JOINT MULTI-SHIFT AND MAGNITUDE LEAST SQUARES (MSMLS) ALGORITHM FOR TIME EFFICIENT LOW SAR AND LOW PEAK RF PULSE DESIGN

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Target Audience MRI physicists and engineers.

Purpose During the last decade, several numerical methods for RF pulse design have been developed. Recently, the magnitude least squares[1] (MLS) and the multi-shift conjugate gradient least squares[2] (msCGLS) algorithms have been proposed to relax the phase constraint in the resulting magnetization and to efficiently design RF pulses with minimum power. Up to the present day, a joint implementation of the multi-shift acceleration with the MLS phase relaxation has been missing. In this study, we present a multi-shift MLS (msMLS) algorithm which presents both advantages of the MLS and the multi-shift approach to 1) drastically accelerate computation time 2) get a better choice of the trade-off solution between accuracy and RF power 3) get a lower peak RF and RF power for the same level of accuracy in the obtained magnetization.

MLS algorithm	msMLS algorithm

for $\lambda = \lambda_1, \lambda_2, \ldots, \lambda_N$
  for j < max_it
    solve $\|\| Ax-b \|\|^2 + \lambda\|\|x\|\|^2$
    φ = angle(Ax);
    b = b.*exp(i φ);
    stop if $\|\|Ax-b\|\|/\|\|b\|\|<\varepsilon$
  end
end
	for j < max_it
	  solve by msCGLS $\|\| Ax-b \|\|^2 + \lambda\|\|x\|\|^2$
	  φ = angle(Ax_1);
	  b = b.*exp(i φ);
	  stop if $\|\|Ax-b\|\|/\|\|b\|\|<\varepsilon$
	end

Fig 1: *MLS and multi-shift MLS algorithm*

Methods The msCGLS algorithm computes simultaneously a set of solution of the least squares problem $\min_x\|\mathbf{Ax}-\mathbf{b}\|^2+\lambda\|\mathbf{x}\|^2$ (1) where λ is the regularization parameter which controls the trade-off between solution power and accuracy. This system has to be solved in order to find the RF pulse for several applications including transmit SENSE[3], k-t points[4], optimal control large tip angle pulses[5], SPINS[6] etc. Rapid solution of eq. (1) is therefore important. Furthermore, the ability to control the trade-off by means of the so-called L-curve makes the application of msCLGS very important for minimum power and minimum SAR RF design. By relaxing the phase constraint, that is, solving the problem $\min_x\| \, |\mathbf{Ax}|-\mathbf{b}\|^2$ (2), an extra degree of freedom is available, resulting in better tip angle accuracy. A solution of (2) is achieved by an iterative algorithm where during each iteration a modified version of (1) is solved which is time consuming. In addition, problem (2) has to be solved for each regularization parameter, increasing even further the computation time. To take profit of the advantages of msCLGS as well as MLS, we modified the MLS algorithm by implementing the msCGLS step resulting in the msMLS method (Fig 1). The msCGLS algorithm computes the solutions of a regularized least squares problem for a whole set of regularization parameters in about the same time a standard algorithm solves it for just one parameter. Note that the loop over the λ values is avoided. Also, note that the updating of the phase vector φ is performed on the basis of the most strongly regularized solution x_1, which ensures a smooth phase variation. To test the MLS versus the new MLS RF waveform, we compute SPINS[6] pulses for a 7T 2ch head coil with a homogeneous target magnetization. The transmit maps are shown in Fig. 2. The input values for the regularization parameters are: $\lambda_1=10^4$, $\lambda_2=10^{3.5}$, $\lambda_3=10^3,\ldots, \lambda_N=10^{-6}$ (N=21 values). The SPINS 3D k-space trajectory and corresponding gradients are shown in Fig. 3.

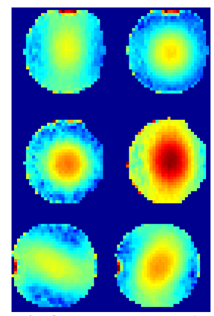

Fig 2: *transmit profiles for channel 1 (left) and channel 2(right). Central sagittal, coro-Nal and transverse slices are shown*

Results The computation time for MLS is 177s, while for msMLS is 9.5s on a 4CPUs @3.10GHz PC, Matlab (Mathworks) implementation. The acceleration factor is similar to the total number of the regularization parameters. A plot of the power-error curves is shown in Fig. 4. The RF waveforms for which the error is about 10% are indicated and plotted in Fig. 5. Not only is msMLS much faster than MLS, but also achieves better solutions in terms of power (and thus SAR) and peak RF. The reduction factors are 70% and 65%, respectively. The obtained tip angle distributions are very similar (Fig. 6).

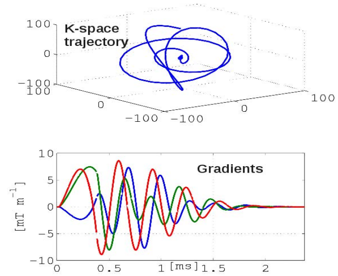

Fig 3: *SPIN 3D k-space trajectory and corresponding gradient waveforms*

Discussion There are three beneficial effects of the joint multi-shift MLS algorithm: peak RF, RF power and computation time are drastically reduced. In particular, the solutions of the RF design problem seem to be more efficient in case of the msMLS as it is shown in the divergence between the two curves in Fig. 4. This can have important consequences especially at high field MRI where SAR is a limiting factor for the full exploitation of the RF transmit system.

Conclusion The multi-shift implementation of the MLS algorithm for RF pulse design is presented. Drastic reduction in computation time and improved efficiency of the obtained RF pulses are shown.

References [1] Setsompop K et al. MRM 2008 , [2] Sbrizzi A et al. MRM 2011, [3] Katscher U. et al MRM 2003, [4] Cloos M et al. MRM 2012. [5] Grissom WA et al. MRM 2009, [6] Malik SJ et al. MRM 2012

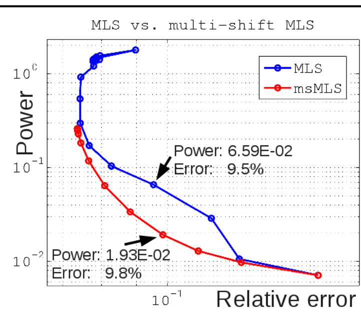

Fig 4: *MLS vs msMLS pulses. Power and relative error*

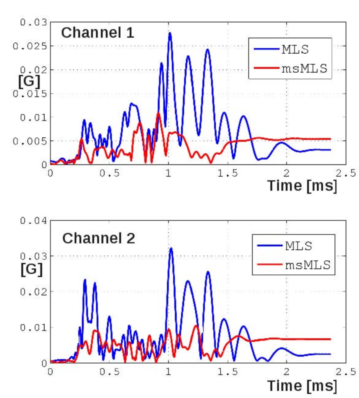

Fig 5: *RF waveforms*

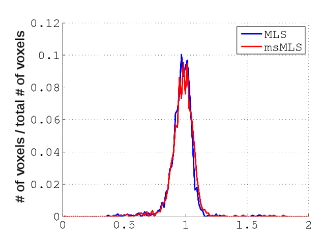

Fig. 6: *Histogram of flip angle distributions*