Generalized model compression method for peak local SAR estimation

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Introduction: A fundamental constraint on the application of Parallel Transmit Systems (pTx) is the management of the local deposition of power in human tissue, quantified by the specific absorption rate (SAR). The modeling of the complex behavior of the spatial distribution of SAR in pTx arrays poses problems not encountered in conventional single-channel systems due to prohibitive computation requirements associated with voxel-by-voxel SAR estimates in numerical tissue models. The model compression method [1] dramatically reduced the complexity of estimating the peak local SAR by monitoring so-called virtual observation points (VOPs) instead of searching exhaustively over all voxels in a 3D model. The VOPs can be pre-computed once for a given model and array configuration and applied in subsequent computation to efficiently estimate peak local SAR due to a given pTx RF pulse. By monitoring the peak local SAR with VOPs, e.g. 36 VOPs out of 300,000 voxels [1], the peak local SAR can be incorporated into pTx pulse design [2] and has been demonstrated to reduce peak local SAR by 20~40% compared to conventional pTx pulse designs that only employ global power constraints. The accuracy of the upper bound of local SAR estimation via VOPs depends on an overestimation parameter, ε, which is under flexible user control such that a tighter, more accurate bound (smaller ε) requires more VOPs. Here we present a generalization of the original model compression method [1], whereby we maintain the same accuracy in peak local SAR estimates, but with a reduced number of VOPs.

Methods: SAR Calculation: The dissipated power at a voxel v can be calculated as [2]

$$\sum_t q(t) = \sum_t \mathrm{Re}(\vec{E}_v(t)\cdot \underline{\underline{\sigma_v}} \cdot \bar{\vec{E}}_v(t)) = \sum_t \mathrm{Re}\left(\sum_{k=1}^{N}\sum_{l=1}^{N} \left(b_k(t)\cdot \bar{b}_l(t)\right)\left(\vec{S}_{k,v}\cdot \underline{\underline{\sigma_v}} \cdot \bar{\vec{S}}_{l,v}\right)\right),$$

with electric field E_v, and complex conductivity tensor σ_v, $b_k(t)$ is the RF pulse on transmit channel k, $S_{k,v}$ is the pre-calculated electrical field vector in voxel v due to a unit signal in channel k, and N is the number of transmit channels. By representing the RF pulse as a time-varying vector, the dissipated power is $\sum_t q(t) = \sum_t b(t)' S_v b(t)$ where the matrix, S_v, is positive semi-definite.

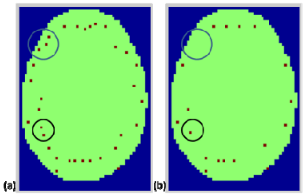

Fig. 1: The location of VOPs (red) in the single slice of Ella model (a) original method (33 VOPs), (b) generalized method (18 VOPs), some VOPs are removed in the generalized method (inside blue oval), and some VOPs are merged into one VOP (inside black oval).

VOP Generalization: In the original Gebhardt's method [1], to reduce the computational complexity of the SAR estimate, the spatial voxels in a 3D numerical model are clustered into several VOPs such that a voxel v belongs to cluster A_j, if it satisfies $S_v \le A_j$. I.e., for any RF pulse, the local SAR at voxel v is lower than the local SAR given by the VOP A_j. Therefore, the peak 10g local SAR of all the voxels in the 3D model is lower, for any RF pulse, than the peak 10g local SAR of all the VOPs. In the generalized method, we extend the voxel classification such that each voxel is not only clustered into a single VOP, but also into a joint set of VOPs. Namely, a voxel v belongs to a cluster dominated by a VOP if it satisfies the condition that there exists a linear combination of VOPs such that $S_v \le \sum_k \lambda_k A_k$ (Eq 1) where the coefficients λ_k are nonnegative and the λ_k sum to unity. In other words, for any RF pulse, the local SAR at voxel v is lower than the weighted local SAR according to Eq 1, and therefore lower than the peak local SAR of the VOPs. Then, the peak local SAR of all the voxels in the model is upper-bounded by the peak local SAR of the VOPs. To demonstrate the benefit of reducing the number of VOPs, we applied both the original [1] and generalized method to a single slice in the head of the numerical ELLA model [3] with an 8-channel array at 7T. As it is shown in Fig. 1, the generalized method needs 19 VOPs but the original method requires 33 VOPs. Some VOPs produced by the original method are removed in the generalized method (inside blue oval) and some VOPs are merged into one VOP in the generalized model (inside black oval).

Implementation: The largest eigenvalue of the matrix S_v represents the maximum local SAR deposited at the voxel v by a unit power RF pulse. We defined the overestimating factor, ε, as a unitless fraction relative to this maximum among all voxels. We formulated a greedy approach to determine the VOPs for the generalized approach. Given an overestimating factor, ε, which determines the accuracy of the local SAR prediction, we clustered all the voxels in the model by iterations over the following two steps. We continue the iterations until all the voxels in the model are clustered.

1. In the jth iteration, find the un-clustered voxel v such that the matrix S_v has the largest eigenvalue. This voxel v can have the maximum local SAR deposition among the un-clustered voxels. We choose the virtual observation point with additional overestimating factor, $A_j = S_v + \varepsilon I$.

2. Find all un-clustered voxels whose SAR matrix is upper-bounded by any non-negative linear combination (Eq 1), of VOPs, $A_1,\ldots,A_j$, and place them in the cluster j.

The performance of this approach was demonstrated by using a human head model (ELLA, virtual family [3]) and a model of an eight-channel pTx array at 7T. The E and B fields were estimated by a 3-mm isotropic FDTD simulation using REMCOM (REMCOM Corp., State College, PA). The number of tissue voxels within the head and shoulder model was ~ 270,000. We determined the number of VOPs for several different values of the overestimating factor, ε, and compared the required number of VOPs to the original method [1].

Results: Fig. 2a shows the number of VOPs determined by the generalized (blue) and Gebhardt's [1] original (red) methods, where the generalized approach captures local SAR estimates at an overestimation level of ε=3% with approximately 3.6-fold fewer VOPs (Fig. 2b). For this initial demonstration, we considered the linear combinations (in Eq 1) of only two VOPs, but note that the proposed algorithm can take into account all such possible linear combinations of VOPs. In Figure 2b, the ratio of the number of the required number of VOPs to achieve a given overestimation factor is shown, demonstrating the largest gains (~factor 4.8) for the highest fidelity of local SAR estimation.

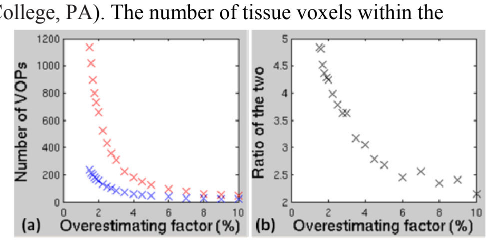

Fig. 2: (a) The number of Virtual Observation Points: Generalized (Blue), Gebhardt's (Red), (b) The ratio of the two, n_original/n_generalized

Conclusions & Discussions: The generalized model compression method for local SAR estimation captures more dependencies among the voxels in the model than in the original method of generating VOPs. It decreases the number of virtual observation points required to estimate local SAR by more than a factor of four compared to the original model compression method [1] for overestimating factors less than 2%. The generalized method also removes redundant virtual observation points, which cannot be the point of the peak local SAR. The generalized method may have utility for iterative pTx pulse design method with local SAR constraints [2]: In this pulse design method, the peak local SAR at the VOPs is constrained in the pTx RF pulses. Instead of having the maximum as a constraint, to simplify the constraint as well as to make feasible to use the conventional pulse design methods(spoke, 2D spiral, composite, etc) , the peak local SAR is approximated the weighted sum of the local SARs at the VOPs. Then, in each iterative step, the weighting factors are updated to make weighted sum closer to the peak local SAR. With the generalized method, we have smaller dimension of the weighting factors, which is equal to the number of VOPs, and thus reduced dimensionality of the search space. The proposed method may also have utility for the SAR optimal pulse design proposed by Graesslin et al [4], which relies on the selection hot spot locations.

References: [1] Gebhardt, p1441, ISMRM 2010, [2] Lee, p105, ISMRM 2010, [3] Christ, Physics and Medicine and Biology, 2010. [4] Graesslin, p4932, ISMRM 2010

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