Models of Source Currents in the Brain

R.J. Ilmoniemi*

Summary: Electroencephalography (EEG) and magnetoencephalography (MEG) provide signals that are weighted integrals of source currents in the brain. In addition to technical aspects, the two methods differ in their sensitivities to various cerebral sources. Moreover, it is more difficult to determine the lead fields of EEG than of MEG. If it can be assumed that only one localized source is active at a particular time, the source location, direction, and amplitude can be found with the dipole model. However, if the assumption of a single localized source is violated, erroneous results are obtained. If a few sources are responsible for the measured fields, multiple-dipole models can be used. In the general case one must start from the fundamentals of estimation theory. The use of a priori information, together with experimental data, will provide the best possible solution to the inverse problem. In the case of minimal prior information, the so-called minimum-norm solution is obtained. With the help of supplementary information, the resolution can be further improved.

Key words: MEG; EEG; Inverse problem; Estimation theory; Dipole model; Minimum-norm estimate.

Introduction

A major goal in EEG and MEG studies is to determine both the locations of brain activity and the amplitudes of the sources as function of time. This is impossible in the general case, since the solution of the inverse problem of finding currents on the basis of the measured electromagnetic field is non-unique, even if the electric and magnetic fields are both obtained without error everywhere outside the head (Helmholtz 1853). In practice, the non-uniqueness is aggravated by the small number of EEG or MEG channels and by noise. As a consequence, the equations describing the inverse problem are severely underdetermined – it is said that the inverse problem is ill-posed.

In spite of the seemingly hopeless non-uniqueness of the problem, useful information can be extracted from the signals. In estimation theory approach, experimental data and a priori information are used together to determine the posterior probability density for the source distributions. From this probability density, which may even be called the solution of the inverse problem (Tarantola 1987), one can compute, e.g., the maximum likelihood estimate or an estimate that minimizes either the expected squared error or some other cost expectation. In another approach, the source-current distribution is described by a model with a small number of parameters, which are estimated on the basis of experimental data, e.g., by determining the solution that will result in the smallest discrepancy between measured signals and those computed from the model.

Source models may be used profitably when they are based on sound a priori information; the model should not be too restrictive for the situation under study. For example, the single-dipole assumption is suitable when one knows in advance that only a small region of the brain gives rise to the measured fields. Then, the model can provide an accurate estimate of the location and dipole moment of the source. If, however, the assumption of localized activity is violated, there is no guarantee that the dipole fit will give meaningful results.

MEG and EEG

Figure 1 shows an experimental setup for an evoked-response measurement with EEG and MEG simultaneously. The electric field \( \mathbf{E} \) is sampled with electrodes attached on the scalp. The voltage measured between a pair of electrodes \( i \) and \( j \) is determined by \( \mathbf{E} \) through a line integral:

\[
V_{ij} = \int_i^j \mathbf{E} \cdot dl
\]

EEG measurements always give the potential difference. Hence there is no reference electrode problem.
that would need special handling. Equation 1 shows that one must always take into account both electrodes in the interpretation of voltage measurements. The magnetic field $B$ is measured with Superconducting Quantum Interference Devices (SQUIDs). Each magnetometer channel records the flux of the external magnetic field threading the sensor coil:

$$B_k = \int_{\text{coil } k} B \cdot dA$$  \hspace{1cm} (2)

Typically, contour maps are generated from the electric and magnetic data. These often reveal important features of the distribution of sources, but, nevertheless, they only describe the fields outside the head. Even if the electric field is extrapolated to the surface of the brain using a detailed model of the skull, the result is still only a description in terms of the field. It is only when the results are put into the form of source currents in the brain with a proper inverse procedure that a straightforward interpretation of the signals can be performed.

It is useful to recognize that, although a single time-varying source within the brain produces identical wave shapes in MEG and EEG, the inverse solution for MEG is in practice more accurate than for EEG. The reason for this difference is mainly the fact that MEG is far less sensitive than EEG to variations in skull and scalp thickness and conductivity.

**Cellular basis for MEG and EEG**

When channels in the membrane of a neuron open, either during a postsynaptic potential (PSP) or in the course of an action potential, a flow of ions results. Currents in an action potential reach a peak and die off in about one millisecond and the flow pattern is quadrupolar. In a PSP, the current pattern is dipolar and may last for hundreds of milliseconds. Because the electromagnetic field of a quadrupole falls off with distance more rapidly than that of a dipole, it is thought that EEG and MEG are mostly due to postsynaptic currents. Since pyramidal cells, which constitute the largest portion of neurons in the brain, are oriented perpendicular to the cortical surface, the general direction of the postsynaptic currents also tends to be similarly oriented. This fact may be utilized in modeling by constraining primary current to flow perpendicular to the cortex.

**Forward problem**

The determination of sources on the basis of measured electromagnetic fields requires a solution to the forward problem, i.e., one has to be able to compute the electromagnetic field from given source currents in the brain. The basis for this task is the theory of electromagnetism, as formulated by Maxwell's equations. These equations describe how the electric field $E$ is produced by charges and the magnetic field $B$ by currents: $E$ points away from a positive charge in all directions, while $B$ circulates around an element of current. Since charges move only by current flow, current can be considered the cause of changes in the charge density. The driving force is the primary current $J^P$, which is defined by

$$J^P(r) = J^I(r) - J^V(r)$$  \hspace{1cm} (3)

where $J^I(r)$ is the total current and $J^V(r) = \sigma(r) E(r)$ is the volume current density driven by $E$; $\sigma(r)$ is the conductivity at point $r$. $J^P$ is often referred to as the source current. It represents the activity we seek to determine on the basis of MEG and EEG data.

The similarity between magnetic and electric recordings may be best shown by writing down the dependence