

Modeling Human Tissues in Pulsed Gradient Fields

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SYNOPSIS: Since human tissues are dispersive (have frequency-dependent electrical properties) and realistic gradient pulse shapes contain a spectrum of frequencies it is necessary to examine how best to model human tissues in pulsed gradient fields for MRI. Here we utilize a full-Maxwell numerical method to calculate the electrical fields created by an ideal gradient field with a time course like that of the front end of a trapezoid in a spherical sample of varying electrical properties. Results indicate that it is not necessary to model human tissues as dispersive for gradient coil calculations.

INTRODUCTION: With growing realization of the significance of peripheral nerve stimulation as a limiting factor in the development and application of MRI (1), a number of methods have been used recently to calculate the electrical fields induced in the human body by gradient fields in MRI (2-5). Most of these rely on steady-state quasi-static assumptions and a single low sinusoidal excitation frequency. Realistic single (non-periodic) trapezoidal and sinusoidal gradient waveforms contain a spectrum of frequencies and human tissues are dispersive, having different electrical properties at different frequencies. It is important to examine possible implications of this combination on calculations of electrical fields induced by MRI gradient fields.

METHODS: A 3D Matlab-based finite difference time domain (FDTD) solver was developed and used to model a sphere of varying electrical properties in an ideal linear gradient field as it is "switched on" with a waveform like the front end of a trapezoidal pulse. To accomplish this a linear source magnetization distribution was defined and varied with time, and the full FDTD method was used in predicting the resulting electromagnetic field distribution. The gradient strength was 0 Gauss/cm for the first 0.1 μ s, then increased linearly to 1Gauss/cm in the next 1.0 μ s and remained at that strength for the final 1.0 μ s of the calculation. Because very high frequency components (very sharp changes) in the time course cannot be realized in gradient fields due to gradient coil inductance and other hardware limitations, we eliminated unrealistically-high frequency components in the excitation waveform by passing it through a digital first-order low-pass Butterworth filter with a 3dB cutoff frequency of 10MHz. The resulting excitation waveform is shown in Figure 1. Separate calculations were performed for a 10-cm diameter sphere having several combinations of relative permittivity ϵ_r and conductivity σ with ϵ_r ranging from 67108.5 (the value for brain at 2kHz) to 1 and σ ranging from 0S/m to 1×10^6 S/m (including $\sigma=0.0834$ S/m, the value for brain at 2kHz). The cell size was 5mm in each dimension and the problem region spanned 50 cells in each direction.

RESULTS: Figure 2 shows the E-field magnitude distribution on a plane passing through the middle of the sphere with 2kHz brain properties at a point in time approximately mid-way up the ascent to 1Gauss/cm. The applied gradient is in the up-down direction within the page, with the magnetic field oriented perpendicular to the page. Figure 3 shows the time course of the E-field magnitude at a location approximately 1cm to the left of the sphere as shown in Figure 2, but with $\epsilon_r=1$. In all calculations but that with $\sigma=0$ S/m, The E-field at this location plateaued at the same value as in Figure 3 (208V/m), but with the following variations: when σ was very low (0.01S/m) the approach was from the opposite direction and when ϵ_r was very high (67108.5) there was a small oscillation in E about this value corresponding to a high-order resonance in the sphere (at about 16.7MHz, wavelength in sphere about 7cm). This oscillation would not occur in practice because due to the dispersive nature of tissues, although brain has $\epsilon_r=67108.5$ at 2kHz, at 16.7MHz brain has an ϵ_r of only 183.5. When the gradient waveform was not passed through a lowpass filter these oscillations were very large and occurred whenever $\epsilon_r > 1$ with frequency of oscillation varying appropriately with ϵ_r . At a location 1cm within the left side of the sphere a behavior with time similar to that in Fig. 3 is seen, but with a plateau value of only 2.16V/m. This plateau within the sphere was never reached when $\sigma=0$ S/m or when $\sigma=1 \times 10^6$ S/m.

DISCUSSION: We have shown with full-Maxwell methods that the electrical fields induced by a gradient field in and around a sphere are independent of the exact electrical properties of the sphere as long as the electrical conductivity is greater than zero and the skin depth is much greater than the sample size. This can be explained with the following rationale: At the low frequencies that dominate gradient fields, dependence on ϵ_r can be ignored and the electrical field is dependent primarily on (in addition to dB/dt) the charge distribution at the surface of the sample. These results indicate that for gradient field calculations quasi-static approximations are appropriate, even for pulsed timecourses, despite the dispersive nature of human tissues.

REFERENCES:

1. Chronik and Rutt, 46:386(2001)
2. Bencsik et al., Phys Med Biol 47:557 (2002)
3. Liu et al., Conc. MR 15:26(2001)
4. Brand and Heid, MRM 48:731(2002)
5. Collins et al., Proc ISMRM, p844 (2002)

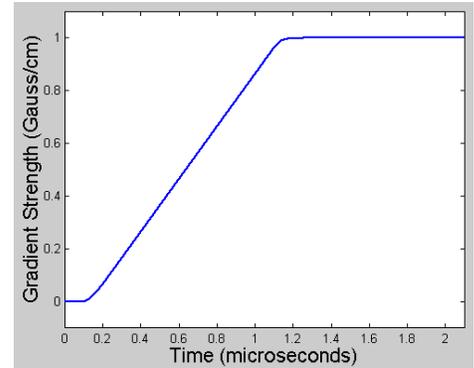


Figure 1: Time course of applied gradient field.

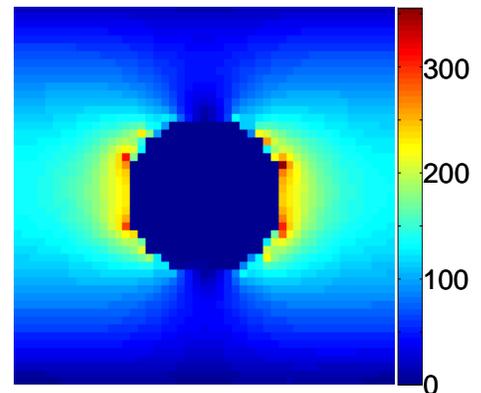


Figure 2: Electrical field magnitude (vector norm) around sphere with electrical properties of brain at 2kHz. Units of V/m.

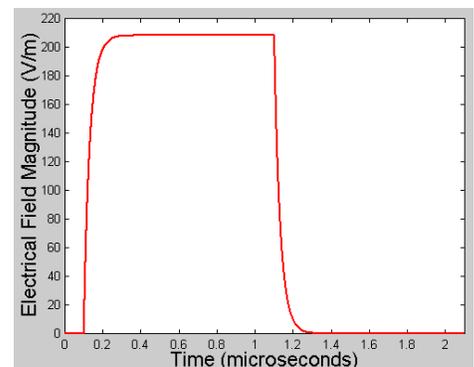


Figure 3: Time course of Electrical field 1cm left of sphere with $\epsilon_r=1$ and $\sigma=0.0834$ S/m.