An Algorithm for Maximum-SAR Targeted RF Hyperthermia

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TARGET AUDIENCE: Researchers and engineers interested in RF hyperthermia and parallel transmit

† maxSAR Optimization Problem

$$\text{MINIMIZE: } SAR(\boldsymbol{b}) = \max_{r=1,\ldots,N_R}(\boldsymbol{b^H R_r b})$$
$$\text{SUBJECT TO: } SAR_{target} = \boldsymbol{b^H Q_{target} b} \geq 1$$

PURPOSE: RF and microwave hyperthermia have been used to treat cancer either through conventional hyperthermia, thermal ablation or thermally-induced drug delivery. Typically, the hyperthermia applicator is an array of RF transmitters tuned to a particularly frequency and coupled to the body region being treated. The excitation problem is to determine the pulse amplitudes and phases to be transmitted from each array element that will induce sufficient heating at a localized hotspot while sparing surrounding tissue. Recently, a hybrid applicator [1] for use in both RF hyperthermia and 7T MR imaging was constructed and a shift in hotspot location with change in the delivered pulse was demonstrated. However, a rigorous algorithm for *targeted* hotspot generation was not described. Here we describe a novel "maxSAR" pulse design algorithm that draws from recent developments of efficient formalisms for local SAR computation in parallel transmission [2]. We demonstrate in simulation that for any target region within the anatomy (corresponding to a tumor), the algorithm produces a pulse that maximizes SAR over that region while constraining SAR at all other voxels (corresponding to healthy tissue) to remain below the regulatory safety limit. This algorithm, combined with hyperthermia optimized transmit hardware, could open up an exciting new area of MR-guided RF hyperthermia.

THEORY: Our goal is to design a hyperthermia pulse that maximizes the ratio of the mean SAR at the target to the peak local SAR in healthy tissue. For a N_c channel array, we can denote the pulse by the complex vector $\boldsymbol{b} \in \mathbb{C}^{N_c}$ representing the amplitude and phase of the pulse applied to each channel. The maxSAR optimization problem is formulated as in † above where $\boldsymbol{Q}_{target}$ is the local SAR matrix spatially averaged over all voxels in the target region, and $\boldsymbol{R}_r$ corresponds to either the local SAR matrices at surrounding healthy tissue voxels, the global SAR matrix, or the average power (identity) matrix normalized by respective hardware or safety limits. In this way, $SAR \leq 1$ corresponds to a hyperthermia pulse whose absolute SAR (in W/kg) is within the regulatory limits in healthy tissue. The RF duty cycle can be adjusted independently from the optimization to achieve the desired absolute value of SAR. Because the constraint is concave, this is a nonconvex problem and can be solved using an interior point algorithm. Our algorithm converts the problem into an unconstrained minimization by approximating the constraint by a continuous log barrier function that approaches zero when the constraint is satisfied and approaches infinity when the constraint is violated. At each iteration of this algorithm, a descent direction is found based on the values of SAR_{target} and SAR as well as both of their gradients and Hessians. Since the number of voxels outside the target is likely very large ($\sim 10^5$) the time for this evaluation would typically be very long, severely limiting the number of iterations that could be performed and thus the accuracy of the solution. However, by making use of a vectorized SAR oracle [2], specially designed to perform this evaluation much more efficiently, the computation time can be reduced significantly, allowing the optimization to be performed in real-time if necessary.

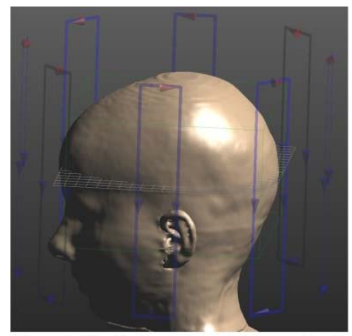

Figure 1: The 8 channel parallel transmit coil model used to simulate electric fields on Ella from the Virtual Family.

METHODS:
We demonstrate the method by producing hotspots within three different 4x4x4 cm cubical targets throughout the brain. An 8 channel loop array operating at 298 MHz (7T) was used as the transmit coil with the Ella body model of the Virtual Family taken to be the patient. Electric fields were simulated using a finite difference time domain method (SEMCAD X). Optimization was performed in MATLAB using the `fmincon` function. To verify the insensitivity of the algorithm to initial conditions, one instance of the problem was solved using several random initial pulse vectors to confirm that resulting optimum pulses were nearly identical. Then, using a zero vector as an initializer, optimization was performed for three different target locations and the ratio of the mean SAR over the target to the maximum SAR outside the target was recorded for each case. The RF duty cycle was chosen to achieve a maximum local SAR of 10 W/kg in healthy tissue. To reduce computation time, the vectorized SAR oracle for computation of SAR and its subderivatives was accelerated through use of a GPU (NVIDIA GeForce GTX 670).

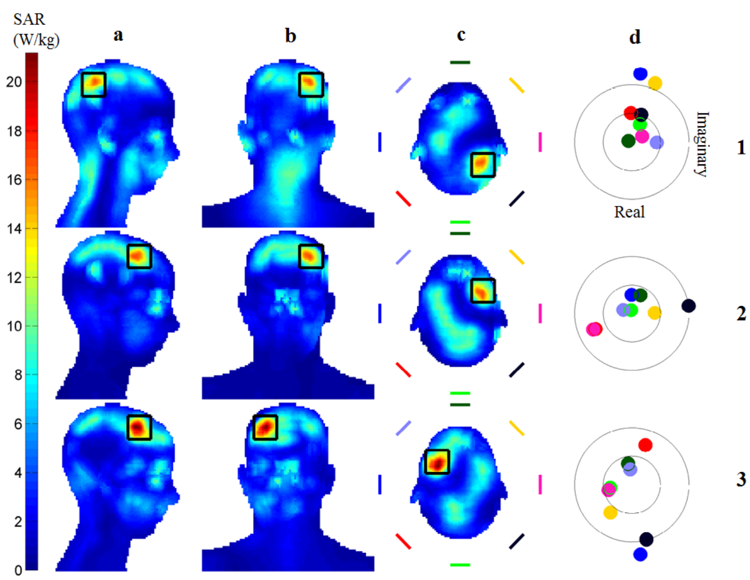

Figure 2: (**a**) sagittal, (**b**) coronal, and (**c**) axial maximum intensity projections of optimized local SAR distribution for the three different 4x4x4 cm cube targets (black squares); (**d**) the optimal complex channel weighting color-coded with loop locations in (**c**).

RESULTS: For each of three cases shown in Figure 2, the hyperthermia pulse generated by the maxSAR algorithm was able to reliably produce a hotspot in the target region. The computation times and maximum SAR achievable in the target region, subject to a maximum SAR of 10 W/kg in surrounding tissue, are reported in Table 1. SAR maximum intensity projections and the complex pulse weighting for the optimized pulse are shown in Figure 2.

DISCUSSION: The results demonstrate that the optimization is able to generate significant hotspots in target regions while limiting the heating in healthy tissue to be below the local SAR limit. The optimization occurs in near real-time, making it possible to assess several different target regions at once without performing an entire electromagnetic simulation.

CONCLUSION: The maxSAR optimization algorithm introduces the possibility of MR-guided hyperthermia. In practice, hyperthermia pulses designed here can be interleaved with imaging or thermometry sequences to monitor the treatment. Improved performance may be possible by combining novel transmit arrays such as antenna elements [1] for improved electric field penetration and SAR control. In addition, using field strengths greater than 7T or applicator arrays consisting of greater than 8 elements, would likely enable smaller target sizes and even more pronounced hotspots.

Target	Computation time (s)	Maximum SAR (W/kg)
1	9.34	16.5
2	10.15	16.1
3	11.94	21.3

Table 1: Optimization results for three target regions.

REFERENCES: [1] Winter et al, PLOS 2013;8(4):e61661 [2] Pendse, 835, ISMRM 2015
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