Effect of CST time domain solver setup and simplifying 7T MRI coil 3-D EM simulation models on power balance and SAR

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Purpose: Power balance, defining as a difference between power delivered to coil input and coil dissipated power (sum of reflected (P_{refl}), radiated ($P_{radiated}$), absorbed by coil load (P_{load}) and coil internal structure powers (P_{inter}), as well as coverage (both in terms of mesh refinement and distance to perfect absorbed boundary (PAB)) of simulation data were never important check points of SAR investigation. Essential mismatch of power balance is strong evidence that simulation data are not reliable. Power balance alone cannot be use for proving SAR simulation data reliability because interactions of MRI coil with scanner environment (scanner gradient shield, RF power splitter, etc.) are also important for correct SAR estimation. Incorrect distance to boundaries and/or omitting scanner gradient shield could strong influence on $P_{radiated}$ and as a result on P_{load} &SAR. Coil tune/match conditions are important for reliable SAR estimation, especially for TX array coil because array element coupling influences on both power balance and current distribution. In some SAR investigations conducting elements were treated as perfect electro conductor (PEC) followed by renormalization of SAR on base of coil quality factors for loaded and unloaded cases. However SAR uncertainty analysis of approaches applied were not a part of the reports. Our goal was to compare simulation results obtained for a commercially available Rapid BioMed 7 T 8-element head coil [1], with different level of simplifications and CST time domain solver setup.

Method: We employed co-simulation of the RF circuit and 3-D EM fields. Agilent ADS was used as the RF circuit tool, and CST time domain solver was used as 3-D EM tools. The realistic coil 3-D EM model includes all construction details for the resonance elements, simulated with realistic dimensions and material electrical properties and the Siemens 7T scanner hole body gradient shield, defined as a copper cylinder with ∅=683mm and 0.045 mm thickness. PAB was offset to the cylinder for 40mm because it is known that electrical contact between shield and PAB screws up correct $P_{radiated}$ calculation. In additional to realistic simulations several model simplifications were applied: a) substitution of conducting elements by PEC; b) excluding of lossy dielectric material from simulation domain; c) excluding of scanner gradient shield and varying distances to PAB as well as their combinations. For tuning the coil for each simulation setup vendor provided procedure was used - a Siemens 7 liter water-based phantom was placed inside the coil. The in-vivo coil performance was evaluated using the Hugo model with different scaling factors: 1, 0.9, 0.8 and models from "Virtual Family". Power balance was calculated on base of 8W power deliver to the coil input and obtained values: P_{refl}, $P_{radiated}$, P_{inter}, P_{load}. Effective resistive impedances of radiation losses ($R_{radiated}$), coil internal structure (R_{inter}), coil load (R_{load}) were calculated on base of sum of each element feed current and correspondent power. Distance to PAB in XY direction was step by step increased until it reached distance to the gradient shield. Thereafter gradient shield was included in numerical domain. Distance to PAB in Z direction was step by step increased until $P_{radiated}$ was converged.

Results and Discussion: Despite of large distance to hole body 7T head gradient shield it is important to include the gradient shield in simulation domain in our case. $R_{radiated}$, which decreases as much as 1.6 time (from 1.84W to 1.15W) in case of increasing distance to PAB in XY direction from 10mm to 250mm, drops to 0.25W with the gradient shield included. At the same time P_{load} increases from 4.2 W to 5.62 W. As a result average head SAR and local 10 gram SAR increased for about 25…40% (depends on load model) for realistic scanner environment simulation relative to short PAB distance simulation values. For PEC based models value of fixed distributed capacitors has to be increased for about 8% to get coil tuned for 7T MRI resonance frequency. Rescaled to correspondent maximum SAR profiles for realistic and PEC based model (gradient shield included in both cases) are noticeable different that can be explained by inequality of current distribution through coil element despite rescaled to correspondent maximum B1+ profiles inside load, especially for transversal one, look similar. PEC based project effective R_{load} (for phantom or human model) is more than 12.5% smaller than for realistic model. It follows that PEC based SAR prediction will underestimate SAR. There is significant influence of time domain solver steady state monitor setup on P_{load} and power balance inside 3D EM structure. To ensure full coverage the steady state monitor must be set below -60 dB. In other cases P_{load} and SAR can be underestimate or overestimate up to 35%. Calculation of power absorbed by coil load using equation $1\text{-}Q_{unload}/Q_{load}$ provides underestimated value (for example for phantom as load calculated value is 0.59 although value obtained from power balance is 0.66). This fact strongly depends on difference between effective impedance of radiation losses for load and unload cases as well as tuning condition for unloaded cases. If power reflected by entire coil for loaded and unloaded cases differs essentially, this means that coupling condition between power source and the coil is not the same. This fact invalidates general requirement (critical coupling) for which the equation was derived.

Conclusion: There is no way to obtain SAR and power balance estimation for actual coil with small uncertainty using simplified coil model and any renormalization approach. If the power balance obtained by simulation failed there is no sense to calculate SAR. It is important to reach converge not only of B1+ data and power absorbed by load by mesh adaptation but also of radiated power including simulation of scanner gradient shield. There is no universal (coil design independent) prediction rule how distance to boundary and scanner gradient shield simulation will influence on SAR. As a result it is important to simulate a coil as close as possible to realistic coil and scanner geometries. The later requires much large simulation domain that is commonly used for MRI coil investigations available in literature.