Significance of Applied Driving Voltage in Calculations of Electrical Fields in a Loaded Gradient Coil

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INTRODUCTION: As the achievable strength and speed of gradient systems have increased to satisfy demanding whole-body MRI applications, peripheral nerve stimulation (PNS) has become a limiting factor to gradient system operation (1). Addressing this problem requires a fundamental understanding of gradient coil induced PNS, and a primary requirement is detailed consideration of the electrical fields induced in the human subject by the gradient coil.

Previous calculations of such a system have relied on consideration of the electrical field induced by the changing magnetic field with no consideration of the electrical field resulting from the applied driving voltage, which is sometimes on the order of kV applied at one location in each coil. Here we present an attempt to use the finite-difference time-domain (FDTD) method to examine the importance of modeling the voltage distribution in gradient coils.

METHODS: Whole-body X and Y gradient coils were modeled (2) (70cm diameter coil, XY axes oblique operation, 40cm imaging region) for use with the FDTD method, with a grid resolution of 5mm in each dimension. A cylinder with a length of 167cm and a radius of 22.75cm and having an electrical conductivity of 0.2 S/m was modeled in the gradient set.

The X and Y gradient sets were driven with two methods: first with 64 current sources distributed throughout each coil driven in series, and then with only a single voltage source in each coil, placed towards the superior end of the coil. All FDTD calculations were performed with the aid of commercially available software ("xfdtd"; www.remcom.com).

To reduce calculation time from a matter of years to a matter of days, the calculation was performed at 500kHz and results were scaled to be indicative of results at 1kHz with a maximum slew rate of 200T/m/s. This scaling method is believed to be valid as long as wavelengths are much greater than problem dimensions and has been used at frequencies up to 10MHz to model 60Hz fields in the human body (3).

RESULTS: Figure 1 shows the model geometry. Figure 2 shows the H_z distribution on a coronal plane through the middle of the coil at a point in time nearly $\pi/4$ through a sinusoidal 1kHz pulse. This magnetic field pattern is practically identical in both driving configurations. Figure 3 shows the E field magnitudes on the same plane in both driving configurations. The field patterns are significantly different, with the electrical fields being larger toward the end where the voltage sources are placed in the case where each coil is driven with one voltage source.

DISCUSSION: As in previous studies (4-6), the electrical field magnitude within the sample is much less than that at its surface (Fig. 3) due to the induced charge distribution at the surface of the weakly conductive sample. This indicates that nerves at the periphery of the subject will be much more easily stimulated than nerves deep within the subject.

The difference in electric fields (Fig. 3) despite the similarity in magnetic fields for different coil driving configurations illustrates that while magnetic fields of gradient coils can be modeled accurately without considering the applied voltage distribution, electrical fields can not. It can be seen that both the magnitude and distribution of the electrical field is significantly different when the coils are each driven with a single voltage source than when they are driven with multiple current sources in series. This result suggests that the common practice of neglecting the effects of driving voltage in the analysis of gradient coil PNS studies can lead to inaccurate results.

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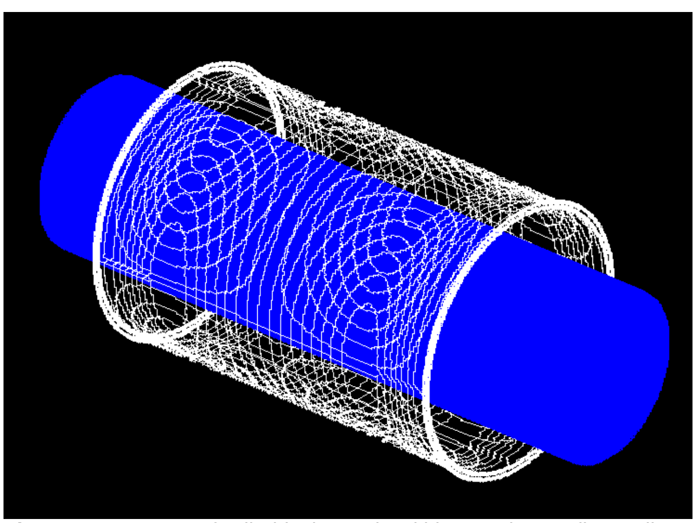

Figure 1: Geometry of cylindrical sample within X and Y gradient coils.

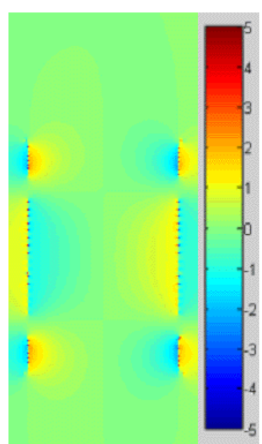

Figure 2: H_z (A/m) distribution – very similar for both driving configurations.

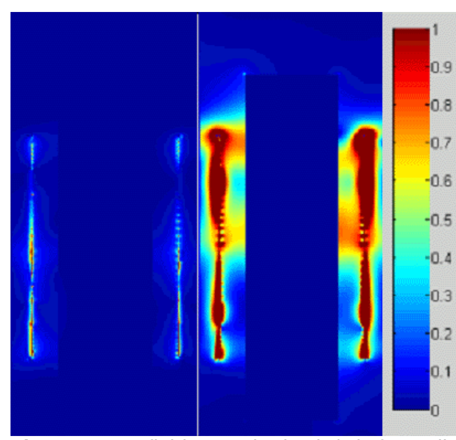

Figure 3: E field magnitude (V/m) for coils driven with (left) multiple current sources distributed throughout each coil and (right) a single voltage source placed toward the superior end (toward top of page) of each coil. Voltage source placement corresponds with location of high electrical fields in this second case.