Analysis of Peripheral Nerve Stimulation Thresholds in Customized Head Gradient Coils

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Introduction: Rapidly varying magnetic gradient fields induce electric fields that can cause peripheral nerve stimulation (PNS) in human subjects. In order to be able to predict PNS thresholds expected for new gradient coils at the design state, we must have two things: (1) accurate methods of computing the total electric fields induced within tissues exposed to real gradient fields, and (2) accurate knowledge of the nerve parameters as they pertain to PNS thresholds. In order to actually obtain accurate nerve parameters though, experiments must be done to measure average PNS thresholds and these experiments must be analyzed using accurate electric field calculations. In particular, the electric field rheobase, which describes the minimum electric field required to cause stimulation of a nerve, cannot be correctly obtained from experiment without an accurate electric field calculation. In this abstract, we apply new methods that we have developed for accurate electric field calculations in real gradient coils and use them to re-analyze previous experimental data in order to improve the rheobase values reported. In addition, these correction factors can provide guidance for the interpretation of previous experiments conducted before accurate electric field calculation methods were available.

Theory: The electric field may be approximated by applying quasi-static assumptions [1] to the general equation for electric field:

$$E = -\nabla \Phi(r,t) - \frac{\partial A(r,t)}{\partial t}$$

where A is the vector potential and Φ is the scalar potential. The approximation neglects the effects of wavelength, skin depth, and tissue reactance. This permits the time dependant factor to be separated from the factor (E_o) dependant only on the fixed wire pattern, object shape, and position: $E(r,t) = (-\nabla \Phi_o(r) - A_o(r))\frac{dI}{dt} = E_o \frac{dI}{dt}$, where I is the current through the gradient coil.

Chronik and Rutt [2] related the stimulation thresholds (SR_{min}, ΔG_{min}) of subjects measured using a gradient coil to the rheobase (E_r) using the minimum gradient strength required for stimulation (ΔG_{min}), the gradient efficiency (η), and the electric field due to the vector potential only (A_o). Following the same basic procedure, but now substituting the total electric field due to both the vector and the scalar potential for the field due to the vector potential alone, the rheobase can be related to the other parameters more correctly as: $SR_{min} = \frac{E_r}{E_o} \bullet \eta$.

Using this relation to re-analyze stimulation threshold data analyzed using vector potential alone will result in rheobase values that are a factor of E_o/A_o larger than those previously reported. Low estimations of the electric field at the surface always lead to artificially low values for the calculated rheobase because rheobase is directly proportional the time average of the applied electric field at the point of stimulation.

Methods: A three dimensional, voxelated image of a human head [3], was used as a model for the calculations. By employing a quasi-static approximation and a finite difference algorithm, the total electric field at each point in the region was calculated.

The total electric field produced by the x-axis of an edge-DSV head-sized gradient coil [4] (where the imaging region was designed to be adjacent to the edge of the coil) was calculated from the known coil wire pattern, with the head object positioned within the coil so that the centre of the head was at (0, 0, 0.177) – this would be equivalent to a subject having their head as far into the coil as their shoulders would allow. The maximum electric field at the surface of the object was extracted for areas around the lips, tip of the nose, bridge of the nose, top of the head, and side of the head.

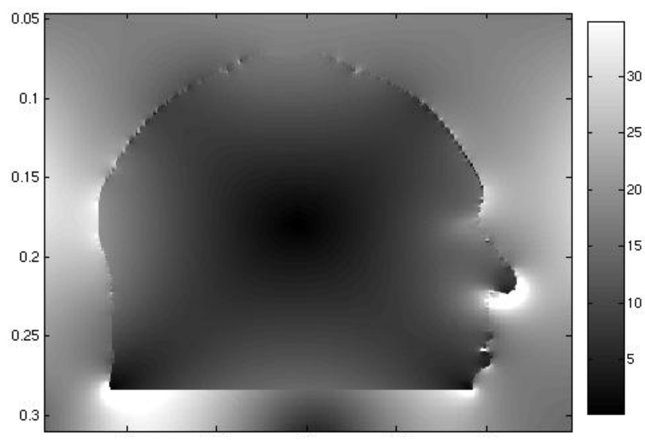
	Outside	Inside
Lips	2.37	0.83
Nose	4.13	2.24
Bridge	1.80	0.00
Crown	1.51	0.71
Side	1.68	0.68

Table 1: Ratio of Maximum Total Electric Field to Maximum Electric Field due to Vector Potential

Results and Discussion: Table 1 summarizes the maximum magnitude of the electric field exposure at the surface for all five locations on the head and face. The values of the electric field are expressed as the ratio of the total electric field to the vector potential contribution alone at that location on the surface. As would be expected, there is a significant difference between the magnitude of the electric field just outside the tissue-air boundary and just inside it. We also found that the location of the maximum electric field due to vector potential is not the same as the location of the maximum electric field due to the scalar potential.

The Figure shows the magnitude of the total electric field in V/m. The total electric fields are most different from the vector potential alone in the areas of the nose and lips. These are also the locations at which subjects experienced stimulation while within this gradient coil [5]. Considering only the vector potential, this previous study reported average rheobase values amongst the subjects tested of 1.26 V/m. The majority of subjects in this previous study reported stimulation in the nose. If the correction factor is based on the value of electric fields just outside the nose (a factor of 4.13 from Table 1), then the corrected average rheobase for the study would be 5.2 V/m. Taking the correction factor based on values inside the nose (factor of 2.24) would yield a corrected rheobase of 2.8 V/m. The value obtained using the field value just outside the nose most closely corresponds to the rheobase values of between 5 and 10 V/m reported by Reilly [6].

These results indicate the importance of combining experimental PNS threshold data with accurate electric field calculations. As we continue to develop improved computational methods, our ability to properly characterize the nerve parameters, particularly the rheobase values, that govern PNS will improve in step. These developments are critical if methods for PNS prediction are to be achieved, allowing gradient coils to be properly optimized for PNS in the future.



Magnitude of electric field in volts/meter for a head situated in an x-gradient coil halfway between the centre and the edge (0,0,0.15m)

References:

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