An Electromagnetic Model for Cool-tip RF Needle Artifacts in Magnetic Resonance Imaging

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Introduction

MRI monitoring of temperature evolution during radio-frequency (RF) thermal ablation is of great interest to provide on-line quantification of temperature distribution. The practical drawback of RF ablation procedure is the quantitative temperature feedback due to susceptibility artifacts of the cool-tip RF needle (Tyco Healthcare). Therefore, a through understanding of artifacts caused by RF needle is essential. In the past, to understand the artifacts caused by metallic instruments, different groups have described the theoretical background of those artifacts based on geometrical distortion and intravoxel dephasing that accompany the presence of a biopsy needle within tissue [1-4]. As an extensive of previous researchers' contributions, we have developed an electromagnetic model to derive the susceptibility artifacts of cool-tip RF needle in magnetic resonance imaging.

Materials and Methods

Theory: In our model, we consider that the cool-tip RF needle is perpendicular to the static magnetic field B_0 which is parallel with z-axis, B (x, y, z) = (0, 0, B_0) as shown in Figure 1. The magnetic scalar potential is given by $H = \nabla\phi$. Since there are no free currents in the problem, we can write $H=-\nabla\phi_m$. Furthermore, since $B=\mu H$ and $\nabla . B=0$, it is clear that the magnetic scalar potential satisfies Laplace's equation, $\nabla^2\phi=0$, throughout all space. In cylindrical coordinates (r,θ, z_c), where the z-axis is along the axis of cylinder, the potential satisfies

$$\nabla^2\phi = \left\{\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial\theta^2} + \frac{\partial^2}{\partial {z_c}^2}\right\}\phi \qquad (1)$$

For a system with cylindrical symmetry, the electrostatic potential does not depend on z_c. This immediately implies that $\partial/\partial z_c=0$. Under this assumption Laplace's equation reads

$$\left\{\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r} + \frac{1}{r^2}\frac{\partial^2}{\partial\theta^2}\right\}\phi = 0 \qquad (2)$$

Consider as a possible solution of ϕ: $\phi(r, \theta)=R(r)S(\theta)$. By symmetry $\phi(r,\theta)= \phi(r,-\theta)$, the general solution of Laplace's equation will be,

$$\phi_i(r,\theta) = \sum_{m=1}^{\infty}\left(C_{im}r^m + D_{im}r^{-m}\right)\cos(m\theta) \qquad (3)$$

When we set m=1, magnetic field H will be,

$$H = -\left[\frac{\partial}{\partial r}, \frac{1}{r}\frac{\partial}{\partial\theta}, 0\right]\phi = \left[\left(-C_{i1} + \frac{D_{i1}}{r^2}\right)\cos\theta, \left(C_{i1} + \frac{D_{i1}}{r^2}\right)\sin\theta, 0\right] \qquad (4)$$

Then magnetic flux density will be $B_i=\mu_i H_i=\mu_0(1+\chi_i)H_i$ where μ_0 is magnetic permeability in a vacuum and χ_i is magnetic susceptibility. In the case of the cylinder model of the cool-tip RF needle, we have to divide the space into five parts as shown in figure 1.The boundary conditions are that the potential must be well behaved at r=0 and r=∞, and also that the tangential and the normal components of H and B, respectively, must be continuous at r=R_1, R_2, R_3 and R_4. At large distance from the cylinder (r →∞), the magnetic flux density $B_5 = B_0$. By combining Eq. 4 and the magnetic flux density information, $C_{51}=-B_0/\mu_5$. At center of the RF needle (r→0), we require ϕ_1 to be finite. Hence $D_{11}=0$. Then the unknown parameters in Eq.4 are C_{11}, C_{21}, C_{31}, C_{41}, D_{21}, D_{31}, D_{41}, D_{51}. To solve the equation numerically by Gaussian elimination, these parameters should be calculated.

Geometry Distortion: Ludeke et al presented the effect of the spatial distortion by susceptibility effects for the first time [3]. Since the gradient is not switched on during read out period, we do not have to consider the phase encoding direction. Under this circumstance, geometrical distortion is given by

$$x' = x + \left(\frac{\Delta B}{G_v}\cos\beta\right), \qquad z' = z + \left(\frac{\Delta B}{G_v}\sin\beta\right) \qquad (5)$$

where $\Delta B = B_i - B_0$ for each r_i, β is the angle of the frequency encoding gradient, G_v is the strength of the frequency, and (x,y,z) and (x',y',z') represent the object and image coordinates.

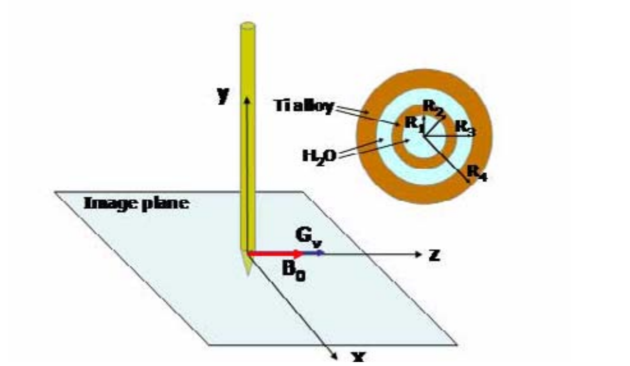

Figure 1. Coordinate system. RF Needle is perpendicular to the orientation of static magnetic field. Upper right is the cross section of the RF needle on image plane.

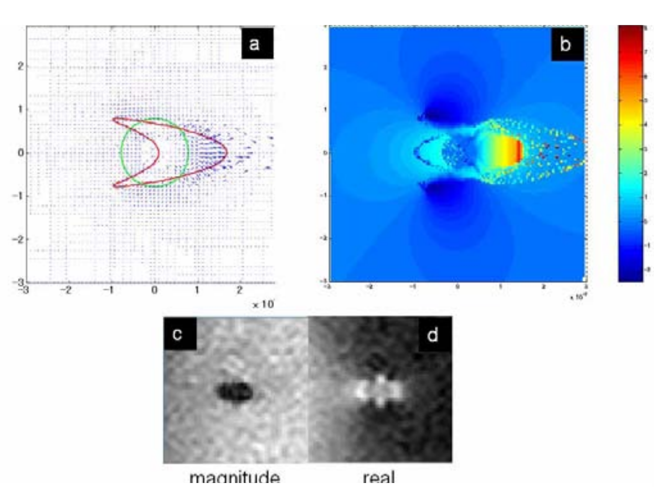

Figure 2. a) The vectors of ΔB on each voxel. The green line is location of the RF needle. And the red line is the contour of the RF needle after distortion. b) The distribution of ΔBx on each voxel. c-d) The MR images of the cool-tip RF needle.

Results and Discussion

All simulations and experiments are based on the spoiled gradient echo sequence (SPGR) (TR/TE:34/14 ms, BW: 7.81KHz).The newly developed simulation tool for calculating magnetic flux density were integrated in the PC/AT machine (Windows XP).

Parameters based on cool-tip RF needle were given as follow: B_0=0.5T, R_1=0.383mm, R_2=0.48mm, R_3=0.5985mm, R_4=0.79mm, $\mu_1=\mu_3=\mu_5=-9.05\times10^{-6}$, $\mu_2=\mu_4=182\times10^{-6}$, $\mu_0=4\pi\times10^{-7}=1.257\times10^{-6}$H/m. G_v=0.030125mT/m. Figure 2a shows the vectors of ΔB considering geometrical distortion. The maximum value of magnitude of ΔB is 9.183×10^{-6}T. The artifacts occur because of these distortions and dephasing by ΔB. Figure 2b shows the magnitude of ΔB. The shape of distribution calculated from our theoretical work is very similar to the artifact on the image shown in figure 2d. We derived the susceptibility artifacts of the cool-tip RF needle (multi-layered structure consists of titanium-alloy and H_2O) by newly developed electromagnetic method. The model for susceptibility-based needle artifacts allows a better understanding for the appearances of needles in MR images. The applicability to clinical procedures has to be examined further by experiments.

REFERENCES

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