Strongly Modulating Pulses: a New Method for Counteracting RF Inhomogeneity at High Fields

N. Boulant[1], D. Le Bihan[2], and A. Amadon[2]

[1]Siemens Medical Solutions, Siemens, St Denis, France, [2]NeuroSpin, CEA-Saclay, Gif sur Yvette, France

Introduction: A new pulse technique for counteracting RF inhomogeneity at high fields has been developed. The method, inspired from nuclear magnetic resonance quantum computing [1], makes use of the detailed knowledge of the voxels' B_1 and ΔB_0 amplitude 2D histogram to generate, through an optimization procedure, gates where the flip angle is made uniform. The use of such 2D histogram instead of the parameters' joint spatial distribution decreases substantially the complexity of the problem, allowing an optimization algorithm to find an RF pulse solution in less than two minutes. In addition, the procedure is based on an exact calculation and does not use any linear approximation. The 3D brain in vivo images obtained at 3 T yield a reduction of the standard deviation of the sine of the flip angle by a factor of up to 15 over a whole human brain, around the target value, compared to when a standard square pulse calibrated by the scanner is used. Finally, calculations tend to show that the new designed pulses can be 2 to 3 times less energetic than standard BIR4 adiabatic pulses achieving similar performance.

Theory: Adiabatic and composite pulses have one thing in common: their phase is not constant over time. If it was not the case, the spin flip angle (FA) would be proportional to the integral of B_1 with respect to time. A dispersion of B_1 then would necessarily imply a dispersion of the FA. The new kind of pulses reported here, called "strongly modulating pulses" in [1], exploits both this phase variation principle and the fact that for constant B_1 amplitude and a phase varying linearly in time, an analytical solution of Schrödinger's equation exists. Using a spinor notation, the Hamiltonian H of a spin ½ at a given position $\boldsymbol{r}$ under a circularly polarized radio-frequency (RF) field of constant amplitude $B_1(\boldsymbol{r})$, in a reference frame rotating at the carrier frequency, is given by (setting h/2π=1 for convenience):

$$H(r,t) = -\frac{\gamma \Delta B_0(r)}{2}\sigma_z - \frac{\gamma B_1(r)}{2}\left\{\sigma_x \cos[\Phi(t)] + \sigma_y \sin[\Phi(t)]\right\}$$

where $\Delta B_0(\boldsymbol{r})$ is the external static field offset, perpendicular to B_1, γ is the gyromagnetic ratio (in rad/T), $\sigma_{x,y,z}$ are the Pauli spin matrices, and $\Phi(t)$ is the time-dependent phase of the RF field. When $\Phi(t) = \varphi_0 + \omega t$, where φ_0 is the initial phase, t is the time and ω the angular frequency, the Hamiltonian is time-independent in the new frame rotating at ω so that Schrödinger's equation can be solved analytically. So far however, the pulse would not allow for the homogenization of the spin FA, whatever the parameters used. The idea therefore is to implement a cascade of N such square pulses evolutions, each being parameterized by a duration τ_k, a frequency ω_k, a $B_{1,k}$ amplitude and an initial phase φ_k to yield for net propagator:

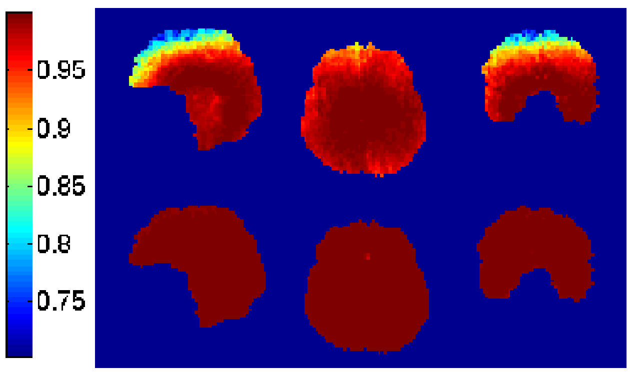
$$U(r,t=\sum_{k=1}^{N}\tau_k) = \prod_{k=1}^{N}\exp(-i\omega_k\sigma_z\tau_k/2)\exp\left(i\left\{(\omega_k+\gamma\Delta B_0)\sigma_z+\gamma B_{1,k}[\sigma_x\cos(\phi_k)+\sigma_y\sin(\phi_k)]\right\}\tau_k/2\right)$$

where the spatial variation here is introduced via B_1 and ΔB_0. Once applied on the initial wavefunction, the calculation of the FA follows. The dynamics now are rich enough to homogenize the FA and yet, their computation is quickly performed, due to the linear time-dependence of the phase. A genetic algorithm combined with a direct search method is used to navigate in this 4N-dimensional parameter space to find a satisfying RF solution, N being gradually increased until the algorithm convergence criteria are met. Yet, optimizing the spins' FA by calculating their evolution in each voxel would be a formidable task for a high resolution 3D image. But if the ΔB_0 and B_1 3D maps are known via a measurement, then the pulse performance can be calculated by looping over a few tens of $\{\Delta B_0, B_1\}$ values and using their corresponding weights in the bi-dimensional histogram, thereby greatly reducing the complexity of the optimization problem.

Methods: We used the actual flip angle imaging (AFI) sequence reported in [2, 3] to measure B_1 and ΔB_0 over the volunteer's brain using a standard square pulse. The same sequence was used to quantify the strongly modulating pulses' performances. We tested a series of 3 strongly modulating and square pulses (30°, 60° and 90°) on a human subject using a 3 T Siemens Trio scanner (Siemens, Erlangen, Germany) and a quadrature head coil, and took only the brain-masked voxels to compute the $\{\Delta B_0, B_1\}$ amplitude 2D histogram to design the pulses. The strongly modulating pulses were designed on the fly during the volunteer's exam.

	30° Pulse	60° Pulse	90° Pulse
Square Pulse	0.445 ± 0.058	0.791 ± 0.080	0.965 ± 0.046
S. Mod. Pulse	0.490 ± 0.019	0.848 ± 0.012	0.999 ± 0.003
S. Mod. Duration	1890 μs	2311 μs	2550 μs
$E_{BIR4}/E_{S.Mod.}$	2.5	3.3	2.1

Table: Mean sine of the flip angle ± its standard deviation over the whole brain for the square pulses calibrated by the scanner and the strongly modulating pulses. The target values were 0.5, 0.866 and 1 for the 30°, 60° and 90° pulses respectively.



Results and Discussion: The means of the sine of the FA ± its standard deviation over the whole brain are provided in the table. The strongly modulating pulses clearly outperform the standard square pulses calibrated by the scanner. The figure provided shows the sine of the FA over three orthogonal slices of the volunteer's brain, for the 90° pulse experiment. To compare the pulses' energy demands with the adiabatic pulses' ones, we selected the tanh/tan BIR4 pulse (5 ms duration) as suggested in [4] and searched via calculations for the parameters that minimize the energy (integral of $B_1^2(t)$ with respect to time) in addition to satisfy a performance criterion commonly reached by the strongly modulating pulses (within 0.01 of the target value, and standard deviation ≤ 0.01). Once found, we computed the energy ratios $E_{BIR4}/E_{S.Mod.}$ (see table). The calculations therefore tend to show less energy demands for the strongly modulating pulses. The strongly modulating pulses reported here only apply to non-selective 3D spoiled gradient echo sequences. Further work is needed to extend their applicability to selective pulses and spin echo sequences.

Conclusion: We have developed a new kind of pulses compensating for RF inhomogeneity. Due to their parameterization and the use of a $\{\Delta B_0, B_1\}$ amplitude 2D histogram, the spins' dynamics calculation is performed quickly, thereby allowing an extensive search in parameter space. The RF pulse solutions returned perform much better than the square pulses automatically calibrated by the scanner, sometimes by up to a factor of magnitude. Finally, the calculations tend to show less energetic demands than for adiabatic BIR4 pulses, making the technique particularly attractive for in vivo applications at high fields.

References: [1] E. M. Fortunato et al. J. Chem. Phys. 116:7599-7606 (2002). [2] V. L. Yarnykh. MRM 57:192-200 (2007). [3] A. Amadon et al. ISMRM 2008. [4] Bernstein et al. Handbook of MRI Pulse Sequences. Elsevier Academic Press (2004).

Figure: Measured sine of the FA for a square pulse calibrated by the scanner (top row), and a 90° strongly modulating one (bottom row). Three orthogonal views are shown (from left to right: sagittal, axial and coronal slices).