Statistical Local SAR Analysis by Latin Hypercube Sampling for 11.7 Tesla Brain MRI

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Introduction: Local specific absorption rate (SAR) analysis is critical to the safety of high-field human MRI studies. Conventionally, local SAR is simulated by positioning one or a few standard human models in a fixed position near a RF coil, which does not address the large inter-subject or position-related variability. Statistical analysis may be performed by conventional Monte Carlo sampling, but the required number of simulations is often too large to be practical. We propose a novel statistical approach based on the Latin Hypercube Sampling (LHS) for efficient statistical simulations. The expectation, standard deviation and sensitivity of the local SAR to changes in conditions, such as the head geometry and the relative position, can be accurately computed with very few sampling points.

Methods: LHS can achieve the same accuracy with much smaller run size than conventional Monte Carlo sampling because it guarantees that the selected runs uniformly spread across the domain of each input variable[1]. More precisely, for a LHS with *n* runs, if the domain of each input variable is partitioned into *n* mutually exclusive internals with equal probability, exactly one run falls in each interval. Because LHS is not unique, a LHS with smaller pairwise correlation is usually preferred. After evaluating SAR at selected runs, a second-order polynomial is fitted for the response surface of the SAR. The mean and standard deviation of SAR is calculated based on the fitted regression surface. Sensitivity analysis is also conducted based on the response surface to assess the relative importance of input variables.

	Head length (mm)	Head breadth (mm)	Longitudinal shift (mm)	Rotation along x-axis (°)	Rotation along y-axis(°)	Rotation along z-axis(°)
Mean	199	154	0	0	0	0
SD	7	6	15	5	5	5

Table 1. The six variables and their means and standard deviations.

Six random variables were chosen in this study (Table 1) based on their hypothesized importance on the local SAR. The first two describe the head geometry, where the means and standard deviations were from published data[2]. The other four random variables represent the relative position of the head with assumed means and standard deviations. An inductively coupled and shielded 11.7-T transmit coil was modeled by a GPU-accelerated finite-difference time-domain (FDTD) code (Fig. 1). The transmitter consists of 24 meshes. Capacitors on each mesh were tuned uniformly so that the birdcage mode appears at 500 MHz. The “Duke” head model was scaled for modeling different head geometries. Some examples are shown in Fig. 1.

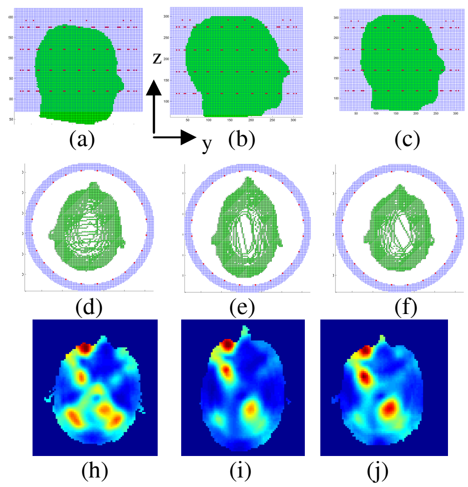

Fig.1 The numerical model with the largest rotation along the x-axis (a,d), the largest length/breadth ratio (b,e) and the largest longitudinal shifting (c,f). The peak local SAR are shown in (h)-(j).

Results and Discussion: The proposed method was verified by a convergence test with using 17 and 34 sampling points respectively. As shown in Table 2, the mean and standard deviation by using 17 sampling points is very close to those by using 34 sampling points. Thus 17 sampling points is sufficient and more sampling points do not help significantly. In a separate test (results not shown here), we compared the results of using 17 sampling points with conventional Monte Carlo simulations of 10,000 simplified head models. It was found that at least 600 sampling points would be required for conventional Monte Carlo sampling to achieve the same degree of statistical accuracy.

	17 sampling points	34 sampling points
Mean	0.82	0.84
SD	0.13	0.12

Table 2. The mean and standard deviation of the 10-gram averaged peak local SAR per unit RF power deposition calculated with different number of sampling points. Convergent results are observed with 17 sampling points.

	Head length	Head breadth	Longitudinal shift	Rotation along x-axis	Rotation along y-axis	Rotation along z-axis
Relative Sensitivity	0.35	60.87	18.82	7.04	2.49	14.02

Table 3. The relative sensitivity of the 10-g averaged peak local SAR to the head geometry and its relative position. The top three most influential factors are head breadth, longitudinal shift and rotation along the z-axis.

From Table 2, it was determined that the so-called k-factor should be 1.21 Watt/kg/Watt if this coil is intended to be safe for 99.7% of subjects (three sigma). However, the k-factor can be relaxed to 0.95 Watt/kg/Watt if it is intended to be safe for 68.2% of subjects (one sigma). In both cases, they are considerably higher (48% and 15% respectively) than the average k-factor, i.e., 0.82 Watt/kg/Watt.

The relative sensitivity of the peak local SAR to the six random variables are tabulated in Table 3. As can be seen, the top three most influential factors are head breadth, longitudinal shift and rotation along the z-axis. Thus it is possible to reduce the peak local SAR variability by using external fixation devices with landmarks to eliminate head shifting and rotating. With a less SAR deviation, the 11.7T coil is safer in the sense of reducing the k-factor.

Conclusions: We propose the use of LHS for statistical analysis of the local SAR of an 11.7-Tesla brain imaging coil. Compared to conventional Monte Carlo simulations, significantly less sampling points are required and the analysis can be performed much quicker. We also demonstrated the possibility of using the LHS to identify the influences of different factors to the local SAR. By reducing the SAR variability associated with some influential factors, the safety of RF coils may be improved in the sense of reducing the k-factor.

References: 1) Iman, R.L. et.al. Journal of Quality Technology 2000: 13 (3): 174-83. 2) Ball R. et.al., Applied Ergonomics, (2010):41:6:832-9