Applying optimized variable-rate excitation for outer volume suppression in fast 3D Proton spectroscopic imaging of the human brain at 3 Tesla

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Introduction:

"Spectroscopic Missing-Pulse SSFP" (spMP-SSFP) is a fast 3D ^{1}H spectroscopic imaging (SI) pulse sequence recently introduced by Schuster et al. [1]. Within this sequence, the volume of interest (VOI) is localized by two spectral-spatial RF pulses and one outer volume suppression (OVS) block consisting of several slice selective 90° pulses with a subsequent spoiler gradient. At most five OVS pulses can be applied at 3 T with current sequence settings, because of specific absorption rate (SAR) and timing limitations, although a higher number of OVS slices would provide more accurate localization and higher suppression of extracranial lipid signals. Already with four OVS pulses 2/3 account of the SAR value are attributed to OVS. Another problem of using OVS in spMP-SSFP is that SAR increases quadratically with B_0, limiting implementations on higher B_0 fields such as 4 T or even 7T. Therefore, improved OVS pulses with reduced SAR are of central importance for improving the performance of spMP-SSFP at 3 T and for allowing its use at higher B_0.

The variable-rate (VR) gradient technique VERSE, proposed by Conolly et al. [2], has been used in MR imaging [3-5] to decrease the power of selective RF pulses by using modulated B_0 gradients and modifying predefined RF waveforms accordingly. However, the non-uniform phase development impairs excitation profiles of off-resonant spins. As this effect increases linearly with B_0, optimizing the offset behavior of VERSE pulses becomes an important issue particularly in clinical high-field MR [5]. In this work, optimized saturation pulses calculated by a genetic numerical algorithm are implemented in spMP-SSFP on a 3 T head scanner. Up to eight OVS pulses could be applied by this means enabling a more precise definition of the VOI without violating SAR or peak amplitude constraints.

Theory:

SAR reduction in the VERSE technique is achieved by modulating RF and gradient amplitude and accordingly varying time-rates such that the slice profile remains unchanged. The shift theorem [2] implies that in order to shift the slice position form isocenter to z_0 one needs to additionally modulate the RF phase by $z_0\gamma\int_t^T g(\tau)d\tau$.

In the presence of a chemical shift $\Delta\omega$, each slice position is displaced by $\Delta\omega/\gamma g$. Since the gradient amplitude g is time dependent in VERSE, the slice profile becomes not only shifted but also asymmetrically smeared. The genetic algorithm was used to find VERSE-like saturation pulses with reduced SAR and acceptable off-resonance behavior.

Method and Experimental:

All measurements were performed on a 3T Magnetom Allegra head scanner (Siemens, Erlangen, Germany) equipped with standard gradients (40 mT/m, 400 mTm^{-1}s^{-1}) and a standard CP Birdcage coil used for transmission and reception. Experimental results were obtained from measurements on a spherical phantom of 180 mm diameter filled with aqueous solution of Na-acetate and Li-lactate (both 100 mM) and on healthy human brain. The following parameters were used in all experiments: TA=102 ms, TE=126 ms, TR=189 ms, $\alpha_1=-\alpha_2=55°$, FOV: 200x200 mm^3 (2D) or 150x150x105mm^3 (3D). Eight OVS pulses were applied in all cases, followed by a crusher gradient pulse of 25 mT/m amplitude and 2 ms duration. Each modulated OVS gradient was balanced by an 800 µs long gradient of appropriate amplitude. The OVS slices of 24 mm thickness were placed to properly adjust the VOI geometry.

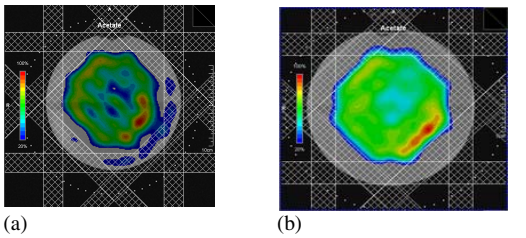
In phantom experiments, the applicability of two VERSE-like modified waveforms for OVS was compared, both with 35% SAR reduction with respect to uniform-rate excitation: first, a 5-lobes sinc pulse multiplied with a sin-bell, with a cosine-shaped rate modulation, and secondly, a RF-gradient pair created by the genetic algorithm. Both pulses were 2.5 ms long. Slice profiles were verified in preliminary simulations as well as in phantom experiments. During the SI measurements, a spectral-spatial RF pulse was used to preselect a slice of 25 mm thickness. Afterwards eight OVS pulses described above were applied on-resonance (on water) in eight oblique OVS slices, which lay orthogonal to the preselected slice. In this way, an octagonal shape within a 16x16 matrix was localized (Fig. 1). The spatial distribution of the acetate signal was measured in both cases to verify the saturation and off-resonance behavior of both waveforms.

In-vivo measurements were performed on a 120x120x58 mm^3 volume with 20x20x12 phase encoding steps with the optimized VERSE waveforms created by the genetic algorithm. Twofold Hanning-filtered *k*-space weighting was used to increase SNR and to reduce the scan time. OVS slices (Fig. 2) for lipid suppression were positioned with the aim to maximally cover scalp regions. An offset of 3.4 ppm was subtracted from the OVS pulse frequency to avoid slice displacement for lipids.

Results:

Fig. 1 shows the acetate images obtained by peak integration (-2.95 ppm off-resonance) as well as the eight OVS regions for (a) the sinc-shaped pulse and (b) pulse created and optimized by genetic algorithm, both described above. Since the OVS behavior of the second RF/gradient pulse pair is clearly superior, the optimized scheme was applied for in vivo measurements.

A scout image of the human brain with 8 OVS slices is depicted in Fig. 2. A spectral map of the marked region with a frequency range of 1.2-2.2 ppm is shown in Fig. 3 demonstrating the detected methyl signal of N-acetyl aspartate and the good localization of unwanted extracranial lipid signal.



(a) (b)

Fig. 1. Acetate images (brightness individually scaled).
(a) sinc, cos-modulated rates, (b) optimized RF and rate variation.

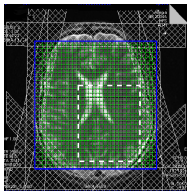


Fig. 2. Scout image of the human brain with 8 OVS slices.

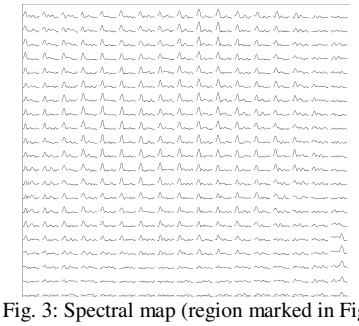


Fig. 3: Spectral map (region marked in Fig. 2).

Conclusion:

The use of pulses with optimized variable rate excitation determined by a genetic algorithm allowed to increase the number of OVS pulses within the spMP-SSFP sequence to eight without violating SAR constraints nor affecting metabolite signal of interest. Additionally, this approach will allow implementations of spMP-SSFP at higher B_0 fields.

References: [1] Schuster C et al., MRM 57:82(2007). [2] Conolly SM et al., JMR 78:440(1988). [3] Conolly SM et al., JMR 78:440(1991). [4] Hargreaves BA et al., MRM 52:590 (2004). [5] Gai ND et al., JMR, EPub ahead (2007) [6] Lunati E et al., JMR 134:223(1998). [7] De Wit A, IDL Genetic Algorithm, http://www.xs4all.nl/~ajwwag/, 2002.