Scalar Potential and Conservative Electric Field Within a Loaded Gradient Coil

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INTRODUCTION: With growing appreciation of the significance of peripheral nerve stimulation (PNS) as a limiting factor in the development and application of MRI, more attention has been devoted to the estimation of electric (E-) 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 throughout the coil (1). We also consider the effect of charge distribution and scalar potential in the coil windings: 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, which results in an electric field throughout space including the loaded sample.

It has been recently reported that the scalar potential distribution on an empty gradient coil can lead to much stronger electric field than electric fields induced by time-varying magnetic fields (2). The scalar potential and conservative E-fields within a loaded gradient coil are reported here.

METHODS: A simple G_x gradient coil has been studied. The coil has a diameter of 0.4m and a length of 1.2m. The wire is divided into 3652 segments and wound into four quadrants. The loaded sample, a digital voxel-based model of a human male body, was obtained from the products of procedures performed in previous studies (3). The model has a resolution of 5mm and 836,518 voxels in total. The effects of coil quadrant order and passive RF shield (conductor cylinder) are investigated. All calculations were performed on a 181x181x501 grid with a 5mm resolution under a constant current rate of 1MA/s, resulting in a slew rate of about 50T/m/s.

Both the vector potential in the empty coil and the scalar potential on the coil wires are seen as electric field "sources" and induce currents and scalar potential distributions in the human subject. The final field distribution is a function of a combination of all these things. The human subject is assumed to have a floating potential and not be grounded: the net charge within the human subject is not allowed to change.
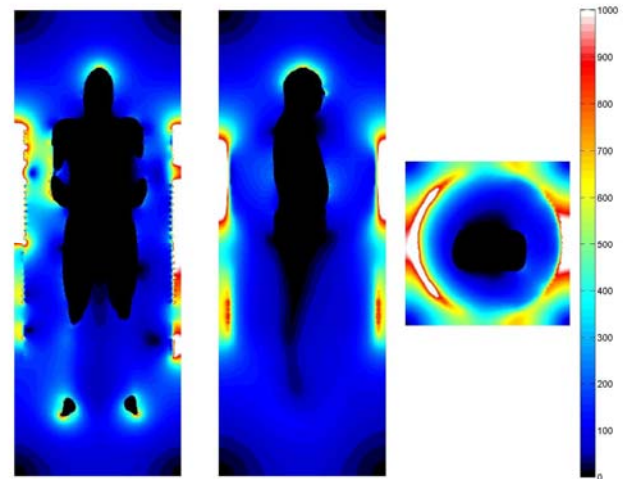

Fig. 1 Coronal, sagittal, and axial views (from left to right) of conservative electric field (V/m) caused by scalar potential on the coil with a current rate of 1MA/s.

RESULTS AND DISCUSSION: Results show that the electric field in the sample due to time-varying magnetic fields is less than 5V/m under a current rate of 1MA/s. The contribution of the scalar potential to the electrical field, however, can be surprisingly strong. Fig. 1 illustrates that the electric field due to the scalar potential can be as large as 1000V/m. There are very strong E-fields around the coil, which is reasonable. Some high E-fields occur on the surface of the sample, in particular on the bulges, such as the head and toe.

Changing the connecting order of the coil quadrants affects neither vector potential nor the E-field due to time-varying magnetic field, but significantly affects the scalar potential and the conservative E-field. The high E-field around the right arm will be relocated upon quadrant reordering. The vector potential and the E-field due to time-varying magnetic field are generally symmetric while the scalar potential and the conservative E-field are not.

Simulations confirm that a passive RF shield can act as a Faraday cage to shield out the effects of the conservative electric field. Inner windings would be expected to serve the same purpose for outer windings. This and other arguments (including the lack of penetration of conservative E-fields into the body) seem to indicate that the conservative E-fields may not be a major factor in PNS. In other studies, however, conservative E-fields at power frequencies (60Hz) and of magnitudes similar to those calculated here can be perceived, and even be intolerable (4). Also, calculations (by many different authors) of the E fields induced in multi-tissue human models by the time-varying magnetic field alone indicate E-field maxima deep within the body (5) where PNS is not known occur, whereas in our results the maximum fields are always at the surface of the body. Even if conservative E-fields are not a major factor in PNS for MRI, they may interfere with electronic devices, and awareness of their existence is worthwhile.

CONCLUSION: We present a method to calculate the total electrical (E-) field within and surrounding a human body in a gradient coil during switching. It is found that at the surface of the body the E-fields originating with the scalar electrical potential in the coil windings can be much stronger than the E-field induced by the changing magnetic fields (the portion considered in most of previous works). Due to the large contribution of the conservative fields, the effects of the order of gradient coil winding and RF shielding on the electrical field are found to be significant.

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4) Clairmont *et al*., IEEE Trans on Power Delivery 1989;4:1338   5) Liu et al., IEEE Trans Biomed Eng 2003;50:804