Minimum SAR for RF Shimming by Allowing Spatial Phase Variation

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Introduction
Specific Absorption Rate (SAR) is a patient safety parameter that should be seriously considered in MRI. There are studies in the literature that minimized average SAR, for a given target transmit sensitivity. In one of these studies SAR due to a given multi-channel transmit coil was minimized with respect to the phase and the magnitude of the excitation currents on the individual channels [1]. In another work the ultimate value of SAR for RF shimming and transmit sense was calculated by the optimization of the field inside a homogenous body model [2]. In these studies target transmit sensitivities were chosen in order to obtain a uniform magnitude field distribution. However SAR change due to the phase variation among the individual points on the target profile was not investigated. In this study by keeping the magnitude distribution of the target transmit profile constant, the phase distribution is optimized to obtain true ultimate SAR for MRI coils. It was shown that with this method it is possible to reduce whole body SAR by orders up to 30, while realizing a desired magnitude distribution for target sensitivity.

Theory
Average whole body SAR inside a homogenous body model is given as
\[ SAR = \sigma / M \int_\text{body} |E|^2 \, dV \]
where \( \sigma \) is the conductivity and \( M \) is the total body mass. On the other hand, for a certain point of interest \((\rho_i, \phi_i)\), the forward polarized field component \( H_f \) is expressed as
\[ H_f = (H_\rho - jH_\phi)e^{-j\phi} \]
where \( H_\rho \) and \( H_\phi \) are the magnetic field components in radial and angular directions respectively. \( H_f \) can be set to desired values at an array of points that forms the target transmit profile. Let the vector \( \alpha \) denote the weighting coefficients for the cylindrical basis functions for an arbitrary EM field expansion. Then the SAR minimization problem is equivalent to minimizing \( \alpha^T R \alpha \) where the constraint on \( H_f \) can be expressed as \( B \alpha = c \) The solution for this problem can easily be found by Lagrange optimizer method as, \( SAR_{	ext{avg}} = c^T (BR^{-1}B)^\dagger c \). Let \( S \) be defined as \( S = BR^{-1}B \) where \( R \) is a conjugate symmetric, positive definite, block diagonal matrix and contains the power deposition integrals due to each separate mode of cylindrical basis expansion. On the other hand \( B \) matrix contains the value of each cylindrical expansion modes of \( H_f \) evaluated at different points of the target profile. \( c \) contains the value of the transmit target profile at different sample points. In MRI usually a magnitudewise uniform transmit field is desired. However this condition does not set a constraint on the phase variation. In other words keeping the absolute value of \( H_f \) equal to unity at each location, an optimization involving the target profile phase distribution can be performed. For this purpose \( SAR_{	ext{avg}} = c^T S \alpha \) must be minimized with the constraint, \( 1 - |\alpha_i| < 1 + \delta \) for \( i = 1, 2,...N \), where \( N \) is the number of points in the target profile and \( \delta \) is the maximum tolerance value for the magnitude of \( H_f \).

Methods and Results
In order to solve the above optimization problem “particle swarm optimization”[3] algorithm is used. A MATLAB (version 7.0,MathworksInc., Natick, MA) program is used to implement the algorithm. A circular target transmit profile of radius 8 cm is used for calculations in a body model of radius 10 cm (Figure1). 45 points was distributed homogenously inside the target profile in order to obtain a uniform field. Phase distribution of the target profile is optimized for different \( \delta \) Homogeneity coefficients for \( H_f \) is calculated for \( \delta = 0 \) at 3 field strengths. The square of the difference between magnitude of each pixel in the target profile and the center pixel is summed and averaged. Table 1 shows the results. Table 2 shows the improvement in SAR with respect to zero phase \( H_f \) distribution, for different values of \( \delta \) at 1.5T,3T and 4.7T. Figure 2 shows the optimum phase and magnitude distribution of \( H_f \) inside the body model at z=0 plane for 3 different main magnetic field strengths.

Discussion
For 1.5 T and 3.0 T transmit target profile guaranteed the forward polarized magnetic field to behave smoothly in the entire slice. In 4.7 T some inhomogeneity effects are visible.

Conclusion
The effect of target transmit profile phase optimization on the average SAR is demonstrated. The optimum phase distribution and the corresponding ultimate SAR is calculated. A maximum SAR reduction factor of 37.8 is feasible with the optimum phase distribution in 4.7 Tesla. The optimum field distribution that gives the minimum SAR is calculated.

References