A wavelet-based optimization for RF pulse design applied to multiband imaging at 7T

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Target Audience

Scientists and developers interested in RF pulse optimization for peak B1 power reduction or improved slice profiles, including multi-band designs for Simultaneous Multi-Slice imaging.

Purpose

There has been recent work on minimization algorithms to optimize RF pulses for Simultaneous Multi-Slice (SMS) imaging, such as Optimal Control[1] and Optimized Phase Schedules for SMS excitation[2]. These minimization techniques have focused on excitation pulses without addressing refocusing pulses for diffusion and spin-echo imaging. In multi-band SMS sequences, refocusing pulses can produce a prohibitively high peak B1 amplitude. Previous work to reduce peak power for SMS pulses includes time-shifted pulse design[3], multi-PINS design[4], and other methods[5-6]. In this work, we propose numerical optimization in the wavelet domain to design multi-band SMS refocusing pulses with reduced peak power and improved slice profiles.

Methods

Wavelet transforms enable compression of the time-domain pulse with high fidelity. Greater than 90% compression of the RF pulse was achieved, with 536 wavelet coefficients producing 6400 (real + imaginary) time domain points. Discrete Meyer prototype wavelets were utilized based on their ability to provide the highest level of compression for an SMS pulse. The presented optimization uses wavelet decomposition and reconstruction functions along with a nonlinear constrained minimization algorithm in MATLAB (Mathworks, Natick, MA). The phase of the pulse remained unconstrained during the optimization. The Fourier transform approximation of an ideal slice profile was selected as the initial condition for the minimization. Wavelet domain coefficients were numerically optimized while iteratively running the resultant pulse through an open source Bloch equation simulator[7] generating the slice profile. The tip angle in degrees of the slice profile was computed using the net magnetization vectors from the Bloch Simulation. An L2-norm minimization was selected and the cost function computes the sum of the squared difference of the slice tip angle profile compared to the ideal slice profile.

Results

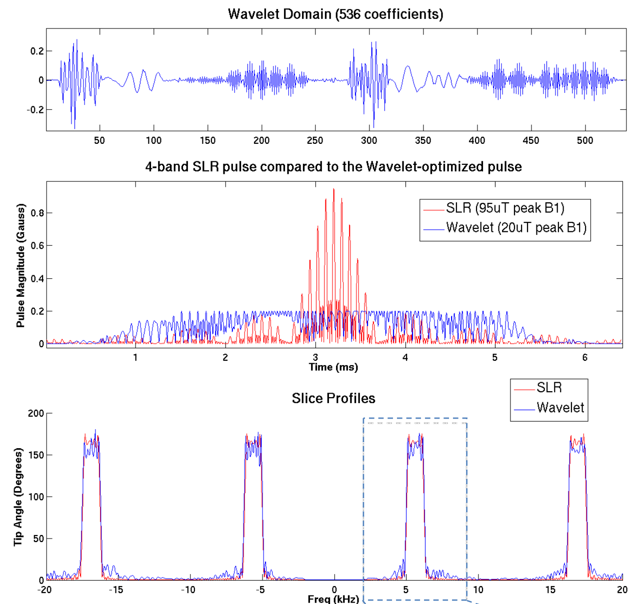
A 4-band pulse with spacing between bands for whole brain coverage was designed. Simulation results demonstrate a wavelet-optimized RF pulse design meeting peak B1 constraints, plotted as the blue trace in Figure 1. Peak B1 was successfully limited to 0.2 Gauss (20uT) while the pulse width remained constant at 6.4ms. The red trace in Figure 1 shows a multiband SLR[8] refocusing pulse, for comparison. The SLR pulse requires a high peak B1 of 95uT (micro-Tesla) to achieve a comparable slice profile to the 20uT wavelet-optimized pulse. Ripples appear large in the plots because of the transformation from Mz to tip angle in degrees. Images were acquired under an approved IRB protocol on a General Electric MR950 (7.0T) scanner using the wavelet-optimized refocusing pulse shown in Figure 1. The GE Healthcare 7T EPI diffusion pulse sequence was modified for this acquisition. A head transmit coil operating in quadrature mode was paired with a Nova Medical 32-channel receive coil. Scan parameters included TE = 72.8 ms, TR = 4 s, full k-space 64x64 matrix, 9 sagittal aliased slices (36 slices after unaliasing) and 4mm isotropic voxels. Images were reconstructed from the raw data file using the GE Healthcare Orchestra reconstruction software development kit in MATLAB that was customized for multiband with Hadamard unaliasing. A subset of the reconstructed images is shown in Figure 2.

Discussion

Arising from the nonlinearity of the Bloch equations, pulses designed with the Fourier approximation exhibit a poor slice profile at high tip angles. SLR pulses achieve a very good slice profile but suffer from high peak B1 amplitudes that are prohibitive at 3.0T and above for SMS acquisitions. Compared to an SLR pulse with a similar slice profile, the wavelet-optimization enables a peak B1 reduction from 95uT to 20uT. Gradient crushers around the refocusing pulse can be employed to mitigate undesired stop-band ripple seen in the wavelet-optimized pulse. Considering the Specific Absorption Rate (SAR), the wavelet-optimized pulse (Figure 1, blue trace) yields a slightly lower integral of $B1^2$ compared to the SLR pulse (Figure 1, red trace), with a ratio of 0.89 for the wavelet pulse divided by the SLR pulse.

Conclusion

Wavelet-based RF pulse optimization may provide a useful design method to achieve RF peak power reduction or an improved slice profile for pulse sequence design. This design method is especially beneficial for multi-band SMS pulses at field strengths of 3.0T and above, yet this method of RF pulse optimization may also be useful if applied to other pulse sequences.



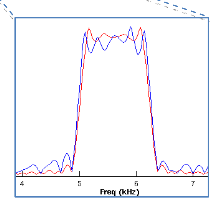


Figure 1: Top: Wavelet-domain representation of the pulse. **Middle**: SLR pulse shown in red; Wavelet-optimized pulse shown in blue. **Bottom**: Slice profile of the SLR (red) and wavelet (blue). Insert shows a zoomed view of one band.

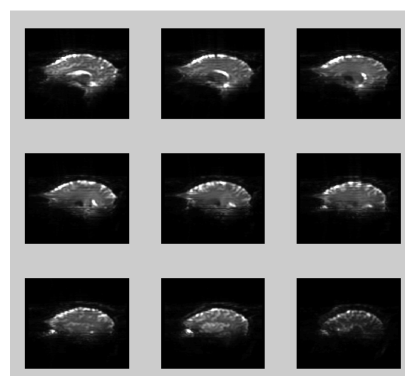


Figure 2: Images obtained at 7.0T with the 4-band wavelet-optimized refocusing pulse.

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