B_1 inhomogeneity mitigation in the human brain at 7T with selective pulses by using Average Hamiltonian Theory

N. Boulant[1], M. Cloos[1], and A. Amadon[1]
[1]NeuroSpin, CEA Saclay, Saclay, France

Introduction: A new type of composite pulses, named "strongly modulating pulses" (SMPs) and designed to mitigate the B_1 and ΔB_0 inhomogeneity problem at high field, was presented and validated at 3T and at 7T in the human brain in [1]. The success of that technique was due to the relatively complex dynamics engendered by the frequency modulation and yet for which an analytical expression of the dynamics existed (allowing to search quickly in some parameter space). The main benefits included: good homogenization of the flip angle (FA), no small tip angle approximation (STA), significantly lower SAR than typical adiabatic pulses, and reasonable pulse durations. The main drawback was their non-selectivity, so that 3D reading techniques and longer scans were required. Here the design of the SMPs is extended to make selective pulses and by using Average Hamiltonian Theory (AHT) [2]. When each sub-pulse of the initial composite SMP indeed is replaced by a time-dependent slice selective pulse played in the presence of a magnetic field gradient, in general no analytical solution exists for the rotation matrix. AHT can however be used to approximate to a certain degree the latter if certain conditions are fulfilled. Such approximation allows again navigating quickly in the parameter space. When a sufficiently good solution is found, a last search algorithm just needs a few iterations to find a good solution corresponding to the true dynamics.

Theory: 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 amplitude $B_1(\boldsymbol{r,t})$, in a reference frame rotating at the carrier frequency, is given by (setting h/2π=1 for convenience):

$$H_{rot}(\vec{r},t) = -\frac{\gamma(\Delta B_0(r) + G(t)z) + \omega}{2}\sigma_z - \frac{\gamma B_1(r,t)}{2}[\sigma_x \cos(\phi_0) + \sigma_y \sin(\phi_0)] \quad (1)$$

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 where φ_0 is the initial phase, t is the time and ω the angular frequency. Because the Hamiltonian does not commute with itself at all times Schrödinger's equation can not be solved analytically. Using AHT, the propagator can however be written as:

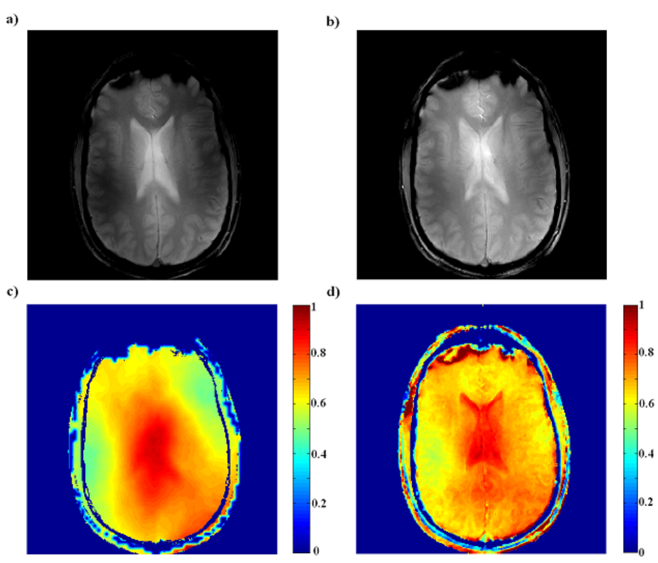
$$U(\vec{r},T) = e^{-i\omega\sigma_z T/2} e^{-iH_{AV}T} \quad (2)$$

where $\boldsymbol{H_{AV}} = \boldsymbol{H^{(0)}} + \boldsymbol{H^{(1)}} + \boldsymbol{H^{(2)}} + \ldots + \boldsymbol{H^{(n)}}$ and is called the average Hamiltonian. It is called the Magnus expansion [2]. Proof of its convergence can for instance be found in [3]. The first term is the zero order term and is given by

$$H^{(0)} = \tfrac{1}{T}\int_0^T H_{rot}(t)dt \quad (3).$$

Looking back at equation (1), we then see that if the integral of G(t) with time is zero, then $\boldsymbol{H^{(0)}}$ does not depend on z and so does $\boldsymbol{U(r,t)}$ to zero order (except for variations of B_1 over the slice thickness but that we neglect here). Note also that it is only the time average of B_1 that matters in equation (3). The zero order approximation however can work poorly if certain precautions are not taken. One can show on the other hand that if $\boldsymbol{H_{rot}(t)} = \boldsymbol{H_{rot}(T-t)}$, i.e. if it exhibits time-symmetry, then $\boldsymbol{H^{(n)}} = 0$ for n odd. To summarize, if the gradient integral is zero and if the Hamiltonian have time-symmetry, to second order the magnetization behaves the same through the slice. Sufficiently far away from z=0, the gradient term in equation (1) becomes larger and larger so that the Magnus series does not converge anymore. One then expects to have an excitation profile consistent with Pauly's analysis [4]. Now because the rotation matrix does not depend to a certain extent on the position within the slice thickness, it can be concatenated with other similar pulses to yield an effective and desired behaviour. Different amplitude, initial phases and frequencies are then optimized using a simplex algorithm to homogenize the FA over the slice of interest. For each trial, the pulse performance is evaluated by looping over the bi-dimensional $\{B_1,\Delta B_0\}$ histogram bin values, thereby reducing the complexity of the problem [1]. Once a satisfactory solution has been found using that algorithm and the AHT approximation, it is passed to a line-search algorithm which this time computes the dynamics without making any approximation. It usually converges fast to a local minimum of the cost function.

Methods: We measured B_1 and ΔB_0 over a volunteer's brain using a standard square pulse and the AFI 3D sequence [5] on a 7T Magnetom scanner (Siemens, Erlangen, Germany), and using a quadrature head coil. We designed on the fly during the volunteer's exam a 30° selective SMP. The returned SMP consisted of 5 sinc sub-pulses, each apodized with a Hanning window, each of 700 µs duration and bandwidth of 4 kHz. They were played in concert with polarity alternated gradient waveforms of 18 mT/m target strength, yielding a slice thickness of roughly 5 mm. The theoretical standard deviation over mean ratio was 4.2 %. For validation, the pulse was inserted in a GRE sequence with TR = 1s, TE = 6 ms, resolution 0.9 × 0.9 mm^2. The same experiment with a square pulse calibrated to yield 30° in the centre of the slice was performed for comparison.



Results and Discussion: The GRE results are shown in Fig.1.a-b. One can see that the SMP was able to bring back up some signal in the regions of low B_1 field (the measured and interpolated B_1 map is shown in Fig.1.c). Because the reception profile also plays a role in the final image, we divided the image **a** by image **b**. In a linear regime, a perfect mitigation of the B_1 inhomogeneity should yield the B_1 profile of Fig.1.c. Although we are clearly not in that regime, the image ratio can still be used to indicate the good correlation between the two.

Conclusion: We have successfully adapted the design of the non-selective SMPs to make them slice selective by using AHT. The experimental results show FA homogenization over the slice of interest and confirm the selective nature of the pulses. The pulses at 7T on the other hand seem to engender too much SAR to be used in a multi-slice 3D sequence in-vivo. Nevertheless it potentially allows the user to obtain a 2D high resolution image (0.4 × 0.4 mm^2) in less than 2.5 minutes.

References: [1] Boulant N et al. MRM 2009;61:1165–1172. Boulant N et al. MRM 2008;60:701–708. [2] Haerberlen U and Waugh JS. Phys Rev 1968;175:453–467. [3] Pechukas P and Light JC. J Chem Phys 1966;44:3897. [4] Pauly J et al. JMR 1989;81:43–56. [5] V. L. Yarnykh. MRM 2007;57:192-200.

Fig. 1. GRE result for a square pulse calibrated to yield 30° in the middle of the slice (a), GRE result for the selective SMP pulse (b), measured B_1 distribution (interpolated) using the AFI sequence (c), and the ratio image(a)/image(b) (d). Such ratio removes the contribution coming from the proton density and the reception profile in the final result.