Time-Optimal 3D Gradient Design for RF Shimming

M. Etezadi-Amoli[1], A. B. Kerr[1], and J. M. Pauly[1]

[1]Electrical Engineering, Stanford University, Stanford, CA, United States

Introduction: At high magnetic field strengths, B1 homogeneity of volumetric coils is degraded. Previous work has shown that a spoke trajectory that plays slice-selective RF subpulses along kz can be used to compensate for B1 inhomogeneity, providing uniform in-plane excitation while maintaining slice selectivity [1-3]. However, not much attention has been paid to the possibility of speeding up such excitations by optimizing the gradient trajectory. In this work, we present a spoke trajectory that uses time-optimal gradient waveforms to achieve a speedup factor of more than 10%. We simulate the resulting RF shim performance assuming an eight coil parallel transmit setup.

Theory and Methods: The spoke trajectory consists of an oscillating gradient in the z direction to traverse the spokes and gradient blips in the x and y directions to transition between the different spokes. We consider two optimization methods. The first is a simple approach that deals with each gradient axis separately and is not freely-rotatable. Optimal trapezoid and triangle waveforms are used to make the fastest transitions, subject to gradient amplitude and slew limitations. The second method uses software published by Hargreaves et al. [4] to formulate the gradient design as a convex optimization problem that can be solved for time-optimal gradient waveforms satisfying moment, amplitude, and slew rate constraints. A unique feature of this approach is that it allows for a freely-rotatable gradient design [4].

Both procedures divide the gradient into segments consisting of the transitions between spokes and the spoke traversals. An initial gradient waveform is created by optimizing each gradient segment separately for minimum duration. This first pass result is the non-optimized version shown in Figures 1 and 2. The next step is to consider consecutive segments. The amplitude of the z gradient at the boundary between segments is allowed to vary until the duration of neighboring segments is minimized. Multiple passes through this nonlinear optimization step result in convergence to the final time-optimum gradient.

We used a seven spoke trajectory designed for a 24-cm FOV, slice thickness of 1 cm, and time-bandwidth of 4. The spokes are arranged in a circle of radius 2/FOV in the kx-ky plane, with the six surrounding spokes having an extent in kz of 70% of the center DC spoke. A maximum gradient amplitude of 4 G/cm and slew rate of 15 G/cm/ms were specified. The order of spoke traversal was chosen such that the DC spoke is reached in the middle of the pulse.

We simulated a parallel transmit RF shimming excitation using the optimum gradient from Figure 1. B1 sensitivity profiles were simulated assuming eight ideal loop coils symmetrically distributed around a cylindrical volume. The shim procedure was done as in [2], and Bloch simulation and RMS error were used to evaluate shim performance.

Results: Figure 1 shows the gradient waveforms resulting from the non-freely-rotatable design. The initial non-optimized gradient is 4.2 ms in duration and the optimized gradient is 3.6 ms in duration, giving a 14% speedup. Figure 2 shows the gradient waveforms for the freely-rotatable design. The resulting gradient is slightly slower than the design in Figure 1 (3.7 ms in duration), but still achieves a speedup factor of 12%. Figure 3 shows the RF shimming results. The RMS error between the resulting shim profile and the uniform target profile was less than 1%.

Discussion: We have demonstrated the use of gradient time-optimization to accelerate spoke excitation trajectories. These trajectories have been shown to provide excellent RF shimming results in Bloch simulations.

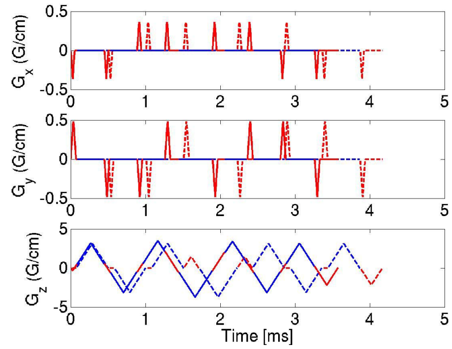

Figure 1: Non-freely-rotatable gradient design, optimized (solid), and non-optimized (dashed). Red denotes transition segments, blue denotes spoke segments.

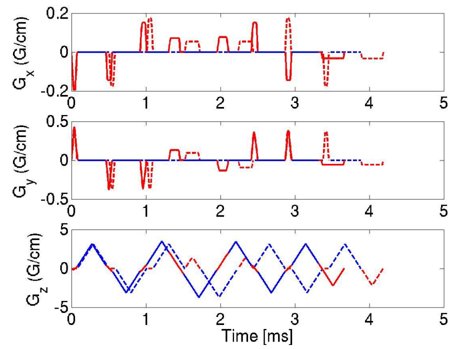

Figure 2: Freely-rotatable gradient design, optimized (solid), and non-optimized (dashed). Red denotes transition segments, blue denotes spoke segments.

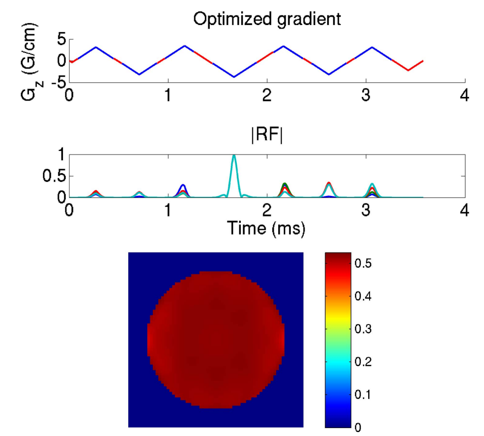

Figure 3: RF shimming design. Top: Z gradient from Figure 1. Middle: Magnitude of normalized RF for four coils. Bottom: Shim results (Bloch simulation of transverse magnetization profile)

References: [1] Saekho et al., MRM, 55:719-724, 2006. [2] Setsompop et al., MRM, 56:1163-1171, 2006. [3] Zhang et al., MRM, 57:842-847, 2007. [4] Hargreaves et al., MRM, 51:81-92, 2004.

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