Effects of Varying Methods of Electric Field Calculation on Analysis of MRI Gradient Coil Magnetostimulation Studies

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Stimulation of peripheral nerves is recognized as a significant limit to useable gradient system performance. There are different ways to compute the magnetic and electric fields that cause stimulation. In this study we compare several common methods and the effect they have on the calculation of nerve electric field rheobase for any representative study of human thresholds in a whole-body gradient coil. It is found that different calculation methods result in rheobase values that vary by a factor of more than two. These differences have serious effects on the ability to model expected magnetostimulation for future gradient coil designs.

Introduction

It is of paramount importance to develop modeling tools that will enable the accurate prediction of magnetostimulation thresholds at the gradient coil design stage. Predicting stimulation thresholds requires two things: the ability to accurately calculate the electric fields causing stimulation, and an understanding of the tissue sensitivity to electric field. In order to develop this later understanding, accurate field calculations must first be used in the *analysis* of magnetostimulation experiments. Only when tissue sensitivity is quantitatively understood can the situation be reversed and modeling be used to accurately *predict* stimulation. The absolute sensitivity of a nerve is parameterized by the rheobase (E_r), which is the minimum electric field that can cause stimulation of the given nerve[1]. The E_r can be estimated from an experimental gradient coil threshold curve[2] through one of the following relations :

$$E_r = B_{stim} \bullet (\eta^{-1}) \bullet SR_{min} \bullet R_{eff} \qquad (1)$$

$$E_r = A_{stim} \bullet (\eta^{-1}) \bullet SR_{min} \qquad (2)$$

where B_{stim} and A_{stim} are the respective magnetic and vector potential fields (per unit current) considered responsible for the observed stimulation, SR_{min} is the slope of the linear gradient threshold curve, R_{eff} is the effective tissue radius through which B_{stim} is considered to be switching, and η is the gradient coil efficiency. Many different methods have been used to compute the B_{stim} or A_{stim} values considered responsible for causing stimulation[3], and their effect on calculated values of E_r is the subject of this study.

Method

A generic whole-body gradient coil (XY oblique operation, 40cm FOV, 35cm radius, η=0.11mT/m/A, unshielded) was modeled using standard methods[4]. Standard numerical methods were used to compute the magnetic (**B**) and vector potential fields (**A**) within the empty coil. An analytic method[5] was implemented to calculate the electric fields in the presence of a cylindrical conductor of radius 23cm. Quasi-static conditions were assumed. Finally, a finite difference time domain (FDTD) method was used to compute the electric and magnetic fields for the case of the coil loaded with a multi-tissue human body model[6] with tissue electrical parameters appropriate for 1kHz[7]. The following field values were extracted and used with equations (1) and (2) (taking SR_{min} to be 62.2mT/m/s[2], and R_{eff} to be 23cm), to tabulate the E_r values that could be reported from a single study of threshold: (a) abs(**B**) at point of stimulation, (b) max. abs(**B**) on cylinder of radius 23cm, (c) abs(**A**) at point of stimulation, (d) max. abs(**A**) on cylinder of radius 23cm, (e) electric field at point of stimulation (analytic cylinder model). The coordinate (-17.5cm, -15cm, -20cm) was used as the location of stimulation in this coil system[2].

Results and Discussion

The effect of different methods of electric field calculation are significant and can be appreciated by considering Fig. 1. Of particular importance is the difference in the location of peak electric fields. It is not clear from these modeled fields alone where within the gradient coil stimulation is most likely. It should also be noted that the peak electric fields do not always correspond to the location of the peak magnetic fields. In a previous stimulation study with a gradient coil of this type[2], stimulation was most often reported in the lateral posterior buttocks. The FDTD calculations shown in Fig. 1 suggest that the highest electric fields intersecting the body indeed occur in that region. The quantitative effect the method of field calculation has on the estimation of E_r is summarized in table 1. When the E_r is estimated from magnetic field calculations (a,b), it is higher than when estimated from direct electric field calculations (c-f) (i.e. via the magnetic vector potential) by a factor of approximately two. This is in part due to the assumption built into equation (1) that the effective magnetic field is uniform and perpendicular to the conducting loop of radius R_{eff}. This assumption always overestimates the electric field and therefore results in higher values of E_r.

Table 1: Rheobase as function of analysis method.

	(a)	(b)	(c)	(d)	(e)
Field:	0.038	0.034	2.9	5.0	5.8
E_r:	5.5	4.9	1.6	2.8	3.3

(units of (a,b): mT/A; units of (c-e): μV*s/m; units of E_r: V/m.)

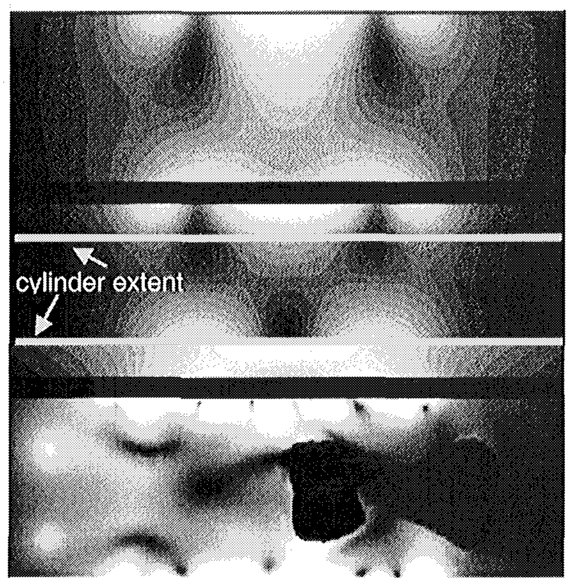

Figure 1: Comparison of the calculated electric fields on a coronal plane (y=-15cm) for the XY gradient coil loaded with: (top) nothing, (middle) a conductive cylinder of radius 23cm, and (bottom) a human body. Note the elevated electric fields in the buttocks region.

References

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