Volume Currents in Forward and Inverse MEG Simulations using Realistic Head Models

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Abstract

Many magnetoencephalography (MEG) forward and inverse simulation models employ spheres, a singular shape which does not require consideration of volume currents. With more realistic, inhomogeneous, anisotropic, non-spherical head models, volume currents cannot be ignored. We verify the accuracy of the finite element method in MEG simulations by comparing its results for a sphere containing dipoles to those obtained from the analytic solution. We then use the finite element method to show that in a realistic model, the magnetic field normal to the MEG detector due to volume currents often has a magnitude on the same order or greater than the magnitude of the primary magnetic field from the dipole. Forward and inverse MEG simulations using the realistic model demonstrate the disparity in results between calculations containing volume currents and those without volume currents. Volume currents should be included in any accurate calculation of MEG results, whether they be for a forward or inverse simulation.

Keywords: Forward MEG, Inverse MEG, Source localization, Volume currents, Finite element method

Introduction

External magnetic fields produced by neuronal activity within the brain can be measured using magnetoencephalography (MEG). A standard method for modeling the activity of these neurons assumes that they act as electric current dipoles. The electric fields produced by the dipoles can be separated into two components: the primary current, which represents the area of neural activity, and the secondary or volume current, which is the electric field that results from the primary current[7,8]. MEG detectors measure the net magnetic field due to both primary and secondary currents.

Attempts to determine the magnetic fields that result from current dipoles, the forward problem, most commonly use a model for simulations consisting of a set of concentric spheres, each with homogeneous and isotropic conductivity. Given this model, the MEG forward problem can be reduced to a closed form analytic solution. However, with more realistic, inhomogeneous, anisotropic, non-spherical head models, a closed form solution is not as easily computed and approximation methods, such as finite or boundary element methods, must be used.

Many realistic head models used for forward simulation do not incorporate the volume currents in the MEG measured magnetic field. We used the numeric finite element method[1,2,5,12,16] to investigate the effects that volume currents have on the total magnetic field measured at the MEG detectors, and their importance in accurately calculating magnetic fields detected by MEG. The accuracy of our numeric model is first confirmed by comparing the model's computed results for a sphere containing dipoles to that of the analytic solution for the sphere; this numeric method is then applied to forward simulations in a more realistic head model.

The task of determining the current dipole's location within the head from the normal component of the magnetic field located at each detector, the inverse problem or dipole source localization, relies on the techniques and modeling of the forward problem. After determining the importance of volume currents in the forward simulations, we used our forward model to perform inverse simulations on the realistic head model and to investigate the importance of volume currents for accurate dipole source localization.

Background

The dipole's primary current density, J_p, results from the electromotive force impressed by biological activity on conducting tissues[11]. Assuming J_p is within a conductive region, G, of the brain with conductivity σ and that the magnetic permeability is homogeneous, $\mu = \mu_0$, the quasistatic approximations of Maxwell's equations in determining the electric field, E, and the magnetic field, B, apply as follows:

$$E = -\nabla\phi \qquad (1)$$

$$\nabla \times B = \mu_0 J \qquad \nabla \cdot B = 0 \qquad (2)$$

$$J = J_p + \sigma E \qquad (3)$$

where ϕ is the electric potential and J is the total current density. The magnetic field is calculated by the Biot-Savart law:

$$B(r) = \mu_0/4\pi \int_G J(r') \times (r - r')/|r - r'|^3 dv \qquad (4)$$

where r' is the coordinate of the dipole and r is the point of detection. Combining equations (1), (3), and (4),

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