Estimating Local SAR Produced by RF Transmitter Coils: Examples Using the Birdcage Body Coil

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Purpose

To quantify local SAR near the conductors of the birdcage coil using symbolic calculations and finite element modeling (FEM). To compare the accuracy of these two techniques.

Introduction

Local SAR is a critical factor in patient safety. The precise calculation of local SAR is difficult because of the inherent geometrical complexity of the interaction between the RF coil and the patient and the dependence of SAR on RF pulse shapes and pulse sequence details.[1,2] Simple models can be solved exactly but cannot accurately incorporate the effects of human anatomy, tissue conductivity and dielectric constants. Numerical methods[3,4] such as FEM, now have the power to take these factors into account, but their accuracy is dependent, in a hard to determine fashion, on factors such as mesh size and the location of the external surfaces used to bound the problems. Ideally, the advantages of the FEM and related numerical techniques should be coupled with standard closed-form expressions (CFE). Birdcage coils are widely used as RF transmitters in high field MRI and are a good test case.

Birdcage Currents and Fields

The birdcage coil consists of N rungs (numbered 1 through N) and N semi-circular arcs at either end. Under quadrature excitation, a traveling wave of RF current moves around the coil. The currents in the end ring arcs and in the rungs are
$I_n^{arc} = I_o \cos[\frac{2(n-1)\pi}{N} - \omega t]$ and $I_n^{rung} = -2I_o \sin\frac{\pi}{N}\sin[\frac{(2n-1)\pi}{N} - \omega t]$.
The maximum current in the rungs is less than that in the end rings by a factor 2 sin[π/N] and the highest SAR values are expected for tissues near the end rings. Integration of the Biot-Savart law over the rungs and end rings of an unshielded filamentary coil model gives, for an unloaded coil,

$$B_1 = -\frac{\mu_o I_o}{2\pi a} N \sin\frac{\pi}{N}\frac{D(D^2+2)}{(1+D^2)^{3/2}},$$

where L and a are the coil length and radius. $D=L/2a$ is the coil aspect ratio. Both the rungs and the end rings contribute to the B_1 field. It can be shown that the rungs contribute a fraction $(D^2+1)/(D^2+2)$ of the total B_1. Thus, for $D = 1$, 2/3 of the B_1 field is produced by the conductor rungs. In practice the RF shield must be considered as this greatly increases the coil current required to achieve a given B_1 and, thereby increases the local SAR near the conductors. The method of images can be used to approximate the effect of the shield but this method is exact only for $D\rightarrow$infinity. The image current is equal but opposite to the coil current. With a_c, a_i and a_s as the radii of the coil, image and shield $(a_c a_i = a_s^2)$ and with $D_i=L/2a_i$ and $D_c=L/2a_c$,

$$B_1 = -\frac{\mu_o I_o}{2\pi} N \sin\frac{\pi}{N}\left[\frac{1}{a_c}\frac{D_c(D_c^2+2)}{(1+D_c^2)^{3/2}} - \frac{1}{a_i}\frac{D_i(D_i^2+2)}{(1+D_i^2)^{3/2}}\right].$$

The quantity $\Gamma = B_1/I_o$ (in μT/A) measures the coil efficiency. Coils with low efficiency require large currents to achieve a given flip angle and have, therefore, high local values of SAR.

Electric Fields Near the Conductor Rungs

Neglecting any field associated with capacitive coupling between the coil and patient (which is small in birdcage coils), $\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t}$ and $SAR = \frac{\sigma < E_o^2 >}{2\rho} = \frac{\sigma}{\rho}E_{rms}^2$, where E_o is the RF amplitude of the electric field and σ and ρ are the electrical conductivity and mass density of the tissue. For an infinitely long conducting wire of negligible radius a distance R_1 from the field point and with a return current at a distance R_2 the vector potential is given by $A_z = \frac{\mu_o I}{2\pi}\ln\frac{R_2}{R_1}$. However, because of the singularity this expression overestimates the field near the conductor. If the current at $x=a_c$ with return at $x=-a_c$ is spread out with a surface density I_o/d over a conducting ribbon of width $d<<a$, it is found that

$$A_z = \frac{\mu_o I_o}{\pi d}[\pi x + (a-x)\tan^{-1}\frac{2(a-x)}{d} - (a+x)\tan^{-1}\frac{2(a+x)}{d} + \frac{d}{4}\ln\frac{4(a+x)^2+d^2}{4(a-x)^2+d^2}].$$

This expression can be combined with that for the image current for an expression that is finite at all locations and can be used as a closed-form approximation to compare with FEM calculations.

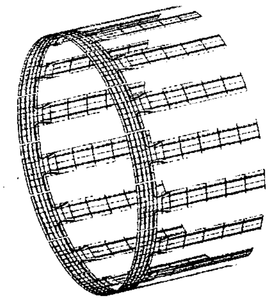

Fig. 1 Birdcage numerical model.

FEM Model

A geometric model of a birdcage coil (Fig. 1) was constructed using the modeling tool ARIES and the electromagnetic fields were found for various loading conditions by use of the finite element program EMAS (Ansoft Corporation, Pittsburgh, PA). The model body coil has 16 elements with the rungs modeled as copper ribbon conductors 5.2 cm wide and 55.7 cm long. The coil radius is 30.7 cm and the copper shield radius is 32.7cm and its length is 65.7 cm. The end ring ribbon width is 5.0 cm. As indicated in Table 1 the CFE and the FEM results are with about 10 percent of one another. Perfect agreement is not expected as the models have certain fundamental differences. By further comparison of FEM and CFE calculations the accuracy of FEM calculations of SAR near conductor boundaries can be validated.

Table 1. B_1 in μT at 64 MHz. (CFE - closed form expression)

CFE Unshielded	CFE Shielded	FEM Unshielded	FEM Shielded
5.625	0.799	4.99	0.872

References

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