RF Concatenation with Spiral In-and-Out Trajectory for Two-Dimensional Large-Tip-Angle Excitation

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Introduction: A time-reversed concatenated RF pulse can be regarded as a composite pulse in which the error in the first half of the pulse is corrected by the second. The method is general in that it is not restricted to a particular tip angle, and is effective since the tip angle of the first pulse is doubled by the second [1]. A major drawback of the method applied in one-dimensional selective inversion is its sensitivity to off-resonance effect. Here we show that the method can be extended to multi-dimensional excitation with multiple coils, and that off-resonance sensitivity is much reduced in two-dimensional excitation with a spiral in-and-out trajectory where the peaks in the two subpulses can be placed close to each other.

Theory: In the absence of relaxation, the net effect of time dependent magnetic field on a magnetization vector is three-dimensional rotation, characterized by an angle ϕ and an axis of rotation (n_x, n_y, n_z). Using spinor domain representation of the Bloch equations, it can be shown that for any magnetic field pulse, if one applies the pulse backward with one of the three Cartesian components (say z) of the field negated, the modified pulse defines a 3D rotation identical to the original one except that the sign of the corresponding rotation axis component (n_z) is reversed. When the two pulses are concatenated, the total rotation satisfies $n_z = 0$. Consider a 180_x pulse for which $\phi = 180$, $n_z = 0$, $n_y = 0$. The concatenation automatically grants one of the three equations. For inversion, n_y is irrelevant, leaving only one equation to be satisfied by pulse design. This leads to greater tolerance to errors in the pulse design. If the off-resonance field is negligible, the production of the second pulse in the foregoing example can be accomplished by playing the first RF pulse backward, while traversing the k-space also backward in time. In purely linear regime, the reversing operation is immaterial since the same k-space points are collected; RF concatenation therefore operates on and reduces undesired non-linear effects in pulse design.

Methods: Matlab simulation was performed on an 8-coil parallel transmit (pTx) system with B_1+ maps calculated from a human head model. The first 90° pulse was obtained by non-iterative, linear method outlined in ref. [2]. The target profile was 2D homogeneous excitation. The second pulse was obtained from k-space time-reversal of the first pulse, and the resulting inversion profile was obtained by Bloch simulation. Off-resonance effect was not included in this simulation. In-vivo and phantom images were obtained with a conventional (non-pTx) 3T scanner with a head coil. 2D inversion profile was obtained by first inverting spins with a 2D non-slice selective pulse (or hard pulse), and then refocusing spins with a conventional slice-selective pulse. The obtained image shows residual transverse magnetization in an axial slice after the inversion, and is sensitive to tip angle error away from 180°.

Results: The leftmost figure in Fig. 1(b) shows the performance of the concatenated RF pulse in homogeneous inversion. The tip angle error is much smaller than that from either non-iteratively [2] or iteratively [3] designed pTx pulse directly targeting 180° tip angle. This conclusion did not change when the latter pulses were built upon a six-turn spiral instead of three. Figure 2(a) shows the performance of a similarly designed pulse in non-pTx brain scan. Non-iteratively-designed 90° pulse based on the measured head coil B_1+ map [4] was augmented by its time-reversed pair for homogeneous inversion. Very little residual magnetization is visible in the water proton image. Figure 3(c) shows the concatenated RF pulse indicating RF peaks near the center of the pulse. This fact makes the 2D pulse less sensitive to off-resonance effect. Off-resonance effect was investigated in a series of phantom images. Figure 3 shows that the residual magnetization becomes large (grey scale is such that white corresponds to full magnetization) near the fat frequency.

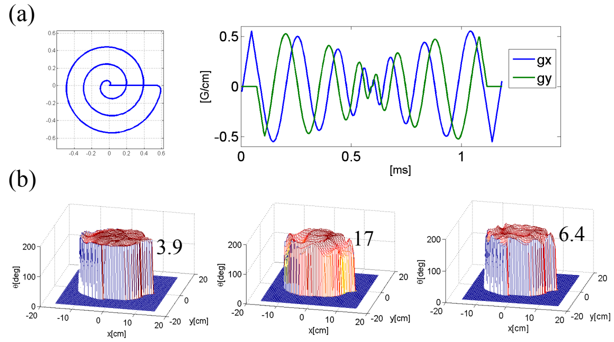

Figure 1. (a) k-space trajectory and gradient waveforms for time-reversed RF concatenation. (b) Simulated tip angle profiles. 2D homogeneous inversion pulse was designed for an 8-channel pTx system by non-iterative $90° + 90°_{rev}$ RF concatenation (left), 180° non-iterative design (center), 180° optimal control-based iterative design (right). The numbers show standard deviation in degrees.

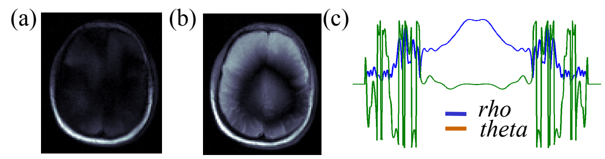

Figure 2. In-vivo head images at 3 T. (a) Uniform inversion at water frequency by $90°+90°_{rev}$ RF concatenation. The first 90° pulse was calculated by a linear method. (b) Image obtained when the design RF pulse is replaced by a nominal 180° hard pulse. Shading represents significant B_1+ variation. (c) Concatenated RF waveform, duration 3.6 ms.

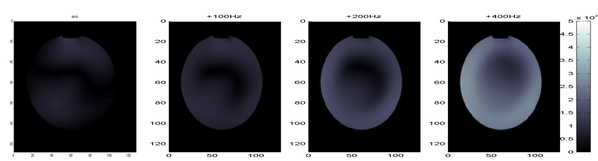

Figure 3. Off-resonance effect in phantom images. The concatenated RF was played with a frequency offset $\Delta f = 0$, 100, 200, 400 Hz (left to right).

Conclusion: We presented a method to construct a large-tip-angle multi-dimensional excitation pulse from a pair of non-iteratively designed half-angle pulses. The concept of concatenated RF pulse as a means to ensure certain symmetry in pulse dynamics may be useful in understanding and designing spatial RF pulses in the non-linear regime. For example, any symmetric RF (i.e. sinc) pulse along the x axis in a constant z-gradient can be regarded as a time-reversed concatenated pulse where $n_y = 0$ is guaranteed at the end of the pulse. For the proposed method to be of greater use in high-field RF pulse design, its off resonance effect should be thoroughly understood. As is demonstrated here, the method is well suited for 2D excitation in which k-space weights are centered near the origin, which are then sampled by a spiral in-and-out trajectory. Further assessment of practical realization of the method as a fast RF design algorithm for pTx is currently underway.

References: [1] Pruessmann KP et al, JMR 2000;146:58 [2] Xu D et al, MRM 2007;58:326 [3] Xu D et al, MRM 2008;59:547 [4] Sacolick LI et al, MRM, in press