Sparse Spokes Pulse Design and B_1^+ Inhomogeneities in Ultra-High Field MRI

M. Jankiewicz[1], J. E. Moore[1], H. Zeng[1], A. W. Anderson[1], E. B. Welch[1,2], M. J. Avison[1], and J. C. Gore[1]

[1]Vanderbilt University Institute of Imaging Science, Vanderbilt University, Nashville, TN, United States, [2]Philips Healthcare, Clevelend, OH

Purpose

At high magnetic fields the wavelengths of the RF pulses transmitted in MRI are comparable to the size of the human torso/head [1], which gives rise to inhomogeneous RF fields. Variations of the RF field (Fig. 1a) can be reduced (Fig. 1b) by the use of slice selective, tailored slice-selective pulses optimized for the desired excitation profile [2]. Such pulses approximate (Fig. 1d) the exact modulation pattern (Fig. 1c) by propagating through *n* points in k-space. To make the pulse length as short as possible, the number of sampled k-space points is kept to a minimum. The pulse then consists of *n* sub-pulses, each corresponding to one of *n* different points in excitation k-space, such that excitation k-space is not traversed uniformly. The complex amplitudes of the corresponding sub-pulses are determined by a minimization procedure. Alternatively, the positions of the spokes can be incorporated into the optimization. We have investigated the design and performance of such excitation schemes for imaging with a human scanner at 7T.

Methods

In our preliminary work we used n = 25 spokes in a transverse slice through a head of a human subject. Pulse design consists of two main steps: **Step I:** The approximated desired modulation pattern (Fig. 1d) was obtained through the minimization of the difference

$$\min[m(r) - |\sum_{j=1}^{n} A_j \exp(2\pi i k_j \cdot r + i\gamma\Delta B_o(r)(t_j - T) + 2\pi i \phi_{eddy})|]$$

where $m(r)$ is the exact modulation pattern (Fig. 1c), i.e., the inverse of B_1^+; A_j is the complex amplitude of the j-th spoke/sub-pulse, $k_j=(k_x,k_y)$ is the position of the j-th spoke in excitation k-space, $r=(x,y)$ is a spatial location within the imaging slice, $\Delta B_0(r)$ is the off-resonance map, t_j is the time at which the j-th spoke is executed, T is the length of the pulse, and ϕ_{eddy} is the eddy current phase map.

The minimization involved optimization of the complex amplitudes A_j along the prescribed excitation k-space trajectory; alternatively, the positions k_j of spokes were also subject to the optimization. We have used multiple C++/Matlab (The Mathworks, Natick, MA, USA) optimization routines to handle this task. Experimental inputs for this step include total phase ($\gamma\Delta B_0$ + ϕ_{eddy}) and B_1^+ maps. Total phase is measured by independently recording the phase of the magnetization for each zero-phased sub-pulse in the absence of transverse gradients G_x and G_y. Several B_1^+ measurement methods in common use have been tested, and a method involving a 2-parameter fit to a GRE image series over a range of flip angles [3] was found to be most accurate. **Step II:** The RF pulse and gradients are designed (Fig. 2).

Each sub-pulse consists of a slice selective Gaussian B_1 pulse and corresponding z-gradient. We have written pulse design routines in Matlab to calculate the gradients and RF pulses. Specific realistic hardware limitations (max B_1: 15 μT, max G: 33 mT/m and slew rate 133 $T/m/s$) were incorporated directly into the optimization routines. The values of the amplitudes are bounded from above, depending on hardware limitations. The duration of the RF pulse is also strictly limited by the maximum allowed gradient and the slew rate. The maxima of triangular gradients are limited by the maximum gradient slew rate and the separation of the spokes in the excitation k-space.

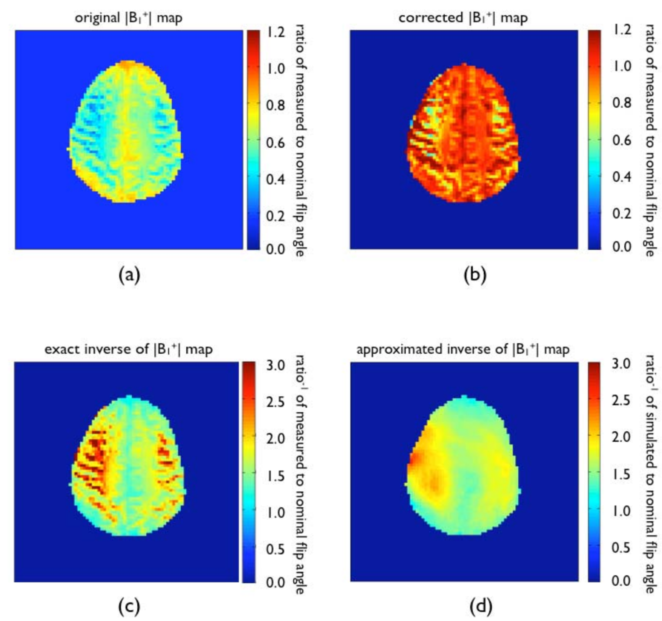

Fig.1: B_1^+ maps (ratio of nominal flip angle, 10°, to measured angle) with up to 60 percent deviations from nominal angle (a) uncorrected, and corrected to ±15 percent (b). The exact desired modulation pattern m(r) (c) is approximated (d) through the optimization routine. Anatomic structures revealed on figures (a)-(c) are likely due to the sensitivity of the B_1^+ mapping technique to T_1 effects.

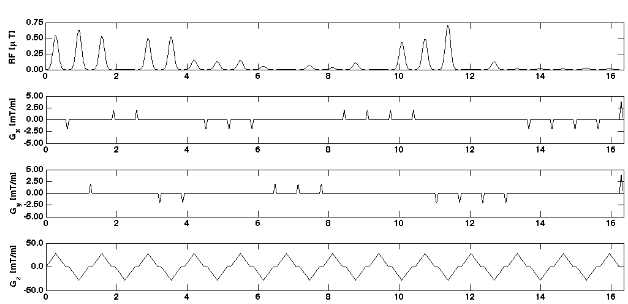

Fig.2: The amplitude of RF pulse together with G_x G_y and G_z gradients. The pulse consists of 25 sub-pulses, each corresponding to a different spoke in transverse excitation k-space. The gradients correspond to a quasi-spiral trajectory.

Results and Conclusions

Results of simulations of the design of RF pulses are promising (compare Fig. 1b with 1a). The pulse can be implemented within existing hardware limitations. The pulse lengths tested here are of the order of ~10 ms, a time short enough to be considered of practical use. Shorter pulses (with fewer spokes) have also been designed; this was accomplished by incorporation of the positioning of spokes into the optimization routine. Approximated modulation patterns effectively correct the modulation profile so that the resulting flip angle map is nearly homogenous, i.e., the deviations of the measured flip angles from the nominal angle are less then ±15 percent in the human head.

RF field inhomogeneities are a major cause of poor image quality in 7T+ systems. The design of new pulses optimized to achieve improved flip angle map homogeneity will enhance image quality, improving and expanding the diagnostic capabilities of ultra high field MRI, and will complement other approaches to overcoming RF non-uniformity at high fields.

Acknowledgments: This work was supported by NIH grant number RO1EB000461. **References: [1]** P. Van de Moortele et al.: B_1 Destructive Interferences and Spatial Phase Patterns at 7T with a Head Transceiver Array Coil, Mag Reson Med 54: 1503 (2005); **[2]** S. Saekho et al.: Fast-k_z Three-Dimensional Tailored Radiofrequency Pulse for Reduce B_1 Inhomomogeneity, Mag Reson Med 55: 719 (2006); K. Setsompop et al.: Sparse Spokes Slice Selective Design for B_1 inhomomogeniety corrections at 7T, Proc Intl Soc Mag Reson Med 15: 256 (2007). **[3]** A. C. Zelinski, et al.: Fast Slice-Selective Radio-Frequency Excitation Pulses for Mitigating B_1^+ Inhomogeneity in the Human Brain at 7 Tesla, Mag Reson Med 59:1355 (2008).