Do constraints on |B1+| also constrain |E| and SAR in high field MR?

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Introduction: Global RF power deposition and local specific absorption rate (SAR) are metrics needed to ensure patient safety. Although recent developments allow global SAR to be monitored effectively in vivo for single or multiple transmit systems (1), local SAR remains a concern as its measurement and tracking calls for more advanced methodology. Since the local SAR is difficult to measure in vivo, one approach to ensure patient safety utilizes simulation software such as xFDTD to compare simulated and measured $|B_1^+|$ fields, under the assumption that a high correlation between the two implies that the simulated local electric fields also align with the unmeasured experimental local electric fields. This abstract utilizes FDTD simulations to examine the extent of electric field and SAR variation in the presence of similar $|B_1^+|$ fields.

Methods and Results: A single channel transmit coil above the abdominal area of a body mesh was modeled (Figure 1) using commercial FDTD software (xFDTD, Remcom, PA, USA). The voxel size was $5mm^3$, and the matrix size was 155x110x417. A unit current source was placed on the coil's surface and frequency was set to 297MHz. To resemble a real-life scenario in which fat-muscle content may vary on an individual basis, a second simulation was performed wherein muscle tissue in the human body mesh was replaced non-uniformly with fat in the abdominal region close to the coil. For both simulations, the convergence threshold was set to -60dB and convergence was confirmed upon completion. Fat was predefined by the simulation software to have the following tissue properties: conductivity=0.041 S/m, relative permittivity=5.22 and density=943 kg/m^3 Muscle properties included conductivity=0.922 S/m, permittivity=66.35 and density=1059 kg/m^3. B1+ maps, electric field maps and SAR maps were extracted from the two simulations and analyzed. Figure 2 illustrates the comparison between the $|B_1^+|$, $|E|$, $|E|^2$ and SAR fields, respectively, in an axial slice. The mean field values for the $|B_1^+|$ and $|E|$ in a 12.5cm x 13cm x 13cm 3D volumetric region of interest, on average deviated less than 8% between the two simulations. Even though $|B_1^+|$ in this slice of interest varied no more than 40%, the $|E|$ field varied more than 400% and $|E|^2$ varied more than 400%. Figure 3 shows contrasting electric field vector orientation between simulation 1 and simulation 2. This discrepancy is relevant for parallel transmit or RF shimming experiments where pulses are designed such that the electric fields from different coils destructively interfere to minimize SAR.

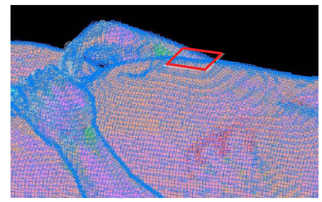

Figure 1. Simulation setup: surface coil(in red) placed above the abdominal area of a human body mesh

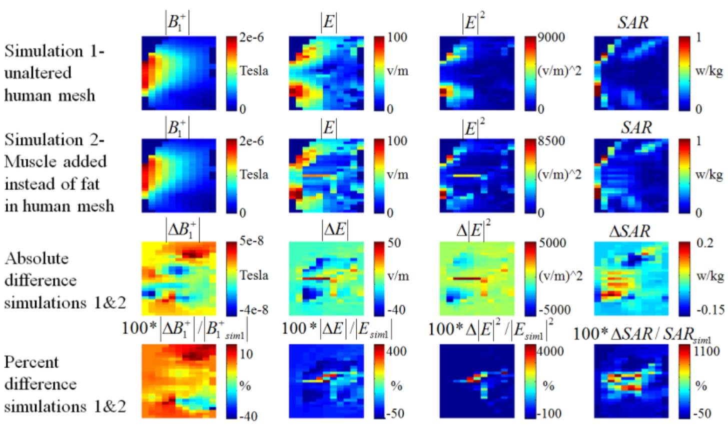

Figure 2. Top two rows: Magnitude of B1+, , $|\boldsymbol{E}|$, $|\boldsymbol{E}|^2$ and SAR maps of the two simulations. Simulation 1 is the baseline simulation where "Hugo", the human body mesh was used unmodified. Simulation 2 had muscle tissue inserted close to the surface of the abdomen instead of fat. Bottom two rows: maps of the absolute and percentage difference between the simulations and the percent difference of the simulation field map, respectively.

Discussion: This study demonstrates $|B_1^+|$ may be highly correlated in two different body tissue distributions while $|E|$, $|E|^2$ and SAR maps can vary significantly. The magnetic fields and the electric fields are coupled via Maxwell equations $E = \frac{\nabla \times B}{\mu(\sigma - i\omega\varepsilon)}$ and $B = \frac{\nabla \times E}{i\omega}$ (where B and E are the magnetic and electric fields with assumed harmonic time variation, μ is the magnetic permeability, σ is the conductivity, ε is the permittivity and ω is the frequency). Thus, any change in magnetic fields would affect the electric fields and vice versa. In the MR experiment, the magnitude $|B_1^+|$ image combines the B_x and B_y components of the magnetic fields into one quantity, ignoring the RF B_z component. Therefore, scenarios exist where the $|B_1^+|$ maps fail to fully capture the behavior of the electric fields. In this example, the average $|B_1^+|$ and $|E|$ field maps in a 3D region of interest varied less than 8% between one simulation to another. Even though the average variation was not large, there was significant variation in particular slice locations, which could lead to SAR hotspots. Additionally, spatial variations in conductivities and tissue densities add another level of complexity, and depending on their relative values in relation to the baseline simulation, can either dampen or intensify local SAR hotspots. Due to the possibility of constructive interference, parallel transmit or RF shimming experiments may be even more susceptible to E-field variation despite $|B_1^+|$ correlation, resulting in increased local heating.

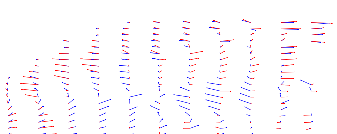

Figure 3. Orientation of electric field vectors. Blue: Simulation 1. Red: Simulation 2.

Conclusions: Even though, $|B_1^+|$ is an easily measurable quantity in MR, it provides insufficient information for aligning electric fields and SAR distributions with one another. Moreover, average differences between field maps provide very little detail about how well fields align locally with each other. Therefore, given the difficulty of aligning all relevant fields between experiment and simulation, utilization of simulation software for coil safety evaluation both for single channel systems and parallel transmit/RF shimming systems should be handled with care.

References: 1. Zhu Y. In Vivo RF Power and SAR Calibration for Multi-Port RF Transmission. ISMRM 09. 2. Zhu Y. Parallel Excitation with an Array of Transmit Coils. Magn Reson Med 2004; 51:775-784.