Multi-stage simulated annealing optimization of self-refocused radio frequency pulses with short T2

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INTRODUCTION

When imaging samples with very short T_2 (e.g. bone and porous media) it is desirable to start acquiring signal immediately after the end of the slice select gradient. Self-refocused RF pulses can be optimized to take into consideration transverse relaxation effects. We investigate the design of such pulses that have duration (T_{rf}) comparable to T_2. We use stochastic optimization methods (simulated annealing) and investigate the effect of different annealing procedures.

METHODS

Self-refocused pulses are designed using simulated annealing global optimization techniques [1] with constraints specifying the amplitude of all magnetization components M_x, M_y, and M_z. The magnetization response is calculated by numerically solving the Bloch equations by including T_2 terms (using Runge-Kutta-Fehlberg 6^{th} order method). The profile of B_1 is varied (indirectly through the use of seventeen Fourier coefficients [2]) until an error function attains its minimum. The error is RMS difference between the target and the calculated magnetization. There are 64 constraints for each of the three magnetization components; 32 pulse elements; and pulse duration T_{rf} = 3.1 ms.

Typically the annealing procedure relies on gradually reducing an initial value of a control parameter (temperature analog in thermodynamics) which is used for searching for the minimum at a certain system configuration (a set of B_1 values). There are different routines for lowering this parameter (e.g. exponentially) until a global or a stable minimum is found. We call this continuous reduction a single-stage annealing. We investigate the effect of multi-stage annealing where the search is forcefully reinitialized with smaller initial value of the temperature and a slower rate of its reduction. This is repeated more than once.

RESULTS

We illustrate the application of multi-stage annealing method by designing a self-refocused RF pulse for exciting a rectangular slice of 8 mm width and a flip angle of 90°. We impose short T_2 conditions by restricting T_2 to be equal to the pulse length (T_{rf}). Fig. 1 shows the optimized B_1 profiles for both single- and multi-stage annealing. In the latter, minimization of the objective function was repeated once after an initial global minimum was reached. The initial temperature in the repeat minimization was halved while the reduction rate was slower by five times. The peak powers for the two pulses are similar while the energy is smaller in the multi-stage pulse. The corresponding magnetization profiles are shown in Fig. 2. Transverse magnetization gain is almost 20% in the case of the multi-stage pulse which will lead to better SNR.

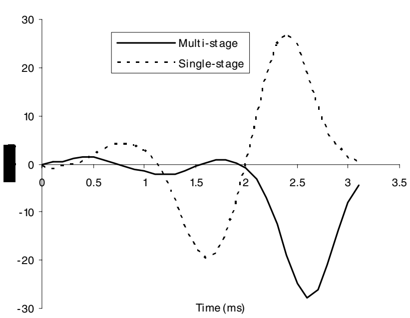

Fig. 1

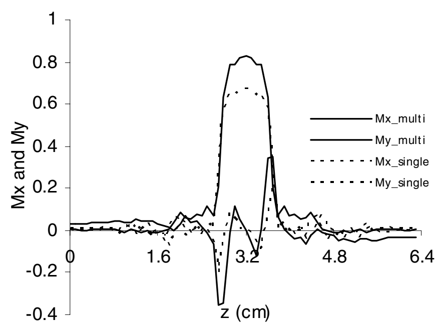

Fig. 2

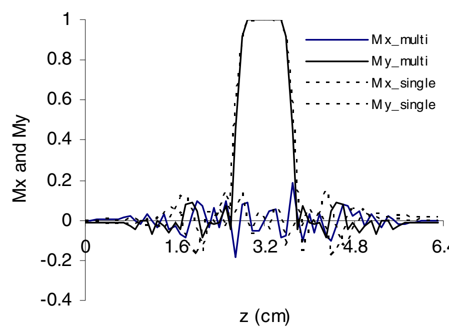

Fig. 3

DISCUSSION

Self-refocused RF pulses have been designed to excite magnetization within a well defined slice under conditions of short transverse relaxation time. It is shown in this study that using multi-stage minimization improves the design significantly. The resulting pulse deposits less energy and combats transverse decay by having a single delayed lobe (where there is little transverse magnetization subject to T_2 decay [3]). This annealing procedure effectively uses a large search step size initially in order to avoid being trapped in a local minimum, while locates the global minimum using a smaller step size. It should be noted that when the problem is not complex (e.g. when $T_2 >> T_{rf}$) the single-stage approach reaches produces as good a solution as the multi-stage as shown in Fig. 3. Finally, the optimized pulse has a similar shape to those obtained analytically using inverse scattering theorem [3].

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