High performance computation of spatially selective excitation pulses regarding realistic experimental conditions

T. Stöcker[1], and N. Shah[1]

[1]Institute of Medicine, Research Centre Jülich, Jülich, Germany

Introduction

Multidimensional spatially selective excitation is an important concept [1], e.g. in the field of *in vivo* spectroscopy or for the challenging task of correcting subject-induced B_1 field inhomogeneities at high field. Recent hardware improvements allow selective excitation pulses in combination with parallel transmit technology (multiple RF transmitters) [2]. However, thus far the computation of these pulses is based on a simplified physical model neglecting relaxation and most of the important off-resonance effects during the pulse. The present approach provides a numerical method to design selective pulses under realistic experimental conditions by utilising general numeric Bloch equation simulations on a high performance computer.

Methods

Within the common physical model for selective excitation, which neglects relaxation and assumes small tip angles, a desired (complex) transverse magnetisation pattern, M_p, is given by

$$M_p(\vec{x}) = i\gamma M_0(\vec{x}) \int_0^T B_1(t)\, \exp[i\vec{x}\cdot\vec{k}(t)]\, dt \qquad (1)$$

where M_0 is the equilibrium magnetisation, $k(t)$ is a given k-space trajectory, and B_1 is the unknown complex RF pulse. A spatially and temporally discrete version of Eq. (1) can be solved for B_1 by suitable generalised matrix inversion methods. The efficiency of such pulses under relaxation and off-resonance were tested by using the MRI simulator package JEMRIS [4]. This simulator performs a general numerical solution of the Bloch equation, i.e. it explicitly accounts for relaxation effects during the application of the RF pulse. Further, it accounts for important off-resonance effects, $\Delta\omega$, such as microscopic random field fluctuations (simulating T_2^*), macroscopic deterministic field inhomogeneities, nonlinear gradient fields, concomitant fields, chemical shift, and susceptibility variations. Therefore, the influence of these effects on selective excitation can be individually studied in a controlled manner. JEMRIS is entirely written in C++ and it utilises a variable time stepping Bloch equation solver and a master-slave parallelisation topology, allowing the simulation of a large spin ensemble. Here, all simulations were performed on a 16 dual-core CPU Opteron cluster.

The simulator computes the effective transverse magnetisation, $M_e(x,t)$, which is used to correct the RF pulse in order to account for effects not governed by Eq. (1). Thus, a minimisation problem is formulated and individually solved for all time steps $n\cdot\Delta t\ (n=1,...,N)$, where $n\cdot\Delta t=T$ equals the pulse length:

$$\left\| M_p(\vec{x}) - M_e[\vec{x}, M_0(\vec{x}), T_1(\vec{x}), T_2(\vec{x}), \Delta\omega(\vec{x}), \vec{k}(n\Delta t), B_1(n\Delta t)] \right\| = \min_{B_1} \quad , \quad n \in \{1,...,N\} \qquad (2)$$

Here, the difference between the desired magnetisation pattern and the effective magnetisation pattern is minimised with respect to the imaginary and the real part of $B_1 = B_{1x} + i\, B_{1y}$. The starting point ($B_{1x}$,$B_{1y}$) for each of the N consecutive 2D minimisation problems is taken from the solution of Eq. (1). Note that the temporal sampling of B_1 is taken from the discrete version of Eq. (1), whereas the time evolution of the effective magnetisation is computed with much higher accuracy by the simulator, i.e. within each interval Δt the Bloch equation is individually solved for each spin isochromat on a parallel computer and the results are merged to compute the norm in Eq. (2). Once a minimum is found for the n-th step of the RF pulse, the final magnetisation states are taken as the starting condition for the next step.

Results

Exemplarily, for an homogeneous spherical object (T1=1000 ms, T2=10 ms; see Fig. 1a) a desired magnetisation pattern (Fig. 1b) was defined and the corresponding RF pulse (Fig. 2a) for a spiral k-space excitation trajectory (Fig. 2b) was computed according to Eq. (1). Simulations were performed for ≈ 30,000 spins and adding small random field fluctuations to each spin isochromat resulting in an effective transverse relaxation time of approx. T_2^*=8 ms. The resulting transversal magnetisation pattern excited by the RF pulse is depicted in Fig. 1c. Note, that this pattern is not the result of an (simulated) imaging sequence but it is the effective pattern of excited spins directly after the pulse. In comparison, the optimised RF pulse sequence computed with the new approach is depicted in Fig. 2c and the corresponding simulated pattern of excited spins is shown in Fig. 1d.

Conclusion and Discussion

A method which adapts selective excitation RF pulses to realistic experimental conditions is presented. The simulations shown in this abstracts are considered as a proof of principle. The impact of these newly designed pulses in real experiments has to be tested in the near future. For future applications, an extension of the concept to handle parallel transmit pulses is straightforward and will have almost no influence on the calculation times. Further, investigating optimised k-space trajectories as well as the incorporation of time dependent off-resonance effects (such as eddy currents) has to be performed.

References

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2. Katscher et al, NMR BIOM. 2006 (19):393-400.
3. Stöcker et al, Proc. ESMRMB, Warsaw, 2006.

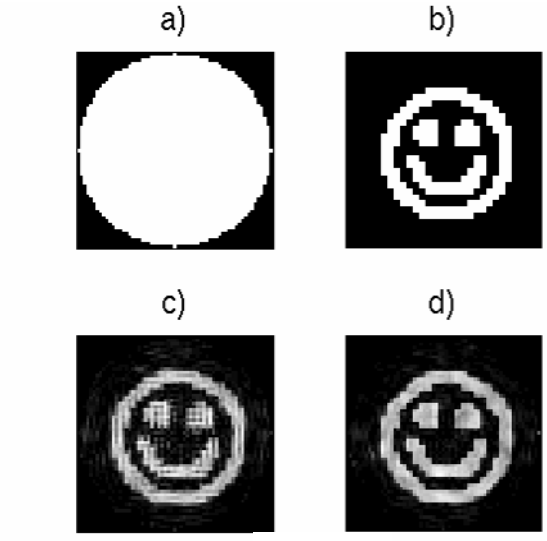

Figure 1

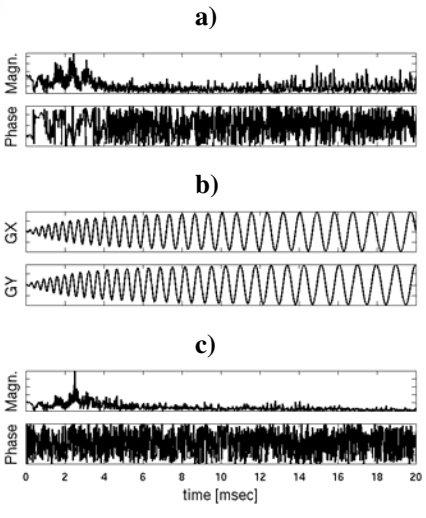

Figure 2