A Distributed Dipole Model for Estimating Epileptiform Magnetic Fields in Brain Tissue

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Introduction: In recent work, we imaged interictal discharges in focal epilepsy patients using concurrent scalp electroencelphalography (EEG) and rapid gradient-echo EPI (TR 47 ms) [1]. We found fast MR signal changes concurrent with the EEG interictal spikes (IS). The MR phase change $\Delta\Phi$ is related to the B_o-aligned component of local magnetic flux density change ΔB_z by $\Delta\Phi = \gamma$ TE ΔB_z, where TE is the echo time and γ is the gyromagnetic ratio. The MR phase changes that we observed suggested 183 nT local magnetic fields inside the tissue. We found that the MR phase signal has a temporal derivative relationship with scalp EEG.

Aims: In this study, we attempt to determine whether 183 nT local magnetic fields inside tissue are compatible with electrophysiology in epilepsy. The nature and strengths of magnetic fields inside neuronal tissue are largely unknown. Most empirical measurements are of magnetic fields outside the brain from superconducting quantum interference devices (SQUID) and magnetoencephalography (MEG).

Methods: We hypothesize a disk-shaped distributed dipole source model (Fig 1) with: (1) active source area A, and (2) current dipole moment density Q (units: nA·m/mm^2). We assume the active cortical area involved in the IS to be 10 cm^2, the minimum area of synchronously active cortex observable on scalp EEG during the IS [2,3]. This is consistent with electrocorticography measurements of the spiking cortical surface in epilepsy patients [3]. The radius of the disk source is therefore 1.8 cm.

In order to estimate the equivalent current dipole moment density Q associated with the IS, we assume the current dipole moment q_{is} of a single bursting layer V pyramidal neuron to be 0.5 pA·m, based on the work of Murakami and Okada [4]. They use the 1996 Mainen model of a pyramidal neuron from the cat visual cortex [5]; this 3-d multicompartmental model is written in NEURON and is available from a public website [6]. They compute the current dipole moment of the cell by vectorially summing the dipole moments for all the compartments. For each compartment, the voltage gradient along its length L_k determines the intracellular current I_k; this gives a current dipole moment $Q_k = I_k L_k r_k$, where r_k is the unit direction vector for that compartment. With q_{is} = 0.5 pAm, assuming neuronal density in the human cortex to be 40,000 per mm^2 [7], and 100% synchronization (epileptiform event), we get current dipole moment density Q = 20 nA·m/mm^2.

We simulated the magnetic field due to this source model using MATLAB. Our approach only accounts for primary sources (i.e., the current dipole density); we assume volume current contributions to be zero for the case of a uniform medium [8]. We used Biot-Savart's law to compute the magnetic field B(r) at r due to current dipoles at positions r_0 using: $B(r) = \sum_{r_0} \frac{\mu_0}{4\pi} \frac{Q \times (r-r_0)}{|r-r_0|^3}$. For simulation purposes, the disk source was approximated by a 1 mm grid of current dipoles corresponding to the chosen density Q. The disk source was placed in the XZ plane centered at the origin (Fig. 1) with the current dipoles pointing along Y. We calculated the Z-component of the resulting magnetic field on a 0.1 mm volumetric grid.

Results: We found that the distributed dipole disk source yielded significant magnetic fields (order of tens of nT) close to the edge of the disk where the curl of current density is largest (Fig. 1) [8]. The magnetic field is weak in the interior of the source where the curl of current density is near zero. In the Z=0 plane, we found local magnetic fields on the order of Bz = 59.7 nT close to the source edge, exterior to the source. Bz decays rapidly as we move away from the source. At MEG-source-to-sensor distance of Z=8 cm above the source, we see a maximal Bz ≈ 10 pT. This is of the order (5-8 pT) of MEG measurements of IS [9].

Discussion: The simplified disk source model shows how we may potentially encounter magnetic fields on the order of 100 nT during an IS. Previous work by Petridou et al. [10] reported 4 nT fields using MR in a 4 mm x 8 mm epileptic cell culture. Our model assumes a homogeneous medium with no boundaries with different conductivities and ignores any volume current contributions that may produce significant additional magnetic fields. We will account for these in future work with a patient-specific anatomical geometry.

References: **1.** Sundaram et al. MRM 2010 **2.** Sutherling et al. Annals of Neurology 1989 **3.** Tao et al., Epilepsia 2005 **4.** Murakami, Okada, J Physiol 2006 **5.** Mainen, Sejnowski, Nature 1996 **6.** http://senselab.med.yale.edu/senselab/modeldb **7.** Pakkenberg et al., J Comparative Neurology 1997 **8.** Hamalainen et al., Rev Mod Phys, 1993 **9.** Barth et al., Science 1984 **10.** Petridou, Bandettini, PNAS 2006

Acknowledgments: We thank Dr. Yoshio Okada for discussions on dipole models. We gratefully acknowledge the receipt of an ISMRM-ASNR seed grant for this work. This work was also supported by the National Institutes of Health (NIH P41 RR019703, NIH P41 RR13218, NIH 1R21 NS076859-01), a CHB-MIT Collaborative Research Fellowship Grant, and the Department of Radiology at Children's Hospital Boston.

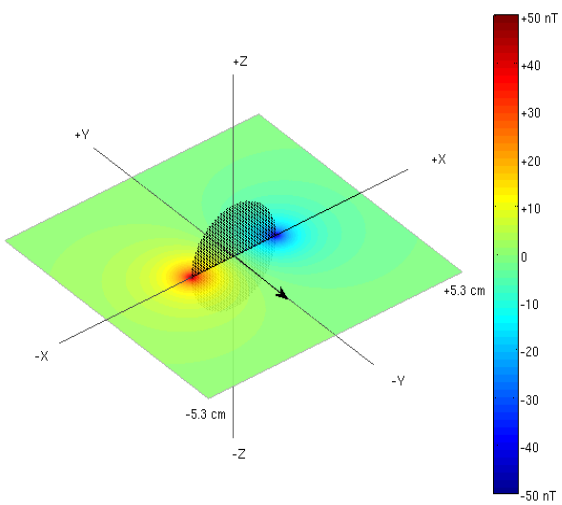

Fig 1. Z-component of the magnetic field due to 10 cm^2 disk source. Primary currents along Y. B_z rendered in the Z=0 plane. Note close to edges of the source, regions with strong B_z (tens of nT).

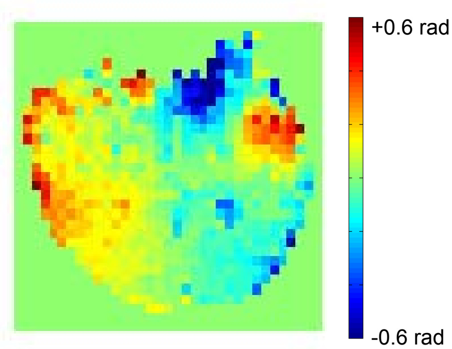

Fig 2. Dipolar pattern in MR phase suggests source radius on the order of 1.5-2 cm.