Two-Step Small Transverse Magnetization Method for the Design of 180° Spatially Selective RF pulses

M. Haas[1], P. Ullmann[2], J. Hennig[1], and M. Zaitsev[1]

[1]Dept. of Diagnostic Radiology, Medical Physics, University Hospital Freiburg, Freiburg, Germany, [2]Bruker BioSpin MRI GmbH, Ettlingen, Germany

Introduction

In parallel RF excitation, the design of two-dimensionally selective pulses in the small tip angle (STA) regime is well established and computationally efficient [1-4]. To design spatially selective pulses with large flip angles, e.g. inversion and refocusing pulses, most approaches to date rely on solving the Bloch equations iteratively [5-7], which requires more computing time than STA design. Recently, a non-iterative approach for large tip angle design has been presented [8], which avoids a Bloch integration altogether, but requires refocusing of each of several subpulses.

In this work an extension of the STA method to a small transverse magnetization (STM) approximation is presented, which in combination with only one Bloch integration can design pulses that produce a 180° rotation around a given axis inside an arbitrarily shaped 2D target area and no rotation outside this area. These pulses can be used for inversion and refocusing, and combine the speed of STA design with the accuracy of a Bloch design method.

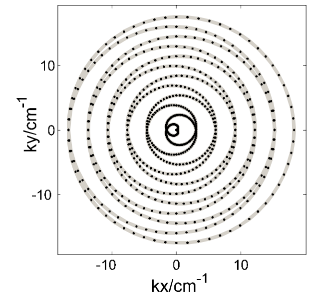

Fig. 1: A double-spiral k-space trajectory with 12 turns used for design of 180° STM pulses below.

Methods

The STA methods start by making the approximation $M_z(\boldsymbol{r}) \equiv 1$. The Bloch equations for the magnetization $\boldsymbol{M(r)}$ can then be simplified to one complex differential equation, with the formal solution for the transverse magnetization $M_t(\boldsymbol{r})$

$$M_t(\boldsymbol{r}) = i\gamma M_0(\boldsymbol{r}) \int_0^T dt \sum_l S_l(\boldsymbol{r}) I_l(t) \exp\left[i(\boldsymbol{k}(t)\cdot\boldsymbol{r} + \Delta\omega(\boldsymbol{r})(T-t))\right], \qquad (1)$$

with RF amplitudes I_l played out by coils with transmit profiles S_l, and while the gradients traverse k-space according to $\boldsymbol{k}(t)$. However, this solution can also be used in the regime where the $M_z(\boldsymbol{r})$ are close to either +1 or -1, which we will call the STM approximation for a situation where an imperfect inversion profile is present (see Fig. 2, left and Fig. 3, left). Consequently, the STM method consists of two steps. First, a standard STA pulse on the first half of the k-space trajectory (see Fig. 1) is designed, specifying the desired rotation axis as the phase of the target pattern. The outcome of this pulse, scaled up to 180°, is evaluated with a Bloch simulation. Then the deviation from the desired pattern (again angle and axis) is calculated as the new target pattern, and Eq. (1) is solved a second time, but on the second half of $\boldsymbol{k}(t)$. Thus, k-space is sampled all over again, and the small transverse magnetization deviations are corrected. Therefore, a STM pulse is twice as long as the corresponding STA pulse. Obviously, this method critically depends on a sufficiently good result from the scaled up STA pulse, which is why spirals are well suited as k-space trajectories.

B_0 off-resonances can be taken into account in both RF design steps as described e.g. in [3], and included in the Bloch integration straightforwardly. Also, VERSE [9,10] is compatible with the method as the two design steps do not need to have an equal number of sampling points in k-space. This can be used to optimize the SAR or the duration of the pulse.

We have designed and simulated such a 180° pulse on a FOX of $(5.5\text{cm})^2$ with the measured B_0-map and transmit profiles of a 4-element RF coil array loaded with a spherical water phantom at 9.4 T. The C-shaped target pattern was defined on a 32x32 grid, the k-space trajectory (accelerated by 1.33) as depicted in Fig. 1 has 12 turns (6 in, 6 out), 768 sampling points, and a total length of 4 ms. The simulations in Fig. 2 were performed on a 128x128 grid. The total design time is ~1 s on a 2.6GHz dual core desktop PC.

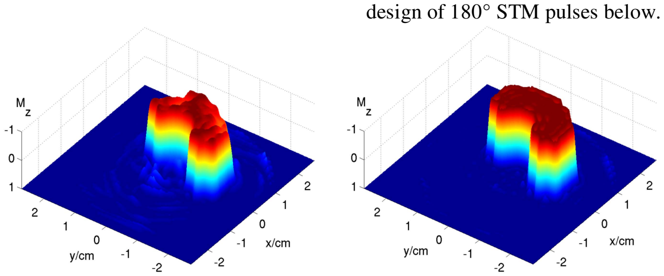

Fig 2: z-magnetization in a $(5.5\text{cm})^2$ field of excitation, produced by a small tip angle pulse scaled up to 180° (left), and after the second half of the STM pulse has been played (right), correcting the deviations from the desired target pattern. Note that the z-axis is inverted.

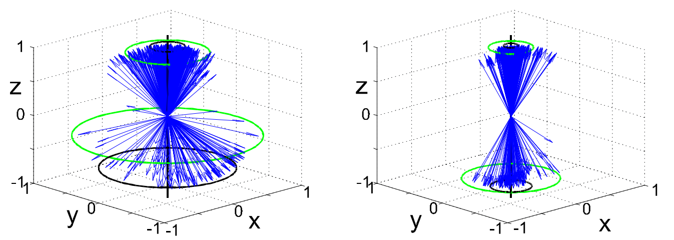

Fig. 3: Distribution of magnetization vectors on the grid after the first half of the STM pulse (left) and at the end (right). Initial magnetization is in +z direction. Vectors pointing upwards are located outside the target area, vectors pointing downwards are located inside. The black circle encloses 68% of the vectors, the green circle encloses 95% of vectors in the respective direction along the z axis.

Results

First we considered initial magnetization in +z direction on the whole grid. The result of the scaled up STA pulse (Fig. 2 left, and Fig. 3 left) exhibits the expected imperfections in the inversion profile, while during the second half of the pulse, deviations both from 0° and from 180° are significantly reduced (Fig. 2 right, and Fig. 3, right).

Although the theoretical framework is based on the assumption of nearly pure z-magnetization, the resulting pulse is described as a sequence of rotations which are carried out irrespective of the initial orientation of the magnetization. Since the axis of the overall rotation is approximately the same at all points inside the target area, STM pulses also work as refocusing pulses, as shown in Fig. 4. Here, the initial magnetization was chosen to be in the transverse plane with 8 phases inside the target area, and along the +z axis everywhere else. The magnetization outside the target essentially stays in place after the pulse (point nr. 9), while the excited part of the initial magnetization undergoes a rotation around the y axis by close to 180°.

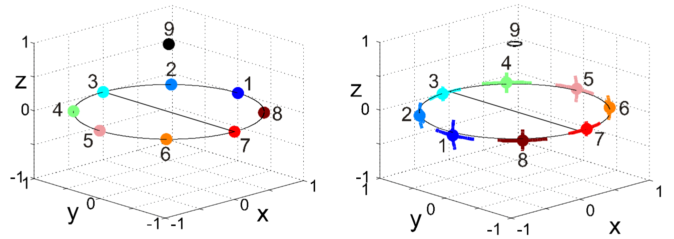

Fig. 4: Left: initial magnetization in the transverse plane (points 1-8) inside the target pattern, and in +z direction outside the target (point 9). Right: Distribution of magnetization after the STM refocusing pulse. Error bars (1-8) and black circle (9) enclose 68% of the corresponding initial magnetization vectors. The mean refocusing efficiency is 95.2% inside the target.

Conclusion and Outlook

The presented method represents a fast pulse design algorithm for 2D spatially selective 180° pulses which is applicable to inversion and refocusing pulses and performs well in simulations. Current and planned investigations include the experimental verification of the proposed algorithm and the analysis of its robustness against experimental imperfections.

References: [1] U. Katscher et al., MRM **49**, 144-150 (2003). [2] Y. Zhu, MRM **51**, 775-784 (2004). [3] W. A. Grissom et al., MRM **56**, 620-629 (2006). [4] I. Graesslin et al., ISMRM 2006, p. 2470 [5] J. L. Ulloa et al., ISMRM 2006, p. 3016 [6] W. A. Grissom et al., ISMRM 2007, p. 1689 [7] K. Setsompop et al., ISMRM 2007, p. 677 [8] D. Xu et al., MRM **58**, 326-334 (2007). [9] S. Conolly et al., JMR **78**, 440-458 (1988) [10] I. Graesslin et al., ISMRM 2007, p. 674

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