DESIGNING RF PULSES WITH OPTIMAL SPECIFIC ABSORPTION RATE (SAR) CHARACTERISTICS AND EXPLORING EXCITATION FIDELITY, SAR AND PULSE DURATION TRADEOFFS

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INTRODUCTION: Recent methods of designing RF pulses for multi-coil TX systems have focused on solving regularized systems of equations. These techniques linearize the equations relating the RF waveforms to the resulting excitation and then penalize RF candidates with high peak and root-mean-square (RMS) voltages (\(V_p\) and \(V_{rms}\), respectively) in an attempt to limit SAR \([1,2]\). This is sensible because in single-coil systems, SAR scales directly with \(V_p\) and \(V_{rms}\). In multi-channel systems, however, the simultaneous transmission of pulses through multiple coils causes their E-fields to interact, possibly adding constructively, which may significantly affect SAR. We account for these interactions in RF design techniques for multi-coil TX systems by explicitly optimizing SAR. This builds on Zhu’s linear-algebraic formulation and optimization of SAR when designing RF pulses on P-channel TX systems \([3]\), which requires knowledge of the steady state E-fields generated per unit of power sent to each TX coil, the tissue’s electrical properties and spatial sensitivity profiles \((b_i)\) maps) of each coil. Then we pose optimization problems that produce RF pulses with optimal SAR characteristics. In particular, we provide a closed-form solution for optimizing mean SAR, introduce a method to explore excitation fidelity, mean SAR and pulse duration tradeoffs, pose a constrained optimization problem that ensures 10g average SAR meets certain constraints, and show how RF pulses generated by a mean SAR optimization algorithm have better properties than those produced via Tikhonov regularization.

METHODS: Regularized RF pulse design. For a P-channel TX system, linearizing and discretizing the equations relating the RF pulses played through each coil to the resultant excitation yields \(m=Ab\) \([2,4]\), where \(m\) is an \(M \times 1\) vector of the target excitation’s samples in the region of interest and \(b\) a \(P\times1\) voltage vector of samples of the RF waveforms containing \(T\) samples of each coil’s RF pulse \(b_i(t)\). \(A\) is an \(M \times P\) matrix incorporating each coil’s \(B_1\) matrix and the fixed k-space trajectory. An example of a regularized RF design algorithm is a Tikhonov regularization: \(\min_{m} [m-Ab]\) + \(\|b\|_2\), with \(\|\cdot\|_2\) penalizing high-energy \(b\) candidates.

Linear-algebraic formulation of SAR and design of RF pulses with optimal SAR characteristics. Analogously to Zhu \([3]\), we derive a matrix-vector expression for \(s(r)\), the SAR at spatial location \(r\), defined as

\[
\frac{1}{3}\sum_{n=1}^{N} \left| E_n(r,t) \right|^2 \rho_n(r)
\]

where \(E_n(r,t)\) and \(\rho_n(r)\) are the amplitude and mass density respectively, and \(E(r,t)\) is the complex-valued 3-D E-field at time \(t\) \([5]\). This is a linear superposition of each TX coil’s E-field, scaled by the RF playing along each: \(E(r,t) = \sum b_i(t)E(r,t)\), where \(b_i(t)\) is the RF played along the \(i\)-th coil at \(t\) and \(E(r,t)\) is a complex-valued 3-D vector of the E-field at location \(r\) and time \(t\) generated by the \(i\)-th coil. This may be written compactly as: \(E(r,t) = F(r,t)b_i(t) + b_i(t)\), where \(F(r,t)\) is an \(N \times P\) matrix incorporating each coil’s \(B_1\) matrix and the fixed k-space trajectory. An example of a regularized RF design algorithm is a Tikhonov regularization: \(\min_{m} [m-Ab]\) + \(\|b\|_2\), with \(\|\cdot\|_2\) penalizing high-energy \(b\) candidates.

RESULTS: We fixed the \(Q\) in Eq. 26 and solved for \(\|m-Fb\|_2\) and \(\|m-\hat{F}b\|_2\) using the LSQR algorithm \([8,9]\) and a mean-SAR optimized set, tuning the parameters of each method such that the optimal residual error vs. mean SAR tradeoffs are explored. To prove that the mean-SAR optimization method outperforms standard regularized-pulse designs, we design a Tikhonov-regularized RF pulse set and a mean-SAR optimized set, tuning the parameters of each method such that the resulting pulses yield equal fidelity-excitations. Fig. 3 compares the voltage and SAR of the pulses generated by each method. Even though the Tikhonov-regularized pulses have lower \(V_{rms}\), they generate 1.29x higher \(\mu_{SAR}\), which reinforces our claim that E-field interactions in parallel TX systems significantly influence SAR.