# Effects of simplifying rf coil 3-D EM simulation models on power balance and SAR

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**Purpose:** Previous SAR simulations of RF coils have neglected power balance (defined as the difference between input RF power and total dissipated power) and the effects of coil distance from a perfect absorbing boundary (PAB). A non-zero power balance indicates a faulty simulation. However, zero power balance alone may not demonstrate the accuracy of SAR simulation, which must fully include interactions of the coil with the scanner environment, such as the built-in gradient coil shield, RF power splitter, etc., that influence radiated power ($P_{radiated}$), and consequently also power absorbed by coil load ($P_{load}$) and SAR. Coil tune/match parameters also affect SAR estimation, especially for transmit array coils, where current distributions are influenced by array element mutual coupling. We compared simulation results, at different levels of simplification, for a commercially available Rapid BioMed 7 T 8-element head coil [1], calculating the power balance and SAR using both frequency domain and time domain 3-D tools.

**Method:** Total dissipated power was calculated as the sum of the power reflected ($P_{refl}$), $P_{radiated}$, $P_{load}$ and thepower absorbed by the coil's structure ($P_{inter}$). We employed co-simulation of the RF circuit and 3-D EM fields [2]. The realistic coil 3-D EM model includes all construction details for the resonance elements, simulated with precise dimensions and material electrical properties. The model was simplified in several ways: a) substitution of conducting elements by perfect electrical conductors (PEC); b) exclusion of lossy dielectric materials; c) varying the distance to PAB; and combinations of these. For each version, the standard vendor-provided coil tuning procedure was simulated, with a Siemens water-based phantom placed inside the coil. The in-vivo coil performance was evaluated using the Ansoft human body models with different scaling factors: 1, 0.9 and 0.8. Effective resistive impedances for radiation losses ($R_{radiated}$), coil internal structure ($R_{inter}$), and coil load ($R_{load}$) were calculated from corresponding power and sum of each element's feed current. The distance to the PAB in the XY plane was stepwise increased up to the diameter of the gradient shield, about 680 mm. The gradient shield was then included, and simulated as a copper cylinder with 0.045 mm thickness and 40mm distance to the PAB. The axial distance to the PAB was also increased stepwise until values of $P_{radiated}$ converged.

**Results and Discussion:** Due to several CST2009 software bugs, the power imbalance could never be reduced below 20% for the CST MWS simulation of the most realistic coil model. Using HFSS the power imbalance was less than 3% for all simulations, and less than 0.5% assuming PEC. Importantly, all conducting elements were modeled as 3D objects, not as 2D resistive or PEC surfaces. With 2D resistive surfaces, HFSS overestimated resistive losses, and the power imbalance could be unpredictably large. Although the gradient shield is quite distant, it was vital to include it in the simulation. When the PAB distance was increased from 10mm to 250mm, $R_{radiated}$ decreased by 60% (from 1.84W to 1.15W), and it dropped further to 0.45W on inclusion of the gradient shield (Fig. 1). At the same time, $P_{load}$ increased from 4.2 W to 5.41 W. As a result, both average head SAR and local 10 gram SAR increased by 25--40%, (depending on coil loading) when the scanner environment was realistically simulated, relative to simulation with a nearby PAB. After appropriate rescaling, the corresponding maximum SAR profiles for the realistic and PEC based models, both including gradient shield, are noticeably different (Fig. 2). This can be explained by unequal current distributions through the coil elements (Fig. 3) even though corresponding rescaled $B_1$+ profiles inside the load are visually similar (Fig 4). For all coil loads studied, the effective $R_{load}$ for PEC models is more than 12% smaller than for the realistic model. Thus PEC model-based SAR predictions will underestimate SAR. Calculation of $P_{load}$ using equation $Q_{unload}/Q_{load}$ also gives an underestimate, resulting from the change in both the $R_{radiated}$ and the coupling between power supply and coil when the coil is loaded. This fact invalidates the condition of critical coupling for which the quality factor equation was derived. Using the realistic model, comparison of $P_{load}$ and SAR calculated with CST and HFSS shows that CST significantly underestimates both quantities (10--20%, depending on load).

**Conclusion:** Accurate SAR and power balance estimates for an actual RF coil cannot be obtained using an over-simplified coil model and the commonly used renormalization approach. Simulations must converge not only for B1+ values, but also for $P_{load}$ and $P_{radiated}$. The effect on SAR of distance to absorbing boundaries and gradient shield depends strongly on RF coil design. Thus coils and their environment need to be specified as accurately as possible, much better than current common practice. If simulation fails to give the correct power balance it is pointless to calculate SAR. In their current implementations, the Ansoft HFSS frequency domain solver provides much more reliable data, and much faster, than the CST time domain solver.

[1] A. Weisser, T. Lanz, Proc. ISMRM. 14 (2006) 2591. [2]Kozlov, R. Turner, Journal of Magnetic Resonance 200 (2009) 147–152.

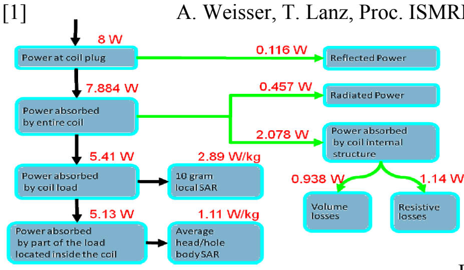


Fig.1. Power balance

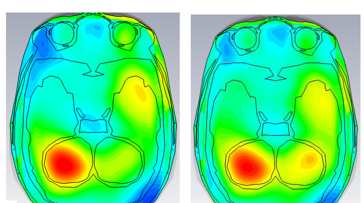

Fig. 2. SAR profile with individual scaling realistic model (left), PEC based (right).

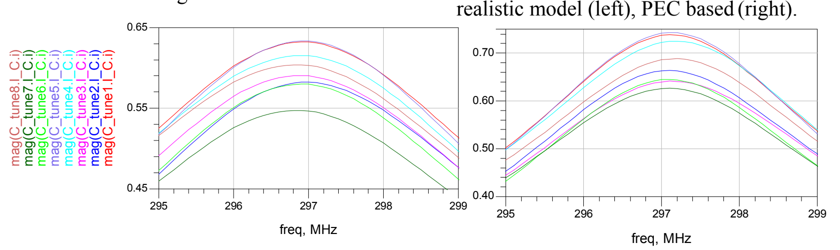


Fig. 3. Current through each coil element: realistic model (left), PEC based (right).

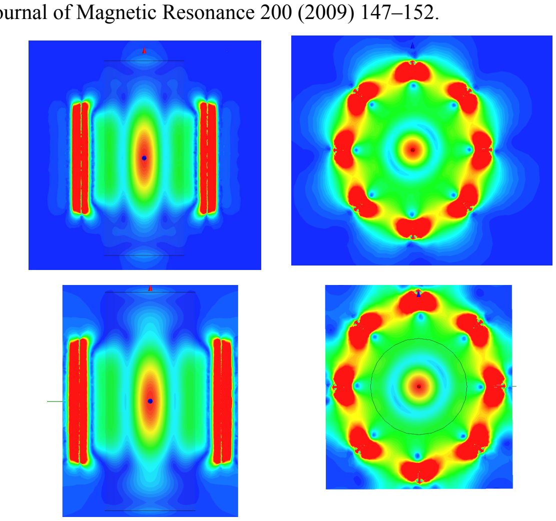

Fig.4. B1+ profiles. Top: gradient shield included; below: distance to boundary 10mm.