RF pulse design for low SAR simultaneous multislice (SMS) excitation using optimal control

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Simultaneous multislice (SMS) excitation is increasingly used to accelerate imaging experiments. Conventional design approaches result in a linear increase in the peak B1 amplitude per slice and are sensitive to flip angle variations. It has been demonstrated that optimal control is a powerful tool for the design of flexible and robust RF pulses. We therefore propose to apply an optimal control approach based on the full time-dependent Bloch equation, including relaxation effects, for computing optimized SMS excitation pulses with minimized B1 peak increase and low SAR.
The optimal control approach to pulse design consists in minimizing the functional

$$J(M,u) = \frac{1}{2}\int_{-a}^{a} |M(T,z) - M_d(z)|_2^2 \, dz + \frac{\alpha}{2}\int_0^T |u(t)|_U^2 \, dt, \tag{1}$$

where the magnetization vector $M(t,z)$ is the solution of the time-dependent Bloch equation $M' = B \times M + R(M)$ (R denotes the relaxation term), z is the slice direction, $M_d(z)$ is a desired slice profile and $B(t,z) = (u_x(t)B_1, u_y(t)B_1, G_s(t,z))$ includes the RF pulse (u_x, u_y) to be optimized as well as the slice selective gradient G_s. The minimizing pulse can be computed using a globally convergent trust-region Newton method with a matrix-free iterative solution of the Newton step involving adjoint consistent numerical simulation of the Bloch equation.
We demonstrate the ability of this approach to generate RF pulses with arbitrary (large) flip angles, slice thickness, slice gaps and slice numbers. The results for two and three slices of 4mm thickness are validated on a 3T MR scanner and indicate the applicability of the proposed method.

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