Parallel Transmit SAR Estimation using FDTD Modeling in the Human Head at 7T

Mohammad Mehdi Khalighi[1], Priscilla Chan[2], and Brian K Rutt[3]

[1]Global Applied Science Lab, GE Healthcare, Menlo Park, California, United States, [2]Electrical Engineering Department, Stanford University, Stanford, California, United States, [3]Radiology Deaprtment, Stanford University, Stanford, California, United States

Introduction: B_1^+ uniformity is a major problem at field strengths above 3T. Parallel transmission (pTx) is used to create a homogeneous flip angle (FA) field, however, there continue to be concerns about safety related to the alterations in E-field and SAR patterns when using pTx. Here we present the results of applying a commercially available package, SEMCAD X (Schmid & Partner Engineering AG, Zurich) to simulate the B_1^+ and E fields induced in the human head when transmitting from a quadrature birdcage head coil at 298MHz. We specifically investigated the design of different pTx pulses, optimized for field homogeneity over different planes through the head. SAR maps were calculated using SEMCAD X and a realistic head model, and the SAR distributions created by different pTx pulses compared to those produced during conventional quadrature transmit (qTx).

Methods: SEMCAD X was used to simulate the B_1^+ and E fields in a 16-rung high-pass birdcage coil loaded with the Virtual Family model 'Ella' (simulating a 26 year old female, model available from the Foundation for Research on Information Technologies in Society, Zurich) A high-pass birdcage coil was modeled as follows: 305mm diameter and 207mm length for the primary, 371mm diameter and 229mm length for the shield, 0.03mm conductor thickness, and at each end-ring gap a 5.6pF capacitor incorporating 8kΩ parallel resistance. The coil was discretized using 7 cells spanning each end-ring and 15 cells spanning the legs to properly resolve the geometry of the coil. The entire simulation space was discretized into approximately 23M cells. With these parameters, the uniform mode resonance frequency was 298Hz. B_1^+ and E fields were calculated over the 'Ella' head/neck model, using single port excitations (I-only or Q-only) to provide inputs for the design of pTx pulses and modeling of parallel transmit fields. Parallel transmit RF pulses were then designed using the spokes method [1], aiming for uniform flip angle on central 5mm axial, sagittal and coronal planes. The pTx pulses were designed using 0.5ms sub-pulses with time bandwidth product (TBW) of 2. For each plane, 3 different pTx pulses were designed: 3, 5 and 7 spokes. The B_1^+ fields generated by SEMCAD X were validated by direct comparison to *in vivo* B_1^+ mapping using the Bloch-Siegert method [2] and a matched geometry high-pass birdcage head coil (Nova Inc, MA, USA) on a GE 7T scanner (GE Healthcare, Waukesha, WI). Using E fields calculated by SEMCAD X over the whole head/neck, average SAR for each pTx pulse was calculated according to [3] using Eq. 1, where σ is conductivity and ρ is the density of the tissue and assuming 30deg flip angle in all cases. These pTx SAR maps were then compared to the quadrature transmit (qTx) SAR maps calculated using a conventional 3.2ms TBW=2 SLR flip angle=30 pulse. All SAR maps were smoothed using a 1cc volumetric kernel, such that local SAR values corresponded to an average over approximately 1g of tissue. In order to characterize and quantify SAR hot spot distributions, SAR histograms were normalized by the global whole-head-averaged SAR value, and then all voxels whose local SAR exceeded 2 times the global SAR were flagged as SAR hot spots; the percentage of hot spot voxels was tabulated.

$$SAR(r) = \frac{\sigma(r)}{2\rho(r)}\frac{1}{T}\int_0^T \|E(r,t)\|_2^2 dt \qquad (1)$$

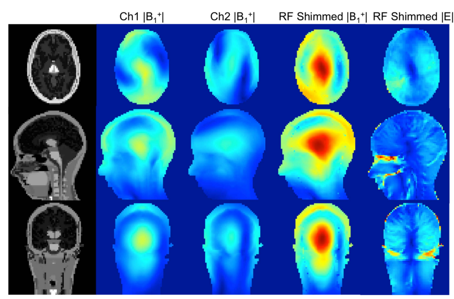

Fig 1: Magnetic and Electric fields of a quadrature Head coil by SEMCAD

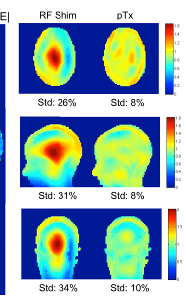

Fig 2: qTx FA map vs. pTx with 5 spokes

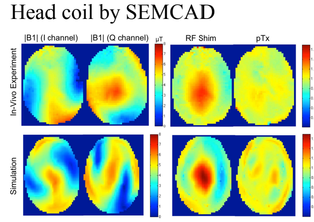

Fig 3: SEMCAD simulations compared with in-vivo experiment using Nova Head Coil.

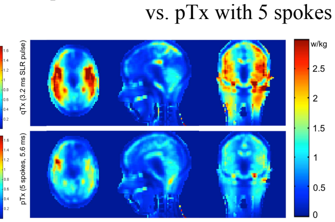

Fig 4: SAR maps cross sections for 30 deg flip angle

Results: Fig 1 shows simulated magnetic (B_1^+) and electrical field (E) distributions over the head produced by single channel and optimally RF shimmed quadrature (qTx) drive. Fig. 2 compares normalized flip angle maps for qTx (left) and 5-spoke pTx (right), the latter pTx pulses having been designed using the simulated single-channel B_1^+ maps from the corresponding slice. The homogeneity of flip angle is improved more than 3 times with pTx compared to qTx (8% std. dev. for pTx vs. 26% for qTx). Fig 3 compares simulated and experimental B_1^+ fields for each channel along with the normalized flip angle map for qTx and pTx, showing good match in all cases (single channel drive, qTx, predicted pTx). Fig. 4 shows the SAR maps for a 30deg flip angle pulse on the axial central plane using qTx with 3.2 ms SLR pulse and pTx, using a 5.6ms long 5-spokes pulse; qualitatively, SAR decreases from qTx to pTx. Fig 5 shows histograms of the SAR maps over the whole brain normalized to the global SAR, indicating similar fractions of hot spot voxels. Table 1 summarizes the comparison between qTx vs. pTx with different number of spokes (3, 5 and 7 spokes) on axial, sagittal and coronal planes. Relative to qTx, the global SAR produced by pTx is higher for 3-spokes, comparable for 5-spokes and lower for 7-spokes. Generally as the number of spokes increases, FA homogeneity improves strongly, global SAR decreases strongly and percentage of SAR hot spots decreases modestly.

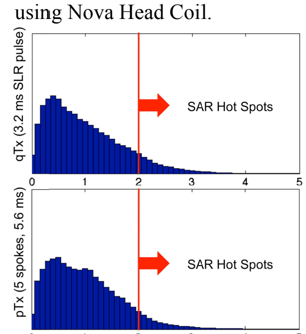

Fig 5: SAR histogram (normalized to global SAR) over whole head

Axial	Inhomog-eneity	Global SAR	SAR Hot Spots	PW
RF Shimming	26.2%	1.1 w/kg	9.6%	3.2 ms
pTx 3 Spokes	11.9%	1.7 w/kg	9.1%	3.2 ms
pTx 5 Spokes	8.4%	0.7 w/kg	7.8%	5.6 ms
pTx 7 Spokes	5.3%	0.4 w/kg	6.9%	8 ms
Sagittal	**Inhomog-eneity**	**Global SAR**	**SAR Hot Spots**	**PW**
RF Shimming	34.9%	1.3 w/kg	9.6%	3.2 ms
pTx 3 Spokes	11.3%	4.1 w/kg	12.7%	3.2 ms
pTx 5 Spokes	8.3%	1.6 w/kg	12.8%	5.6 ms
pTx 7 Spokes	7.3%	0.9 w/kg	11.3%	8 ms
Coronal	**Inhomog-eneity**	**Global SAR**	**SAR Hot Spots**	**PW**
RF Shimming	32.3%	1.3 w/kg	9.6%	3.2 ms
pTx 3 Spokes	13.9%	5.7 w/kg	11.9%	3.2 ms
pTx 5 Spokes	10.3%	1.7 w/kg	10.3%	5.6 ms
pTx 7 Spokes	9.2%	1 w/kg	10.8%	8 ms

Table 1: Comparing the performance of pTx with different spokes and qTx on different planes.

Discussion: SEMCAD X allows the accurate simulation of B_1^+ at 7T in human brain. It is difficult to measure E field *in vivo*, but it can be assumed that the simulated E field distributions are correct, since B_1^+ and E fields were calculated by the same numerical model. Table 1 shows that homogenization of flip angle in sagittal and coronal planes by pTx is harder than it is in the axial plane, and generally requires more power. It also shows that by using more pTx spokes, homogeneity is improved and SAR is decreased at the expense of a longer total pulse width. The overall SAR hot spot distribution is similar between 2-ch pTx and qTx, although more work is required to determine differences spatial pattern of SAR hot spots between pTx and qTx.

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References: [1] Grissom et al., MRM 56:620-629, 2006 [2] Sacolick et al., MRM 63:1315-1322, 2010 [3] Zelinski et al., MRM 28:1005-1018, 2008