On the worst-case whole-body SAR assessment due to far-field exposure

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In this study we report a deterministic approach to evaluate the worst-case whole-body SAR due to far-field exposure. The approach is validated against a statistical approach (Monte Carlo) and the Self-Adaptive Differential Evolution optimization method, for two human numerical models and two frequencies under illumination from twelve plane-waves. It appears that the statistical approach performs worse than the other two methods, because it predicts lower values for the SAR.

Long Abstract

INTRODUCTION

Most of the numerical investigations on the dosimetric assessment of exposure in the far field of electromagnetic sources have been performed using a single plane wave exposure [1], [2]. However, in a realistic environment humans are exposed to multiple waves arriving from various directions and with amplitude and phase distributions depending on the type of environment (e.g., outdoor, indoor). Several recent papers have reported on this situation, using either case models of heterogeneous exposure [3] or statistical approaches [4], [5] to investigate the relation between the whole body specific absorption rate (SAR_{wb}) and the incident electromagnetic field in realistic environments with multipath propagation. It was found that single plane wave exposure does not represent the worst-case. Since in dosimetry we are interested in a conservative approach, in the present study we propose a methodology to calculate the maximum whole body SAR from multiple plane wave exposures, using deterministic and non-deterministic methods and comparing between them.

MATERIALS AND METHODS

Specific absorption rate under multiple plane-wave exposure

Specific absorption rate (SAR) can be related to the electric field at a point by:

$$SAR = \frac{\sigma \left| E \right|^2}{2\rho} \quad (1)$$

where σ is conductivity of the tissue (S/m), ρ is mass density of the tissue (kg/m^3) and E is the amplitude of a (harmonic) electric field in tissue (V/m). If we assume that the electric field E is generated by N independent sources, each one of them having a complex amplitude c_i, we obtain [6]

$$SAR = \frac{\sigma \left| \sum_i c_i \overrightarrow{E_i} \right|^2}{2\rho} \quad (2)$$

The above equation can be written as:

$$SAR = \frac{\sigma}{2\rho} \sum_i \sum_j c_i c_j \overrightarrow{E_i} \overrightarrow{E_j^*} \quad (3)$$

To calculate the whole-body SAR (averaged SAR over a volume), equation (3) can be written as:

$$SAR_{wb} = \sum_i \sum_j c_i c_j M_{ij} \quad (4)$$

where

$$M_{ij} = \frac{\int_{wb} \frac{\sigma}{2\rho} \overrightarrow{E_i} \overrightarrow{E_j^*} \varrho dV}{\int_{wb} \varrho dV} \quad (5)$$

contains the interaction between the electric fields generated by the independent sources.

Deterministic approach

Matrix M is hermitian, thus diagonalizable by the unitary transformation $\mathbf{M_{wb}=UDU^+}$, where U is the unitary matrix and D is a diagonal matrix; its elements are equal to the eigenvalues of M. As a result, the SAR_{wb} is maximized for the maximum value of D, which is the maximum eigenvalue of M.

Monte Carlo approach

It is possible to generate an arbitrary number of incident plane waves with different amplitude and phase, by randomly generating vectors c_i. Then, combining these vectors in equation (4) with matrix M, it is possible to retrieve the SAR_{wb} distribution and its maximum value. In this study we used uniform amplitude and phase probability distributions.

Differential evolution approach

Differential evolution (DE) is a metaheuristics method that tries to maximize a multidimensional real-valued function by iteratively trying to improve a candidate solution with regard to a given measure of quality. It makes few or no assumptions about the problem being optimized and can search a very large space of candidate solutions [7]. A self-adaptive version of the method (SADE) has already been successfully applied to antenna and microwave design problems [8].

Numerical models and technique

The exposure assessment was performed for one adult (Duke) and one child (Thelonious) anatomical model from the Virtual Family [9]. For each of the two numerical models, the following simulation setup was applied: Six different plane waves with incident directions of the corresponding major sides (front, back, top, bottom, right and left) and for two orthogonal polarizations of the electric field per incident direction were used to calculate the M matrix. The calculations of the electric field inside the models were performed for two frequencies (866 and 2450 MHz) using SEMCAD-X (SPEAG, Zurich, Switzerland). Then, the fields were extracted in MATLAB, where the appropriate functions were implemented to calculate the M matrix and the corresponding SAR_{wb} with the three approaches. All the values of SAR_{wb} were normalized to the same total incident field power density corresponding to 1V/m.

RESULTS

Table 1 presents the derived results for the maximum SAR_{wb} using the aforementioned methods and assuming exposure to twelve plane waves. It is clear that SADE, which is a non-deterministic method, achieves the same maximum like the eigenvector approach, which is deterministic and should be able to predict the global maximum. The SADE was run several times and the reported value in table 1 is the average for each case. The Monte Carlo method, on the other hand, cannot predict exactly the worst-case SAR_{wb} value but it can give a value which is up to 0.5 dB lower, when 100'000 arbitrary vectors are used for the calculation. Figures 1 and 2 depict the amplitude and phase distributions, respectively, for the plane waves that result in the values of Table 1 for each method and for the case of the male adult model (Duke) at 866 MHz.

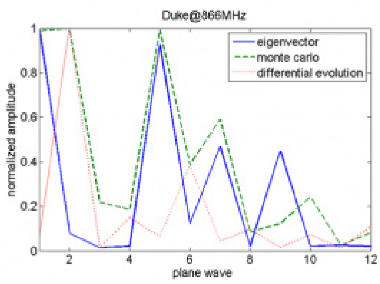

FIGURE 1: AMPLITUDE DISTRIBUTION OF THE PLANE WAVES EIGENVECTORS FOR EACH METHOD OF TABLE 1

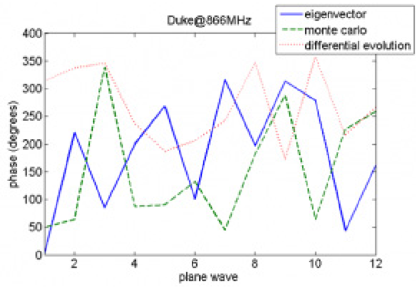

FIGURE 2: PHASE DISTRIBUTION OF THE PLANE WAVES EIGENVECTORS FOR EACH METHOD OF TABLE 1

The most time consuming steps of the above approach are two: The calculation of the plane wave exposures and the calculation of matrix M. Once these steps are performed for any anatomical numerical model, then the maximum SAR_{wb} is readily available with the eigenvector approach and can be verified with the SADE approach. Then, using arbitrary vectors of amplitude and phase distributions that depend on a specific environment, it is easy to generate a statistical model with the Monte Carlo approach, like the one introduced in [4]. It should be pointed out that the results presented here do not necessarily represent the worst-case SAR_{wb} for any exposure situation. This can be achieved only if more than twelve plane waves are used, i.e., by employing intermediate angles for the azimuth and elevation of the plane waves in the calculations.

Method	SAR_{wb} (W/kg)			
	Duke		Thelonious	
	866MHz	2450MHz	866MHz	2450MHz
Eigenvector	9.43E-6	8.28E-6	1.76E-5	1.54E-5
Monte Carlo	8.73E-6	7.33E-6	1.60E-5	1.43E-5
Self-Adaptive Differential Evolution	9.43E-6	8.28E-6	1.76E-5	1.54E-5

TABLE 1: DERIVED RESULTS FOR SARWB WITH THE DIFFERENT METHODS

CONCLUSIONS

In this study we reported a deterministic method to evaluate the worst-case whole-body SAR due to a given multiple plane wave exposure. The method was verified by a metaheuristics optimization method and was compared with a statistical method (Monte Carlo). It can be readily applied to any human numerical model and for any frequency of exposure.

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