Design of Linear-Phase Frequency-Modulated Broadband Refocusing Pulses

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Introduction

Spin-echo experiments frequently require slice-selective refocusing pulses. The bandwidth of these pulses is limited by the maximum radio-frequency (RF) field strength B_{1max} of the MR system. For 3T scanners, this is typically around $B_{1max}\approx 20\mu T$, leading to a bandwidth of about 1 kHz for regular sinc-Gaussian type of refocusing pulses. Such small bandwidths lead to a strong chemical-shift-displacement artefact, which is a relative spatial displacement for spins of different chemical species. The spectral bandwidth at B_0=3T is around 0.5 kHz, leading to a displacement of half a voxel. It is proportional to B_0, while the bandwidth of RF pulses decreases with approximately $1/B_0$ due to limitations of the transmitting RF field strength. In this work, we present the systematic design and experimental verification of linear-phase frequency-modulated broadband refocusing pulses. A wide range of pulses was designed to investigate the underlying relationships of this class of pulses.

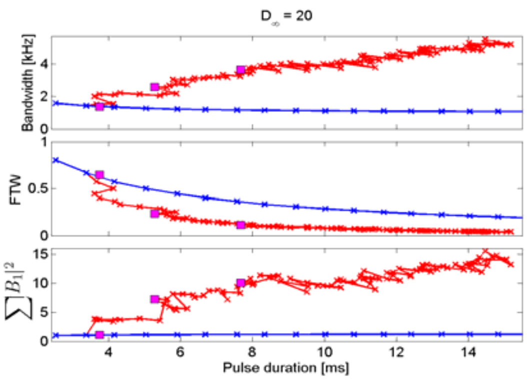

Fig. 1. The resulting physical bandwidth, fractional transition width and energy plotted over the pulse duration, when scaling the pulses to B_{1max}=24μT for both traditional sinc-Gaussian type of pulses (blue) and the broadband refocusing pulses (red). The purple boxes are the selected pulses (Fig. 2).

Theory and Methods

The Shinnar-Le Roux transformation reversibly transforms an RF pulse into two finite-impulse-response (FIR) filters, the *A* and *B* polynomial [1]. The refocusing profile is given by

$$M_{xy}^{+}(\omega) = -B^{2}(\omega) M_{xy}^{-*}(\omega) \qquad (1)$$

Typically, the *B* polynomial is designed with the Remez-exchange algorithm, while the minimum-phase *A* polynomial obeying the condition $|A(\omega)|^2 + |B(\omega)|^2 = 1$ is generated with the Hilbert transformation [1]. Altering the phase response of the *A* polynomial changes the resulting RF pulse shape, while retaining exactly the same refocusing profile, because *A* is not appearing in Eq. 1. In this work, the *A* polynomials were zero-flipped [2,3] in order to minimise the B_{1max} of the pulse. Three different optimisation strategies were implemented for finding the optimal combination of zeroes to flip, an exhaustive search and a genetic algorithm with two different initialisations.

A wide range of refocusing pulses was designed with a flip angle of 172° and time-bandwidth products of 25,30,35,...,500 (in radian). One traditional and two broadband pulses were selected and implemented into the PRESS sequence. The refocusing profile and displacement was measured with T_2 weighted spin-echo sequence in a phantom containing water and sunflower oil. All experiments were performed on a GE Signa HD 3T scanner equipped with a transmit-receive birdcage head resonator.

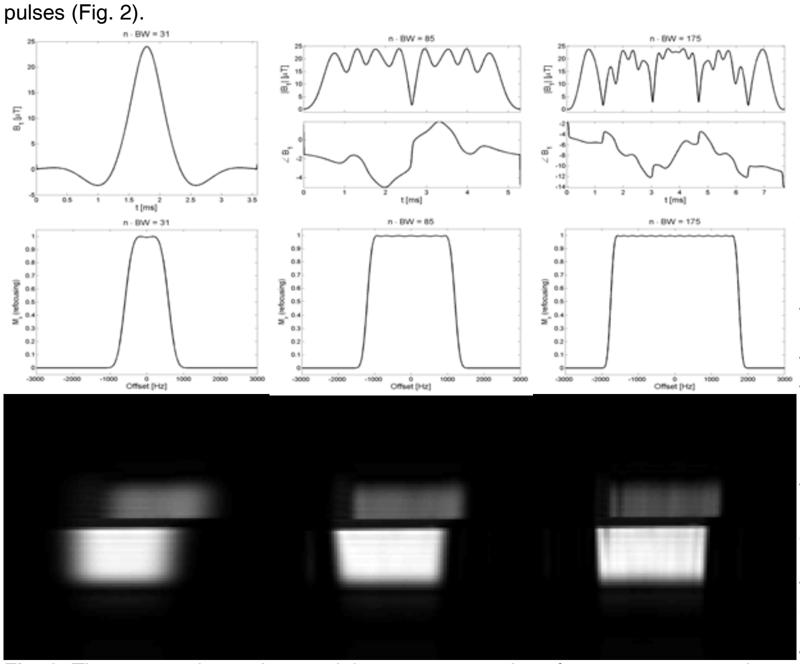

Fig. 2. Three exemplary pulses and their experimental verification in a water-oil phantom. The gradients were adapted to select the same voxel size. The broadband pulses select the voxel in the right-left direction, while up-down is a regular Sinc-Gaussian excitation pulse. The horizontal dark band stems from the chemical-shift displacement (water-fat shift) of the excitation pulse. The chemical shift-displacement is considerably reduced in the direction of the broadband pulses, while selectivity improved. The parameters were B_{1max}=24μT, 256 frequency encodes, 160 phase encodes, TR=1s and TE=26,30,34ms, respectively.

Results

It is possible to flexibly design a wide range of broadband refocusing pulses with the proposed optimisation strategy (Fig. 1). For the exemplary pulses, the bandwidth was increased from 1.2 kHz to 2.1 and 3.0 kHz, while the fractional transition width (transition width over bandwidth) improved from 0.65 to 0.24 and 0.11, respectively. The energy deposition is increased by a factor of 6.8 and 9.5. The experimental verification (Fig. 2) shows its robustness and effectiveness.

Discussion and Conclusion

The broadband refocusing pulses considerably increase the bandwidth and hence alleviate the chemical-shift displacement. The drawback is an increase in energy deposition (SAR) due to two factors. On the one hand SAR is proportional to the bandwidth, while on the other hand pulses with a non-minimum phase *A* polynomial exhibit inherently higher SAR values [1]. SAR is usually unproblematic in spectroscopy due to long repetition times.

The localization accuracy of the PRESS sequence at 3T is considerably improved with broadband refocusing pulses (Fig. 2). It can further extend PRESS localization on human scanners with field strengths of 7T and above, where PRESS currently yields dissatisfying results. Another application is the detection of lactate, which exhibits a great signal cancellation at 3T with TE=144ms due to anomalous *J* modulation [4].

References

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