Simulation of the Effect of Mode Coupling on SAR for a Birdcage Resonator

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Introduction: Specific Absorption Rate (SAR) is an important parameter for MRI. SAR denotes how much RF power is absorbed by the patient. It is necessary that the SAR corresponding to a MR coil is within the safe limits otherwise serious injury or even death may occur. However determination of SAR is a difficult task complicated by the fact that the associated E-field and the temperature rise both are very difficult to measure. Simulation has become a viable alternative due to the easy availability of computing power and commercial fullwave analysis packages. However, despite the progress made, fullwave simulations require substantial computational resources even for modern computers. For example, the frequency domain Finite Element (FEM) [1] based solver can not simulate coil with the popular visible human body mesh [2] due to resource limitation. The FDTD simulators [3] do not have this issue but the computational time generally is much longer and in some cases becomes unrealistic, as is the case for the example shown. To reduce the long simulation cycles, a popular method often used by coils designers is to use a non resonant structure by removing all the capacitors and replacing them with current sources to recreate the imaging mode current profile. Although this method requires only fraction of simulation time compared to the simulation of a resonant structure, it may result in a lower estimate of SAR values. Here using simulation we compare the SAR results for imaging mode only and for all modes. The SAR calculation method shown here can result in substantial reduction in simulation time for complex designs and can be applied for the cases where the conventional FDTD simulation time is unrealistic.

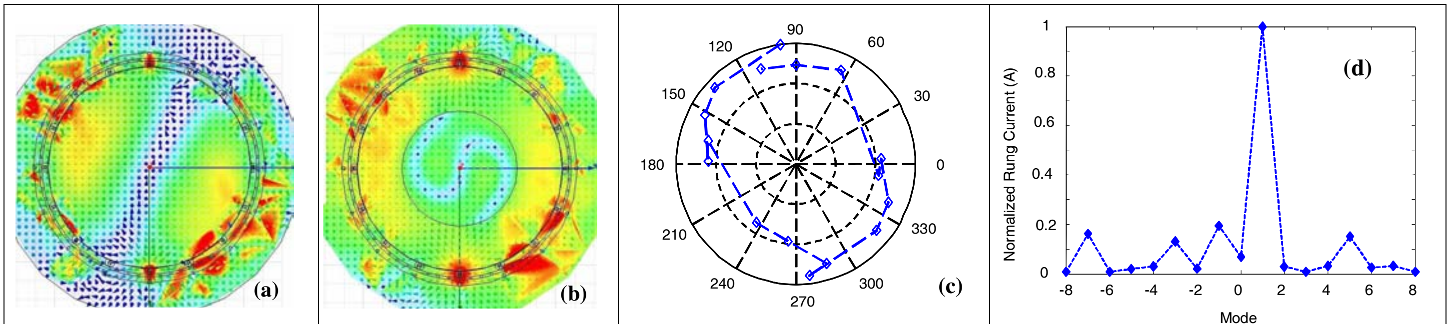

Figure 1. From HFSS; E-field profile (a) without phantom, (b) with phantom, and, (c) rung current profile and (d) power content in each mode.

Methods: The coil designed used in the simulation is the 7T Knee with at 300 MHz, designed and manufactured by Invivo Diagnostic Imaging®. The coil is a 16 rung birdcage with the end-rings placed outside of the shield. Fullwave simulations were performed using Ansoft HFSS®, both with and without phantom (see Fig. 1(a-b)), and the one port reflection coefficient (S11) measurement using a network analyzer, showed the validity of the simulation results. Note that the electric field profile for the loaded coil (Fig. 1(b)) is different from the unloaded case (Fig. 1 (a)). The reason for this will be apparent from the current profile given in Fig.1(c) where, the current distribution in the rungs clearly deviates from the uniform current distribution of the imaging mode. Although the imaging mode is clearly the dominant mode, the presence of other non-imaging mode is also apparent. Note that for imaging mode only the electric field at the center region of the coil is low, which results in a low SAR region at the center, but this is not true for the loaded as case indicated by the non-zero field magnitude at the center due presence of non-imaging modes.

The current distribution in the coil can be expressed as the sum of the current distributions of the individual modes as shown in (1). Using the orthogonally of the modes, a_m can be calculated from the dot-product shown in (2). The magnitude of a_m, for the current profile shown in Fig. 1(c) calculated using (2) is presented in Fig. 1(d). Note that this technique can be applied on a measured current distribution as well. Fig. 1(d) supports the observation from the current and E-field profiles that most of the power is contained by the imaging mode and all other modes contains less than 20% of the imaging mode power. Also note that the mode profile shown in Fig. 1(c-d) will be very dependant on how the coil is excited. In this example a four port excitation was used. The E-field profile for each mode can be simulated separately with the human head/body mesh, using XFDTD, using the "non-resonant" simulation method described earlier. The total E-field is calculated from combining the E-fields from all modes using (3) and the total SAR is then calculated from (4). Note that the factor $\sigma/2\rho$ can be estimated from the simulated SAR and E-field matrix for a particular mode.

Equations: $\tilde{I}_{total} = \sum_m a_m \cdot \hat{I}_m$ (1) $\quad a_m = \tilde{I}_{total} \cdot \hat{I}_m$ (2) $\quad \tilde{E}_{total} = \sum_m a_m \cdot \hat{E}_m$ (3) $\quad SAR = (\sigma/2\rho)\cdot\left|\tilde{E}_{total}\right|^2$ (4)

Summary and conclusion:

K factor for imaging mode only:

$$K_{head} = \frac{SAR_{\max 10g}}{Power_{rms}} = \frac{49.256 \cdot {}^{W}\!/\!{}_{kg}}{47.50 \cdot W} = 1.1374 \cdot {}^{1}\!/\!{}_{kg}$$

K factor for all modes present in the coil

$$K_{head} = \frac{SAR_{\max 10g}}{Power_{rms}} = \frac{100.87 \cdot {}^{W}\!/\!{}_{kg}}{50.60 \cdot W} = 2.0013 \cdot {}^{1}\!/\!{}_{kg}$$

In summary, we show using simulation results that the impact of non-imaging modes excited in a loaded coil can be significant and must be taken in to account. The K-factor for the 7T 16-rung head coil for all modes present in the coil is 75% higher than the result considering the imaging mode only We also present a technique to calculate the SAR due to all modes present in a coil using simulation results and current profile. While the method presented requires some effort, it can result in a dramatic reduction in simulation time compared to the conventional simulations using commercially available FDTD solvers.

References: [1] Jin J., *The Finite Element method in Electromagnetics*, John Wiley and Sons, New York, 2002
[2] The Visible Human Project, http://www.nlm.nih.gov/research/visible/visible_human.html
[3] Kunz KS., *The Finite Difference Time Domain method for Electromagnetics*, CRC Press, 1993