The ultimate local SAR in MRI

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Target Audience MRI researchers who want to know how their pTx pulse design's peak local SAR compares to the lowest achievable value allowed by Maxwell's equations.

Purpose Previously the ultimate SNR [1] and ultimate global SAR [2] were calculated in spheres and cylinders by using plane wave or spherical mode expansion in uniform phantoms. We extend this analysis to the calculation of the lower bound for peak 10g local SAR that can be achieved with an arbitrary transmit coil in a uniform cylindrical phantom. For this purpose, we use eigen-decomposition of EM fields in the cylinder and a compressed set of local SAR matrices. The results form a metric for the performance of MRI coils and pTx pulse design algorithms.

Methods We expanded the electromagnetic field in a uniform cylinder (ε_r =60, σ =0.7 S/m) of diameter 20 cm and length 26 cm at 3 T (123.2 MHz) using cylindrical modes [3] which form a complete orthonormal basis set for solutions to Maxwell's equations in the cylinder. To determine the sufficient number of modes required for an accurate estimation of the ultimate local SAR we checked the convergence of the calculations by solving the following problem: $\min_{\mathbf{x}}\left\{\max_n \mathbf{x}^H\mathbf{Q}_n\mathbf{x}\right\}$ subject to $\sum_{m=1}^{M} B_{1+,c}(\mathbf{x}_0)[\mathbf{x}]_c = 10\mu T$, where $\mathbf{Q}_n$ is the n^{th} SAR matrix of the phantom model. This min-max optimization problem is convex and can be solved by noting that $\min_{\mathbf{x}}\left\{\max_n \mathbf{x}^H\mathbf{Q}_n\mathbf{x}\right\} \Leftrightarrow \min \gamma$ subject to $\mathbf{x}^H\mathbf{Q}_n\mathbf{x} \le \gamma \ \forall n$ .We then compressed the set of SAR matrices in the uniform cylinder in a much smaller set of virtual observation points (VOPs) allowing fast control of local SAR in the pulse design process[4]. Least-square optimum pulses were calculated for the set of cylindrical modes using an optimization approach which explicitly constrains global and local SAR[5]. The algorithm sought to achieve a uniform 10° flip angle excitation across the phantom. Calculating the pulse several times with different local SAR constraints result in a L-curve that shows the tradeoff between flip angle target fidelity and ultimate local SAR. For comparison, we generated the L- curve for a 16-channel loop transmit array and the same uniform phantom. Loop array simulations were performed with by using the FEKO EM solver (EMSS-SA).

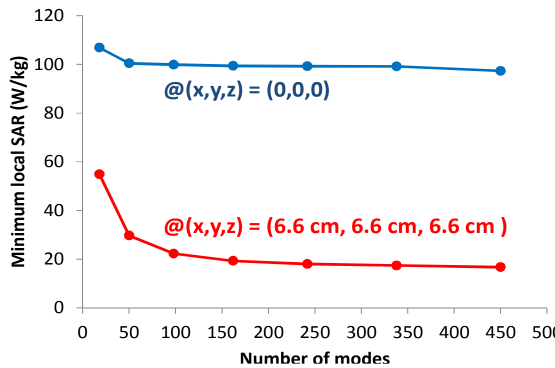

Figure 1 Convergence curves for local SAR when B1+ is constrained at (0, 0, 0) and (6.6, 6.6, 6.6) (in cm)

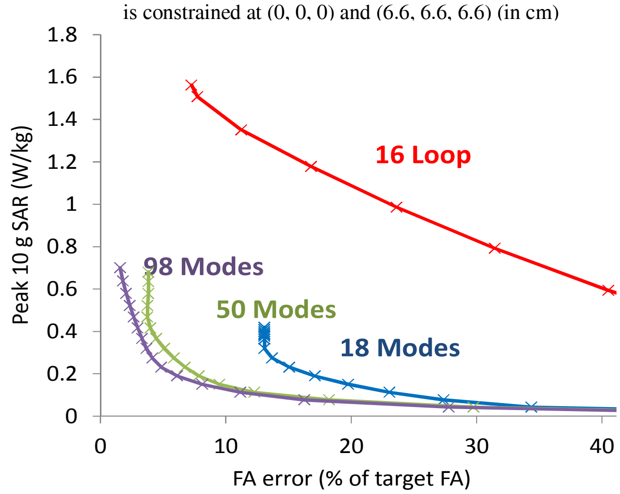

Figure 2 The L-curves are shown for different number of cylindirical modes in comparison to 16 Loop Array.

Results Figure 1 shows the convergence curves for peak 10 g local SAR obtained by solving the min-max optimization problem subject to $B_{1+} = 10\mu T$ constraint in the middle of phantom and 6.6 cm away from the origin in x, y, z. Convergence curves show that ≈100 modes are sufficient to express the field in order to calculate the ultimate local SAR with an acceptable error. Figure 2 shows the L curves obtained by using 18, 50, 98 cylindrical modes. For comparison, the L curve for 16-channel loop array is also shown. The relative position of the L curve of the loop array with respect to ultimate L curves shows that there is still large room for improvement in ptx coil design to reduce local SAR. Figure 3 shows the 10 g local SAR and flip angle distribution in an axial plane for 98 mode ultimate local SAR solution and the 16-channel loop array. Both solutions have a flip angle error of 10% however the ultimate local SAR is roughly 1/10th of the loop array.

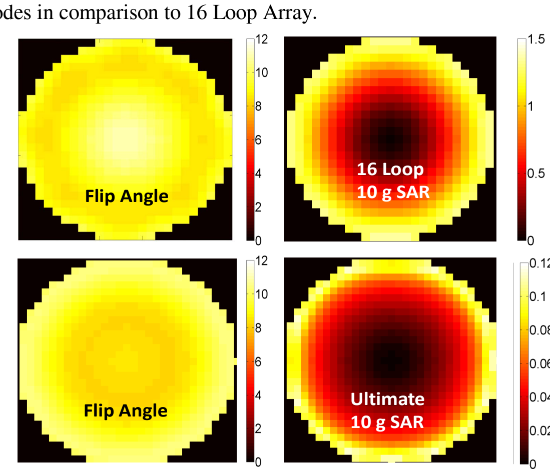

Figure 3 Flip angle and 10 g local SAR distribution is shown in the axial plane for 16 element loop array and the ultimate local SAR solution approximated with 98 modes.

Discussion We used an isotropic resolution of 8mm for all SAR calculations in which 20 voxels are used to average the SAR in 10 g of material. Although this is a reasonable number for averaging, the effect of using higher resolution should be investigated further.

Conclusion We calculated a lower bound for peak 10 g local SAR (ultimate local SAR) that can be obtained with arbitrary transmit coil array in a uniform cylindrical phantom. We calculated the trade-off between ultimate local SAR and the excitation fidelity (L-curves). The ultimate L-curves can be used as a figure of merit for pTx coil arrays. As an example we compared the L-curve of a 16-channel loop array to the ultimate L-curves obtained by cylindrical mode expansion.

Reference [1]Ocali ,O. (1998).MRM 39:462-473[2]Lattanzi,R.(2009).MRM 61:315-334[3] Eryaman, Y.(2011),MRM 65: 1305–1313 [4]Gebhardt, M. (2011). MRM **66**(5): 1468-1476[5]Guerin B (2012)Proc.Intl.Soc.Mag.Reson.Med 20 #2215

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