Scalar Potential and Conservative Electric Field in a Gradient Coil

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INTRODUCTION: With growing realization of the significance of peripheral nerve stimulation as a limiting factor in the development and application of MRI, more attention has been devoted to the estimation of electric fields induced by time-varying magnetic fields generated by gradient coils. It is clear that charge distribution and scalar potential in the sample have strong effects on the final electrical field distribution (1). We have recently reported that the scalar potential distribution on the gradient coil can also have significant effects (2).

To create rapid current changes in gradient coils, a very strong electromotive force is required to overcome the inductance of the gradient winding. In order to create the voltage drop and drive the current, the scalar potential must be a function of position along the winding, and an electric field throughout space results.

Here we present a numerical method to calculate the scalar potential and resulting conservative electric field in a gradient coil. We compare these fields to those induced by the time-varying magnetic field (or vector potential) of the same coil, as well as look at the effects of the gradient shield windings, order of winding the quadrants, and the presence of a passive RF shield on the conservative electric field.

METHODS: A simple Gx gradient coil with shielding windings designed with constrained length/minimum inductance methods (3) has been studied. The coil has a diameter of 0.64m and a length of 1.04m while the shielding has a diameter of 0.87m, and a length of 2.15m. The wire for the coil has a total length of 350.5m of wire wound into four quadrants with 39 loops each. The wire is divided into 18,892 segments including 5840 segments in the gradient shielding. Figure 1 gives a side view of gradient coil quadrants, which are identified as A, B, C, and D. The total inductance of each segment was determined after using Neumann's formula to calculate the mutual inductance between it and all other segments. Ignoring the resistivity of the wire, the scalar potential was calculated as to produce the voltage drops necessary to drive the desired current in the presence of this inductance pattern. The resulting scalar potential distribution on the wire was then held constant as the scalar potential throughout the coil was calculated on a 195x195x451 grid with a 5mm resolution. The scalar potential at each location on the grid was calculated with an iterative relaxation method, using the simple average of the scalar potentials of the six nearest neighbors. Typically, the scalar potential distribution converged after 200,000 steps. The conservative electric field is the grad of the scalar potential. The effects of gradient coil shielding, order of gradient quadrant winding, and RF shielding have been studied here. The effects of gradient shield windings were studied by comparing three cases: 1) a complete model of all the windings, 2) a model ignoring the scalar potential on the gradient coil shield winding but considering the effect of the windings on inductance in the coil, and 3) a model ignoring the shield winding altogether. Four different RF shields have been modeled including a long continuous cylinder, a short continuous cylinder, a long cylinder with 8 complete longitudinal slots, and a short cylinder with 8 such slots. All of the RF shields have a diameter of 0.5m. Both scalar potential and electric fields are proportional to the ratio of current variation. All calculations are for a slew rate of 168 T/m/s. This is the slew rate resulting from a current change of 1MA/s in the complete coil.

RESULTS: Figure 2 illustrates that the electric field due to the scalar potential in the wires (2a-e) can be much larger than that due to the vector potential (2f). Comparing (b) with (a), the gradient shielding affects the electric field only far from the imaging region. This is because that the scalar potential on the coil windings has the dominant effect within the coil volume, but for this particular design, the shield windings extend well beyond the length of the primary winding layer. Figure 2 (c) and (d) have quadrant order of ABDC and ADCB, respectively while Fig.s 2 (a), (b), and (e) have the winding order of ABCD. The winding order has no effect on magnetic field or vector potential but the scalar potential distribution has been re-organized because the latter highly depends on the winding order. Fig. 2(e) shows the conservative electric field in the presence of a short, continuous, cylindrical passive RF shield. This acts as a Faraday cage to shield out the effects of the conservative electric field. Addition of slots to the RF shield resulted in a field pattern nearly indistinguishable from that in Fig. 2(e), and use of a much longer RF shield resulted in reduced conservative electric fields throughout the gradient coil volume.

DISCUSSION: The contribution of the scalar potential to the electrical field can be surprisingly strong compared to that from the vector potential. At the center of the coil, the field in Fig. 2(a) is 455 times stronger than that in Fig. 2(f). The RF shield can screen most of the scalar potential effects, so in body gradient coils, which usually have a RF body coil and shield within them, effects of the scalar potential may be dramatically reduced. However, at the center of the coil, the conservative field with the shield (Fig. 2(e)) is still 2.7 times stronger than that from the vector potential (Fig. 2(f)). The conservative electric fields may be asymmetric, though the magnetic field (Fig. 3) and vector potential distributions are symmetric. The importance of the conservative electric fields may help to explain the lack of correlation between results of peripheral nerve stimulation experiments and theories related to the vector potential (4).

REFERENCES:

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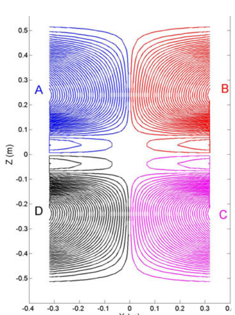

Figure 1 Diagram of the gradient coil quadrants. (shield windings not shown)

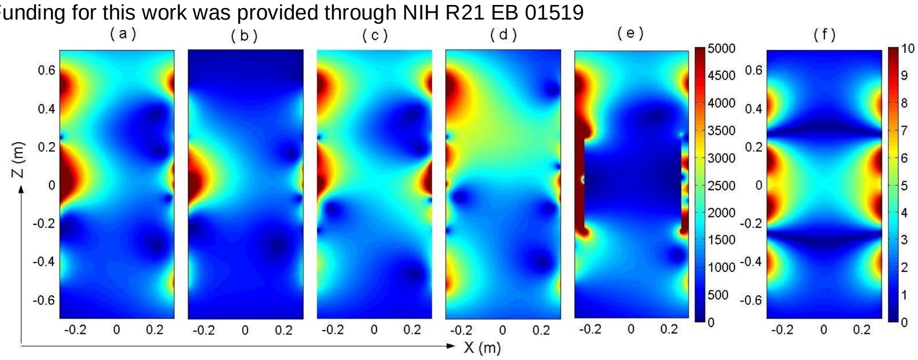

Figure 2 Conservative electric field caused by scalar potential on the coil (a-e) and induced electric field caused by vector potential (f) (V/m). (a) Complete model; (b) Gradient coil without shield; (c) and (d) Complete model with a quadrant order of ABDC and ADCB, respectively ((a), (b), and (e) have order ABCD); (e) Complete model with a short RF shield.

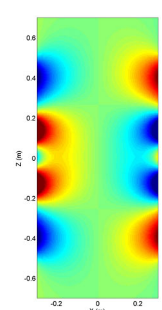

Figure 3 Z-component of magnetic field in complete gradient coil.