Design of a Variable-Rate Selective Dual-Band FOCI Pulse for Spin Labeling

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Introduction: For pulsed arterial spin labeling (pASL) the quality of the spatially selective inversion is decisive to minimize errors and maximize contrast. This comprises the homogeneity and the degree of the inversion as well as the steepness of the transition zones of the inversion. Commonly, adiabatic pulses like the hyperbolic secant (HS) [1] or the frequency offset corrected inversion (FOCI) pulse [2] are used. For a complete inversion, the adiabatic condition has to be met. Therefore, a compromise between the pulse parameters and the maximum available B_1, i.e. coil voltage, has to be found. Especially, when using dual-band adiabatic inversion pulses, such parameters can no longer be found without sacrificing the quality of the inversion profile. In this work, we present a variable-rate selective excitation (VERSE) [3, 4] - transformed FOCI pulse that conserves the advantageous properties of a FOCI pulse, however reduces the maximum required RF power. This way, it is possible to meet the adiabatic condition even when using it as a dual-band inversion pulse.

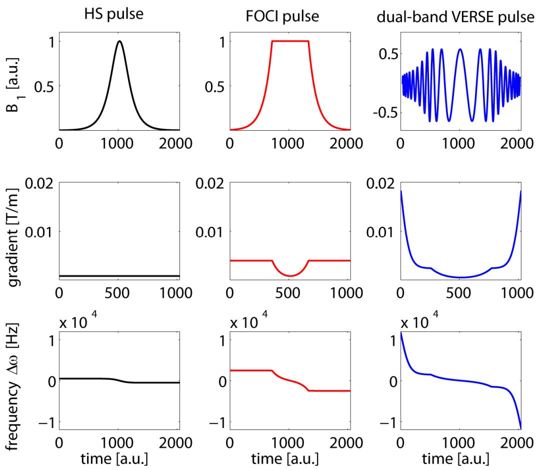

Fig. 1: B1 envelope, gradient waveform and frequency sweep of the HS, FOCI and dual-band VERSE pulse as calculated for the measurement. The B_1 envelope of the dual-band FOCI pulse as used for the measurement is not shown.

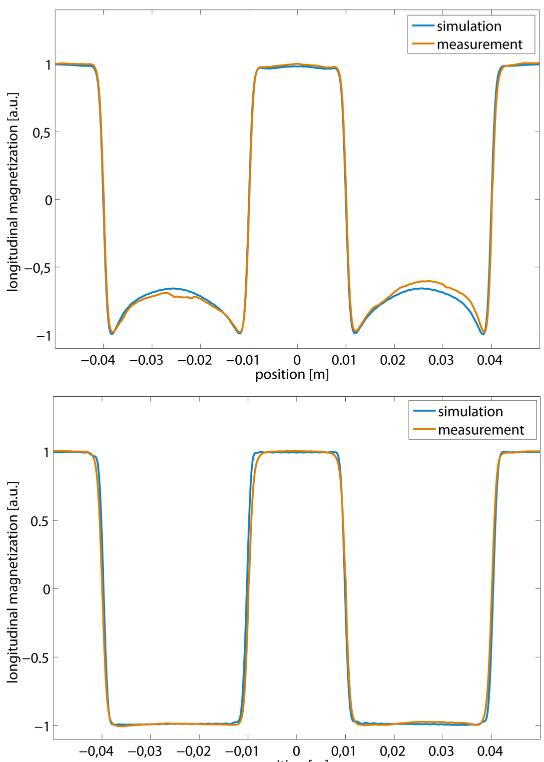

Fig. 2: Simulated (blue) and measured (yellow) slice profiles of the dual-band FOCI pulse (upper panel) and its VERSE-transformed pendant (lower panel). The longitudinal magnetization is plotted against the position.

Material and Methods: We created a HS inversion pulse with standard B_1 envelope and frequency offset $\Delta\omega$. Given bandwidth BW = $\mu\beta/\pi$, length T_P and B_1-truncation of the pulse, the parameters μ and β were calculated such that μ had been maximized. Following the approach of Payne and Leach [5] this HS inversion pulse was then transformed into a FOCI pulse by using a "C-shaped" modulation function with a factor of five. Adjacent, the generated FOCI pulse underwent a VERSE transformation by using an analytic scaling function [6] which bases on the Fermi function. The scaling function λ depends on three parameters and is given by:

$$\lambda = (A - B)F_n + B \text{ where } F_n(x) = \frac{F_i(x) - 0.5}{F_i(0) - 0.5} \text{ and } F_i(x) = 1/(1 + e^{((|x|-1)/t_c)}) \text{ with } x\epsilon[-1; 1].$$

Given the parameters t_c and A of the scaling function, the value of B was numerically calculated such that the original pulse duration was preserved. To achieve the dual-band properties of the pulse with the slice centers separated by d from the isocenter, the B_1 envelope was modulated with a cosine according to the following equation:

$$B_{1,mod}(t) = B_1 \cos\left(2\pi d\left(-\frac{k_{max}}{2} + k_{sum}(t)\right)\right) \text{ with } k_{sum}(t) = \gamma\int_0^t G_{VERSE}(t')dt' \text{ and}$$

$$k_{max} = \gamma\int_0^{T_P} G_{VERSE}(t')dt'.$$

Inversion profiles were obtained by implementing the pulses in a modified gradient echo sequence without phase encoding. The inversion pulses were followed by spoiler gradients, a nonselective 90° excitation pulse and a read-out in slice-selection direction. Two measurements were necessary, one with and one without the inversion pulse. The difference of both datasets yields the absolute longitudinal magnetization. Together with the phase information the actual slice profile can be reconstructed as the phase changes from π to $-\pi$ at the position where the sign of the longitudinal magnetization changes. The measurements were performed on a 3T whole-body MR scanner (Magnetom Skyra, Siemens Healthcare Sector, Erlangen, Germany) using the body coil for transmission and signal detection. A water bottle served as a phantom. The matrix dimension in readout direction was 1024 with a FoV of 200 mm leading to a resolution of 0.20 mm. Other imaging parameters were TE/TR = 11 ms/18000 ms and bandwidth = 80 Hz/px. The parameters of the inversion pulse were: T_P = 10240 ms, BW = 1000 Hz and B_1-truncation = 0.1 % leading to μ = 2.12 and β = 1485 rad/s. For the VERSE scaling function we used A = 0.60, B = 4.68 and t_c = 0.07. The voltage of the transmitter coil was maximal for the inversion pulses. The slice profile of a FOCI pulse and its VERSE-transformed pendant were recorded. They were calculated to invert two 30 mm thick slices with their centers separated by 50 mm. Profiles were evaluated and compared to Bloch equation simulations of the slice profiles. The simulations were calculated with an in-house MATLAB (The MathWorks, Natick, MA, USA) script. Thereby, a rotation matrix based on the Cayley-Klein parameters [7] is recalculated for every time step. For a fair comparison the simulation of both FOCI and VERSE pulse were carried out with the same $B_{1,max}$.

Results: The pulses calculated for the measurements are shown in Figure 1. The VERSE scaling function reduced the peak B_1-field to 61 % of the original value, however increased the peak gradient by a factor of 23.4 compared to the HS pulse and by 4.7 compared to the FOCI pulse. The inversion profiles of FOCI and VERSE pulse are compared in Figure 2. The simulated and the measured slice profiles show a very good agreement. Despite the maximum coil voltage, the profiles of the FOCI pulse depict an incomplete inversion. This "belly-shaped" form is characteristic for a FOCI pulse that does not meet the adiabatic condition and could be verified by the simulation. In contrast, the reduced power requirement of the VERSE pulse in combination with the same transmitter voltage fulfills the adiabatic condition leading to a complete inversion of the magnetization at the center of the slices. The inversion efficiencies are plotted in Table 1.

Tab.1: Mean longitudinal magnetization of both slices in their centers, i.e. 0.88 slice thicknesses.

	measurement	**simulation**
FOCI pulse	(-0.75±0.10) a.u.	(-0.75±0.10) a.u.
VERSE pulse	(-0.99±0.01) a.u.	(-0.98±0.01) a.u.

Conclusion/Discussion: The presented pulse allows for the simultaneous inversion of two slices while conserving the high inversion profile quality and the low sensitivity to chemical shift displacements of a single-band FOCI pulse. Although the scaling function can generally be chosen to minimize B_1, limitations due to the maximum available gradient strength and slew rate, in practice, lead to a trade-off between both. Due to its properties, the presented dual-band pulse can be beneficial for the acquisition of ASL perfusion data of paired organs when a 3D readout is used. Especially for the 3D measurement of renal perfusion with pulsed ASL, the kidneys can be labelled without labelling the aorta which leads to shorter bolus arrival times and a higher perfusion contrast.

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