Discrepancy Between Peripheral Nerve Chronaxie Times as Measured Using Electric and Magnetic Stimuli

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Introduction: Rapidly varying magnetic gradient fields induce electric fields that can cause peripheral nerve stimulation (PNS) in human subjects. It is expected that nerves exposed to either electric fields or changing magnetic fields would display consistent threshold characteristics. It is this hypothesis, which has motivated the use of electric field exposure criteria from literature to guide the establishment of magnetic field exposure criteria in MRI. Specifically, gradient coil stimulation thresholds have been expressed in terms of nerve stimulation parameters obtained from electric field exposure studies. In this study, we are testing the validity of this hypothesis. The electric field required for stimulation of a peripheral nerve (E_{stim}) in a time τ is well approximated by the following strength-duration relationship (1):

$$E_{stim} = E_r \cdot (1 + \tau_c / \tau) \qquad [1]$$

E_r is called the electric field rheobase and it is the minimum electric field required for stimulation of the nerve. The chronaxie time (τ_c) is the electric field pulse duration for which the threshold is twice the rheobase value. When translated in terms of changing magnetic field parameters, the relationship takes the following form (1):

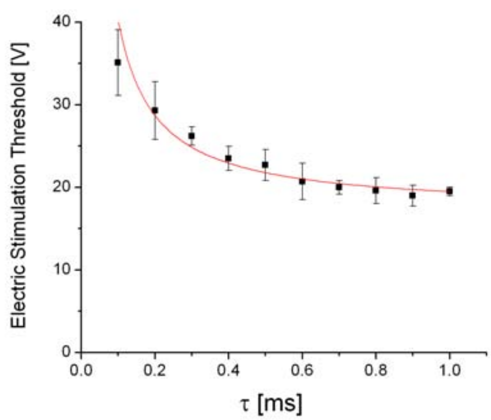
$$\Delta B_{stim} = (dB/dt)_{\min} \cdot \tau + \Delta B_{\min} \qquad [2]$$

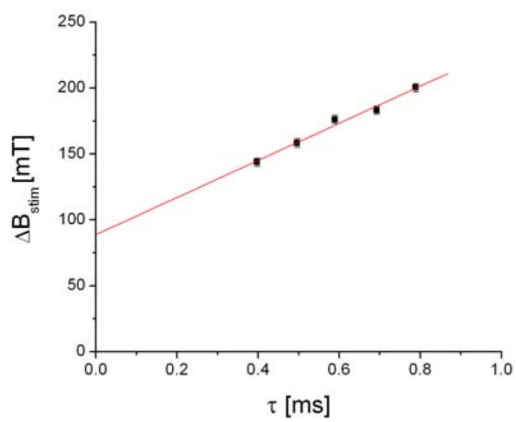
where ΔB_{stim} is the total change in magnetic field required to cause stimulation when switched over a time τ, $(dB/dt)_{min}$ is the minimum rate of change in the magnetic field required to cause stimulation, and ΔB_{min} is the minimum change in magnetic field required to cause stimulation. Estimates of τ_c can be obtained directly from the measurements of the stimulation curve parameters:

$$\tau_c = \Delta B_{\min} / (dB/dt)_{\min} \qquad [3]$$

It should be noted that τ_c is estimated directly from the shape of the stimulation curve, independent of any electric or magnetic field calculations.

Methods: Twenty healthy human volunteer subjects were tested for both electric and magnetic field stimulation thresholds. A Grass S48 electric field stimulator was used with a pair of 0.5 cm diameter circular electrodes applied to the forearm. A unipolar pulse train of 100 variable duration electric field pulses separated by 1 ms, was applied each second. The amplitude resulting in stimulation was measured as a function of the pulse duration, ranging from 100 to 1000 μs. Chronaxie times for each subject were obtained by fitting Eq. [1] to the data. A figure-eight coil design was constructed for magnetic field stimulation. The coil was composed of two square winding sections of 5 cm length, producing a peak magnetic field of 0.825 mT/A. The coil was positioned such that the peak induced electric field was over the same location and direction in the forearm as used for the electrode measurements. The magnetic field pulse sequence was trapezoidal, with a flat-top duration of 1 ms and a variable switching time ranging between 100 and 1000 μs. The total change in magnetic field required to cause stimulation was recorded as a function of the switching time. The chronaxie times for each subject were obtained by first fitting Eq. [2] to the data and then applying Eq. [3].





Results and Discussion: Example stimulation curves for a single subject are shown in the above figures, for electric (left) and magnetic (right) field exposures. The chronaxie times obtained from the fit of equations [1] (left) and [2-3] (right) to the figures are 134 +/- 23 μs and 631 +/- 91 μs for the electric and magnetic field cases respectively. It should be noted that the two models fit the data very well over the range of τ values relevant to MRI gradient coil operation. The average chronaxie times over all 20 subjects for the electric and magnetic field exposure conditions were 109 +/- 11 μs and 651 +/- 53 ms (+/- std err) respectively. In this controlled experiment, the chronaxie times for nerves stimulated via electric fields are significantly shorter than those measured via magnetic field exposure ($P = 3.24 \cdot 10^{-9}$). This result suggests that it may not be correct to use nerve stimulation parameters from previous electric field studies to establish guidelines for gradient coil operation in MRI.

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References: [1] W. Irnich, F. Schmitt. MRM 33:619-623(1995).