High Bandwidth Low Power Spatial Saturation Pulses for 7T

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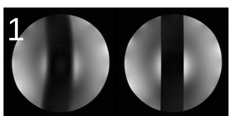
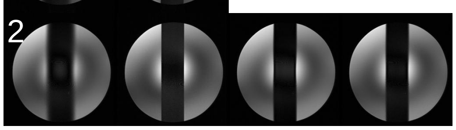
Introduction: Quadratic phase saturation pulses[1-3] allow significant increases in bandwidth with reduced peak RF amplitude (peak B_1) -- and so significantly reduced power requirements -- compared to conventional linear phase designs. For ^{1}H applications at 7 Tesla, controlling peak B_1 amplitudes is essential due to reduced RF coil efficiency with increasing frequency. Using filter optimization tools provided in MATLAB (Mathworks, Inc., USA) integrated into Shinnar-LeRoux design tools ([4]), a family of quadratic phase saturation pulses with scalable B1 dependence was constructed and evaluated in 7 Tesla phantom studies.

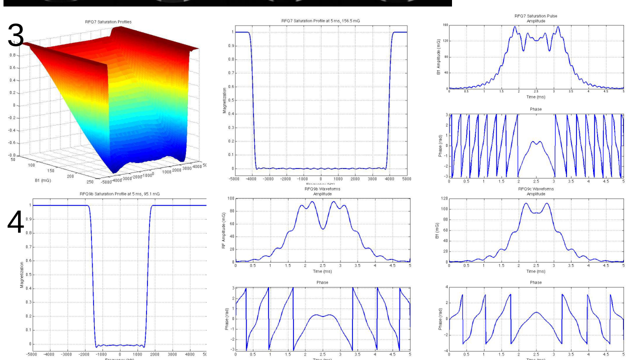
Methods: Pulses were designed in Matlab (Mathworks, Inc., Natick MA) using routines derived from Pauly's routines[4], with the following extensions. The Remez exchange algorithm now uses the function cfirpm which takes as an argument a frequency response function. The standard function, lowpass.m, is replaced by lowpassquad.m, which specifies a quadratic phase over the pass band parameterized by a linear delay d and a quadratic shift k. Frequency in this routine is normalized by the reciprocal pulsewidth. An a polynomial is then generated from the resulting complex b polynomial, and the complex RF pulse backcalculated using the usual piecewise constant representation[4].

The pulse waveform is then simulated by calculating the Cayley-Klein parameters as a function of frequency offset and RF amplitude to determine the appropriate scaling. Iteration over the parameter set is then performed to produce a waveform with the desired bandwidth and peak B1 amplitude to produce saturation of the z magnetization.

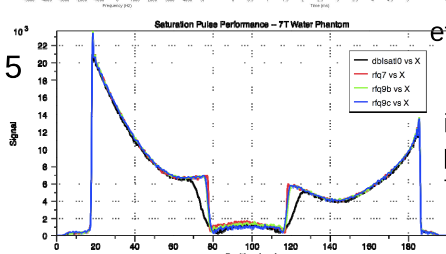
rfq7 has a time-bandwidth product of 40, requiring a peak B1 of 15.6 μT for a 90 degree flip angle at a 5 ms duration. The sweep parameter was 650, with .1% passband ripple and .14% stopband ripple. rfq9b has a lower time-bandwidth product of 16 (allowing an increase in the sweep parameter and a corresponding decrease in the peak B1) with a sweep parameter of 1800, producing 90 degree flip angle at 9.52 μT. Reducing the sweep parameter to 1200 increases the peak B1 requirement to 11.1 μT. For comparison, the linear phase pulse has a time-bandwidth product of 6.4 with a peak B1 of 8.9 μT at a 4 ms pulsewidth.The pulses were then integrated into a pulse sequence module to allow graphical prescription of the sat pulses and compiled into a gradient echo sequence. This sequence was then run on a GE Signa 7T Human MR Research System (GE Healthcare, Waukesha, WI) on a high permittivity (doped water) 17 cm diameter spherical phantom in a head transceiver array (Nova Medical, Wilmington, MA). Saturation pulse performance was compared with a standard linear phase SLR pulse optimized for 1.5T operation.







Results: Figure 1 shows the effect of B0 distortion on the saturation profile for the linear phase pulse (left)and the rfq7 quadratic phase pulse. Figure 2 shows comparative saturation profiles for (from left) linear phase, rfq7, rfq9b, and rfq9c quadratic phase pulses in a doped water phantom. Note the variation in saturation effectiveness due to flip angle variations within the phantom, as well as the sharpness of the profiles. Figure 3 shows the simulated saturation profile for rfq7 vs frequnecy and B1, as well as the saturation profile at 15.6 μT, and the amplitude and phase waveforms. Reducing the sweep parameter reduces the effective pulse width and increases the peak B1 to achieve a given flip angle. Figure 4 shows the simulated saturation profile for rfq9b, followed by the amplitude and phase waveforms for rfq9b and rfq9c. Finally Figure 5 shows the measured profiles in Figure 2 for all 4 pulses, showing the sharper transitions in the quadratic phase pulses, and that rfq9b and rfq9c provide nearly the same sharpness as rfq7, despite the lower time-bandwidth product.



Conclusions: The higher sat pulse bandwidth avoids the distortion of the saturation band by field inhomogeneity produced by magnetic susceptibility variations at 7T. The design procedure described above provides a pulse whose response is scalable in B1 over the range of interest, allowing straightforward adjustment of pulse duration and amplitude without the need to redesign the pulse kernel for each flip angle as mentioned in [3]. B1 reduction can be traded off against passband distortion. These pulses will likely restore the flexibility in the use of spatial saturation pulses found at lower field strengths and so facilitate a number of imaging and spectroscopy studies.

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