B1+ inhomogeneity compensation using 3D parallel excitation is enhanced by simultaneous linear and nonlinear gradient encoding

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Introduction

Three-dimensional spokes parallel excitation pulses have been proposed and demonstrated for compensation of flip angle inhomogeneities caused by inhomogeneous transmit RF (B_1+) fields [1,2]. These pulses are capable of exciting uniform flip angle patterns within a target slice given a sufficient number of spokes and parallel excitation channels. However, while flip angle homogeneity generally improves with the number of spokes in the pulse, since pulse duration also increases the number of spokes that can be used is limited by the competing desire to limit off-resonance sensitivity, as well as the need to fit the pulses into time-limited sequences (e.g. fast spin echo). It is also desirable to reduce the number of parallel excitation channels required to achieve a given level of flip angle homogeneity, since both B1+ measurement and pulse design become more time consuming as the number of channels is increased. Recently, parallel excitation in combination with nonlinear gradients has been proposed in the context of increasing spatial resolution of excited patterns in the periphery of an object [3]. In this work we demonstrate another benefit of combining parallel excitation with nonlinear gradients, which is that simultaneous linear and nonlinear gradient phase encoding significantly improves the performance of spokes parallel excitation pulses, allowing the use of fewer transmit channels or fewer spokes compared to spokes excitation with linear gradients only.

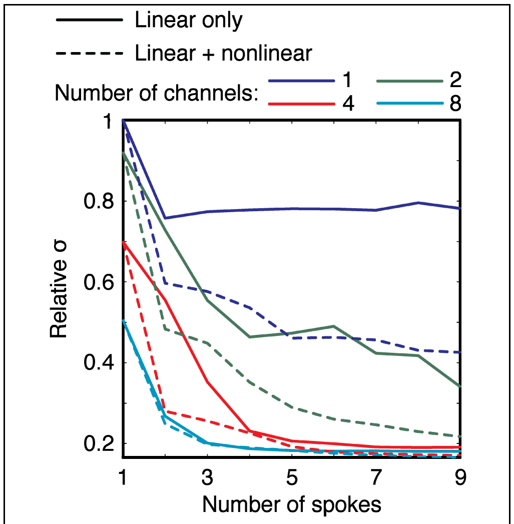

Figure 1: *Normalized flip angle standard deviation (a measure of inhomogeneity). Including nonlinear gradients in the set of channels available for phase encoding in spokes pulses dramatically improves the homogeneity of the excited patterns, particularly for small numbers of transmit channels and pulses with a small number of spokes.*

Theory

The transmit RF (B_1+) fields of a coil array generally contain higher spatial frequencies near the periphery of an imaged object, where the intensity of the individual elements' fields decays the most rapidly and traveling wave behavior leads to spatially complex combined field patterns [4], while fields in the object's center tend to be smoother. As a result, the flip angle patterns required to compensate the array's inhomogeneity will also contain higher spatial frequencies near the object's periphery, and lower frequencies near its center. Nonlinear gradient encoding is well-suited to this problem, since quadrupolar and other higher-order gradient fields encode higher spatial frequencies at the object's periphery [3]. This may permit the use of fewer spatial encoding steps in a spokes pulse, or fewer transmit channels in a parallel excitation array.

Pulse Design

Spokes pulses were designed for a simulated 8-channel transmit array at 3 Tesla [5] using a hybrid greedy and local joint RF and gradient small-tip pulse design algorithm [6]. 1-, 2-, and 4-channel arrays were also synthesized by combining neighboring channels with birdcage phases. Spokes pulses (1 to 9 spokes) were designed to excite a uniform pattern within the simulated object, and the flip angle standard deviation was calculated for each pattern. Pulses were designed both with linear (x and y) in-plane gradient phase encoding, and also with simultaneous linear, quadrupolar (2xy and x^2-y^2), and z^2 (= x^2+y^2) phase encoding.

Results

Figure 1 plots the flip angle standard deviation of pulses designed with linear and linear + nonlinear phase encoding gradients. Substantial reductions in flip angle standard deviation relative to a birdcage mode are achieved by the inclusion of nonlinear gradients, especially for a small number of transmit channels. Figure 2 shows selected comparisons demonstrating that simultaneous linear + nonlinear phase encoding enables either a substantial reduction in pulse duration for a fixed number of transmit channels, and/or fewer transmit channels for a fixed pulse duration. For a 100us phase encoding blip, the peak g/cm across all designs in the 24 cm FOV were 1.61 g/cm (2xy), 1.4 g/cm (x^2-y^2), and 3.27 g/cm (z^2), with peak field strengths of 8.41 g, 9.65 g, and 19.61 g, respectively, which are within the capabilities of current linear gradient systems.

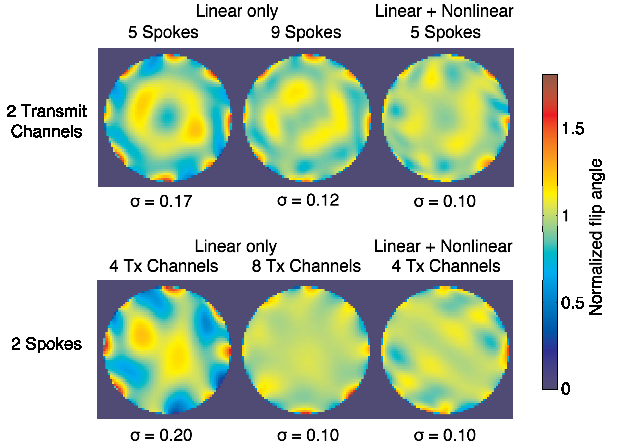

Figure 2: Normalized flip angle patterns *(Top) Spokes excitation with two transmit channels and linear encoding fields achieves a large (17%) flip angle inhomogeneity, which can be mitigated by increasing the number of spokes from 5 to 9 (an 80% increase in duration). Alternatively, using simultaneous linear and nonlinear gradient encoding provides the same homogeneity without increased pulse duration. (Bottom) The performance of 2-spokes excitation pulses with linear encoding only and 8 transmit channels can be achieved with the same pulse duration and 4 transmit channels when linear and nonlinear fields are used simultaneously.*

Conclusion

The benefit of simultaneous linear and nonlinear gradient encoding was demonstrated in simulations for the compensation of B_1+ inhomogeneity using parallel excitation spokes pulses. Exciting simultaneously with linear and nonlinear gradients permits the reduction of spokes pulse duration, and/or a reduction in the number of parallel excitation channels required to achieve a given level of flip angle homogeneity, thereby improving the overall effectiveness of parallel excitation spokes pulses.

References

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