Physiological Basis of EEG/MEG Signals, Forward Models and Source Reconstruction

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Content

• Neural activity
• Forward models
• Source reconstruction
Physiological sources

MEG/EEG signals derive primarily from cortical current sources.

Strong, focal subcortical activity can also give rise to MEG/EEG.
Action potentials and synapses

• After an action potential is received neurotransmitters are released

• They bind to the receptors of a postsynaptic neuron creating Post-Synaptic Potentials (PSPs)

• These are caused by ions flowing in and out of postsynaptic membrane (eg Cl)
Postsynaptic potentials

- Depending on whether the neurotransmitter is excitatory or inhibitory, **electrical current flows** from the postsynaptic cell to the environment, or the opposite.

- The membrane of the postsynaptic cell becomes depolarised (more likely to generate an action potential) or hyperpolarised (less likely to generate an action potential). Action potentials not picked up by EEG/MEG.
Primary current

- Negative ions flowing out of cell and positive ions into it, make cell positive voltage.

- PSP effects last tens to hundreds of milliseconds.

- Postsynaptic potentials of neighboring cells can be similar (ensemble encoding).
• Pyramidal neurons of the cortex are spatially aligned and perpendicular to the cortical surface

• Spatial and temporal alignment of membrane potential creates dipoles

• Action potential are not sufficiently correlated over space and time to contribute to dipoles
Dipoles

- Primary current, $J_p = \text{dipole}$
- Secondary current, $J_v = \text{volume current (Ohmic return current caused by dipole)}$
- MEG is sensitive to primary and volume currents
- EEG is sensitive to volume currents
Right hand rule

Magnetic field, $\mathbf{B}$, induced by primary current vector
Also, field induced by volume currents
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• **Forward models**
• Source reconstruction
Volume conduction

- When a dipole is in a conductive medium, electrical current spreads through this medium (the ‘volume’ or ‘secondary’ currents). They reach the scalp to induce the voltage differences that EEG is sensitive to.

- Brain, skull and scalp have different conductivities

- The skull has a higher electrical resistance than the brain => the electrical signal spreads laterally when reaching the skull

Volume currents for a thalamic dipole source computed using a finite element volume conductor model (see later).
Spherical head model

• Approximate the shape and electromagnetic properties of the head using a three concentric sphere model

• For brain, skull, and scalp

• Assume homogeneous conductivity in each sphere

• The potential on the scalp (and each surface) can be computed analytically by solving the quasi-static (freq<1kHz) approximation of Maxwell’s equations.
Forward solution for EEG

Potential at r due to primary current

\[ V_0(r) = \frac{1}{4\pi\sigma_0} \int J_p(r'). \frac{r - r'}{\|r - r'\|^3} \, dr' \]

Solve following equation for potentials on all surfaces, V(r)

\[ (\sigma_i + \sigma_j) V(r) = 2\sigma_0 V_0(r) - \frac{1}{2\pi} \sum_{ij} (\sigma_i - \sigma_j) \int_{S_{ij}} V(r') \frac{r - r'}{\|r - r'\|^3} \, dS_{ij}' \]

The latter sums are surface integrals of over brain-skull, skull-scalp and scalp-air boundaries
Forward solution for MEG

Magnetic field at (vector) position \( r \) due to all primary (vector) currents

\[
B_0(r) = \frac{\mu_0}{4\pi} \int J_p(r') \times \frac{r-r'}{\|r-r'\|^3} \, dr'
\]

Magnetic field at position \( r \) due to volume currents

\[
B_v(r) = \frac{\mu_0}{4\pi} \sum_{ij} \left( \sigma_i - \sigma_j \right) \int_{S_{ij}} V(r') \frac{r-r'}{\|r-r'\|^3} \times dS_{ij}
\]

The latter sums are surface integrals of current over brain-skull, skull-scalp and scalp-air boundaries, which require voltage distribution over each surface (ie. EEG forward solution). The total magnetic field is given by

\[
B(r) = B_0(r) + B_v(r)
\]
boundary element model

Boundaries between brain, skull, scalp modelled using MRI data

Assumes homogeneous conductivity in each partition
Finite element head model

Five compartments (scalp, skull, CSF, brain grey and white matter)
Many thousand elements in each with different conductivity.

Diffusion Tensor Imaging data used for estimation of gray/white matter conductivity.

Also use of Electrical Impedance Tomography (EIT)

Sagittal cut through Finite Element volume conductor model of the human head

Spherical head models are a better approximation for MEG than EEG because MEG is also sensitive to primary currents
Tangential and radial dipoles

- Tangential dipole is oriented parallel to the cortical surface
- Radial dipole is oriented towards or away from it
- MEG is not sensitive to radial dipoles
- Lower amplitude closer to centre of head (bigger reduction for MEG)
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Equivalent Current Dipole (ECD) Source Reconstruction

Assume a small number of dipoles, typically less than ten, perhaps bilateral.

For each estimate 6 parameters, $a$, $(x,y,z$ location, 2 direction, 1 strength)

$\#\text{ data points}=\#\text{ sensors x # time points}$

Small number of parameters compared to amount of data (good)

Optimisation problem is highly nonlinear (bad)

MEG data, $y=f(a)+e$.

May need prior information to seed optimisation
Distributed Source Reconstruction

A. Cortical Sources

From an MRI, create a cortical mesh with eg. 3000 vertices.

Place a dipole perpendicular to cortical surface at each vertex

For each dipole, we only need to estimate the strength, $j$

The sensor dipolar patterns seen earlier form columns in a gain or ‘lead field’ matrix $K$.

MEEG/EEG data in column vector $y$. To find sources, need to solve a linear optimisation problem (good)

But we have fewer sensors than sources (bad). Constraints needed.
ECD vs Distributed

Typically ECD methods are used to estimate early components of ERPs which are usually highly localised.

ECD methods useful for subcortical reconstruction.

Distributed solutions are used for reconstructing later components of ERPs. These more cognitive components are often highly distributed throughout cortex.

There are also distributed solutions for volumes. Unlike distributed source solutions for cortical meshes we also need to estimate direction of dipoles (implemented by estimating current strength in x,y,z directions).
EEG Data: Somatosensory Stimulation

Scalp distribution
21ms post-stimulus

Distributed Source Reconstruction

ECD
EEG Data: Auditory Oddball

Scalp potential

Distributed Source Reconstruction

ECD
Bayesian Source Reconstruction

\[
p(Y | J, \mathcal{M})
\]

likelihood

\[
p(J | Y, \mathcal{M})
\]

posterior

\[
p(J | Y, \mathcal{M}) = \frac{p(Y | J, \mathcal{M})p(J | \mathcal{M})}{p(Y | \mathcal{M})}
\]

posterior

likelihood

prior

evidence
Bayesian Source Reconstruction

• Formal statistical comparison of constraints (priors) used in distributed source reconstruction methods, using model evidence

• Multiple Sparse Priors (MSP)

• Flexible models that can be intermediate between ECD and distributed solutions
Distributed source solutions with different constraints

Reconstruction of EEG data from face perception experiment

Multiple Sparse Priors
Spatial Coherence
Minimum Norm
Dynamic Causal Modelling

\[ \dot{x} = f(x, u, \theta) \]

Extrinsic connections

Intrinsic connections

Extrinsic lateral connections

Neural Mass Model
Mismatch negativity (MMN)

A  with backward connections

FB

IFG

STG

A1

STG

A1

input

Forward
Backward

B  and without

IFG

STG

A1

input

C

Garrido et al., PNAS, 2008
Summary

• **Neural activity**
  Primary dipole currents reflect postsynaptic potentials in cortical pyramidal cells. Due to ensemble coding and spatial orientation. These induce volume currents to which EEG is sensitive. MEG sensitive to primary and volume currents.

• **Forward models**
  Spherical model is computationally simpler but ignores eg. anisotropy of conductivity. More appropriate for MEG than EEG. More realistic head models from BEM and FEM methods. MEG not sensitive to radial dipoles.

• **Source reconstruction**
  ECD methods have few parameters but are nonlinear. Better for early ERP components. Distributed solutions are linear but due to large number of parameters require additional constraints. These constraints can be compared using Bayesian methods. Latest methods explicitly model neural activity.
References


http://www.scholarpedia.org/article/Volume_conduction

http://www.mrc-cbu.cam.ac.uk/research/eeg/eeg_intro.html

http://www.fil.ion.ucl.ac.uk/spm/doc/biblio/Keyword/MEG.html
