs were generated in this study. Type A pulses were created with the unified algorithm[2], considering the influence of both the fluctuating and the static quadrupolar Hamiltonians. Type B pulses were calculated using the Krotov algorithm[1] and its implementation by Maximov[7,8], considering the influence of the static Hamiltonian alone.

<u>Results</u>: *In vivo* measurements on a healthy rat were performed on a small-bore 9.4T scanner[10]. In Fig. 2 (left), parts I, II, and III show UTE, SQ- and TQ-weighted images acquired with A, B, and rectangular $\pi/2$ pulses. Also, the corresponding difference maps (Fig. 2, middle) and SNR differences (Fig. 2, right) in percent are presented. Pulses of type A deliver 10% higher TQ- and 16% higher SQ-weighted SNR than rectangular pulses, and produce 5% lower TQ- and 3% higher SQ-weighted SNR than B pulses. B pulses achieve 16% higher TQ- and 13% higher SQ-weighted SNR than $\pi/2$ pulses in brain tissue. The SNR in the UTE image measured with $\pi/2$ pulses is comparable to that of pulse B (4%), or lower, compared to pulse A (18%).

<u>Discussion/Conclusions:</u> Measurements using SMPs deliver the expected contrast and higher signal in both SQ- and TQ-weighted images. Differences in SNR in UTE images do not penalise the performance of the sequence significantly because the SNR is sufficiently high. A unifying framework[2] was implemented in case relaxation processes are present. The technique is very sensitive to input conditions. Maximov's implementation[7,8] of the Krotov algorithm[1] was applied in the dissipation-free case. The algorithm is slower and does not converge in the case that relaxation is present. The performance of both algorithms strongly depends on spectral density parameters[6]. Optimisation for human *in vivo* measurements should consider the relaxation parameters for the corresponding brain tissue.

<u>References:</u>

1. Krotov V., Global methods in optimal control theory. CRC Press, 1995; Vol. 195.
2. Machnes, S., et al. Physical Review A 84.2 (2011): 022305.
3. Shymanskaya A, et al. ESMRMB Congress (2016) 29 (Suppl 1): Abstracts, Friday: S123–S245, pp 152-153
4. Fiege D., et al., MRM 69.6 (2013): 1691-1696.
5. Shah N. J, et al. NMR in Biomedicine 29.2 (2016): 162-174.
6. Tsang A, et al. MRM 67.6 (2012): 1633-1643.
7. Maximov I, et al. J. Chem. Phys. 2008; 128.18: 184505.
8. Maximov I, et al. J. Chem. Phys. 2010; 132.8: 084107.
9. Stirnberg R, et al. Proc Int Soc Mag Reson Med 2009; 17:3574.
10. Felder J, et al. J Transl Med. 2017;15(1):264.

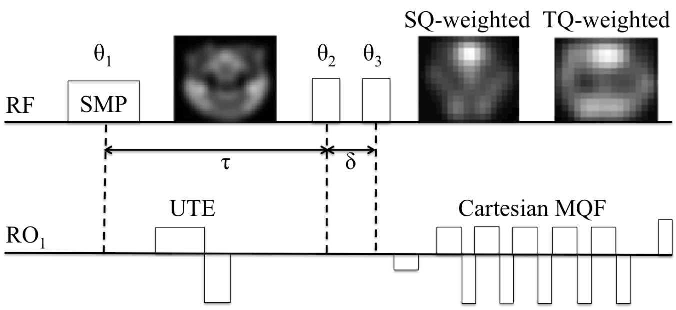

Fig.1: Enhanced SISTINA sequence[4,5]. Images are acquired with type B SMP pulse.

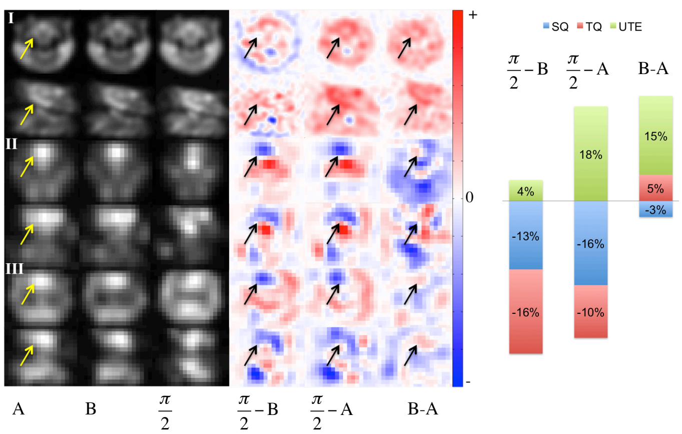

Fig. 2: I: UTE images (left) acquired with A, B, and rectangular pulses, with corresponding difference images (middle); II: SQ-weighted images; III: TQ-weighted images. Arrows indicate ROI.