Introduction to EEG and MEG source modelling

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Outline

Motivation
Source and volume conduction models using anatomical information aligning sensors with anatomy
Source reconstruction equivalent dipole fitting distributed models scanning methods
Summary
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**Motivation**
Source and volume conduction models using anatomical information
aligning sensors with anatomy
Source reconstruction equivalent dipole fitting
distributed models
scanning methods

Summary
Motivation 1

Strong points of EEG and MEG
- Temporal resolution (~1 ms)
- Characterize individual components of ERP
- Oscillatory activity
- Disentangle dynamics of cortical networks

Weak points of EEG and MEG
- Measurement on outside of brain
- Overlap of components
- Low spatial resolution
Motivation 2

If you find a ERP/ERF component, you want to characterize it in physiological terms.
Time or frequency are the “natural” characteristics.
“Location” requires interpretation of the scalp topography.

Forward and inverse modelling helps to interpret the topography.

Forward and inverse modelling helps to disentangle overlapping source timeseries.
Superposition of source activity
Biophysical source modelling: overview

forward model

physiological source electrical current → body tissue volume conductor → observed potential or field

inverse model
Outline

Motivation

**Source and volume conduction models**
- using anatomical information
- aligning sensors with anatomy

Source reconstruction
- equivalent dipole fitting
- distributed models
- scanning methods

Summary
What produces the electric current
Equivalent current dipoles
Volume conductor

described electrical properties of tissue

describes geometrical model of the head

describes how the currents flow, not where they originate from

same volume conductor for EEG as for MEG, but also for tDCS, tACS, TMS, ...
Volume conductor

Computational methods for volume conduction problem that allow for realistic geometries

BEM  *Boundary Element Method*

FEM  *Finite Element Method*

FDM  *Finite Difference Method*
Volume conductor: Boundary Element Method

Each compartment is
  homogenous
  isotropic

Important tissues
  skin
  skull
  brain
  (CSF)

Triangulated surfaces
describe boundaries
Volume conductor: Boundary Element Method

Construction of geometry
  segmentation in different tissue types
  extract surface description
  downsample to reasonable number of triangles
Volume conductor: Boundary Element Method

Construction of geometry
  segmentation in different tissue types
  extract surface description
  downsample to reasonable number of triangles

Computation of model
  independent of source model
  only one lengthy computation
  fast during application to real data

Can also include more complex geometrical details
  ventricles
  holes in skull
Volume conductor: Finite Element Method

Tesselation of 3D volume in tetraeders or hexaheders
Volume conductor: Finite Element Method

tetraeders

hexaheders
Volume conductor: Finite Element Method

Tessellation of 3D volume in tetraeders or hexaheders

Each element can have its own conductivity

FEM is the most accurate numerical method but computationally quite expensive

Geometrical processing not as simple as BEM
Volume conductor: Finite Difference Method

Easy to compute
Not very useful
Volume conductor: Finite Difference Method

\[ \frac{V_1 - V_0}{R_1} + \frac{V_2 - V_0}{R_2} + \frac{V_3 - V_0}{R_3} + \frac{V_4 - V_0}{R_4} = 0 \]

\[ I_1 + I_2 + I_3 + I_4 = 0 \]

\[ V = I*R \]

\[ \Delta V_1/R_1 + \Delta V_2/R_2 + \Delta V_3/R_3 + \Delta V_4/R_4 = 0 \]

\[ (V_1-V_0)/R_1 + (V_2-V_0)/R_2 + (V_3-V_0)/R_3 + (V_4-V_0)/R_4 = 0 \]
Volume conductor: Finite Difference Method

Unknown potential $V_i$ at each node
Linear equation for each node
approx. $100 \times 100 \times 100 = 1,000,000$ linear equations
just as many unknown potentials

 Inject some current $+I$ and $-I$ at two of the nodes

 Solve for unknown potential
EEG volume conduction
EEG volume conduction

Potential difference between electrodes corresponds to current flowing through skin

Only tiny fraction of current passes through skull

Therefore the model should describe the skull and skin as accurately as possible
MEG volume conduction

MEG measures magnetic field over the scalp

Magnetic field itself is not distorted by skull but also from the volume currents. Only tiny fraction of current passes through skull, therefore the model can ignore the skull and
Practical differences between EEG and MEG

- Fixed sensor positions in MEG
- Flexible cap in EEG

MEG requires head size to be known in analysis using individual anatomical MRI. Position of sensors is accurately known.

EEG requires the electrode positions to be known in analysis.
Obtaining geometrical data
3D scanning instead of MRI
3D scanning - pipeline for EEG modelling

Surface scan

Individualised template
3D scanning
3D scanning – EEG source model accuracy

comparing head models

MRI+polhemus

comparing electrode locations

MRI+polhemus
3D scanning - Electrode position accuracy

Homölle & Oostenveld
in preparation
Forward modeling - summary

Using geometrical data
scalp, skull and brain tissue
locations at which MEG/EEG data is recorded

Measure geometrical data
ideally with MRI and Polhemus
optionally with 3-D scanner

Mathematical volume conduction models
Biophysical source modelling: overview

**forward model**

physiological source
electrical current

body tissue
volume conductor

observed
potential or field

**inverse model**
Outline

Motivation
Source and volume conduction models using anatomical information aligning sensors with anatomy

**Source reconstruction**
equivalent dipole fitting
distributed models
scanning methods

Summary
Source reconstruction – overview of methods

Single and multiple dipole models
  Minimize error between model and measured potential/field

Distributed source models
  Perfect fit of model to the measured potential/field
  Additional constraint on source smoothness, power or amplitude

Spatial filtering
  Scan the whole brain with a single dipole and compute the filter output at every location
  Beamforming (e.g. LCMV, SAM, DICS)
  Multiple Signal Classification (MUSIC)
Single or multiple dipole models - Parameter estimation

\[ y = f(x; a, b, c, \ldots) \]

- \( y \) = potential
- \( x \) = electrode positions
- \( f() \) = forward model
- \( a, b, c \) = source parameters
Parameter estimation: dipole parameters

source model with few parameters
  position
  orientation
  strength

compute the model data

minimize difference between actual and model data

\[ y = f(x; a, b) = a \cdot x + b \]
Non-linear parameters: grid search

One dimension, e.g. location along medial-lateral
  100 possible locations

Two dimensions, e.g. med-lat + inf-sup
  100x100 = 10,000

Three dimensions
  100x100x100 = 1,000,000 = \(10^6\)

Two dipoles, each with three dimensions
  100x100x100x100x100x100 = \(10^{12}\)
Optimization of non-linear parameters

\[ \text{error}(x, y, z) = \sum_{i=1}^{N} (Y_i(x, y, z) - V_i)^2 \Rightarrow \min_{x,y,z}(\text{error}(x, y, z)) \]
Single or multiple dipole models - Strategies

Single dipole:
   scan the whole brain, followed by iterative optimization

Two dipoles:
   scan with symmetric pair, use that as starting point for iterative optimization

More dipoles:
   sequential dipole fitting
Sequential dipole fitting: spread of cortical activity

Assume that activity starts "small"
- explain earliest ERP component with single equivalent current dipole

Assume later activity to be more widespread
- add ECDs to explain later ERP components
- estimate position of new dipoles
- re-estimate the activity of all dipoles
Distributed source model

Position of the source is not estimated as such
  Pre-defined grid (3D volume or on cortical sheet)

Strength is estimated
  In principle easy to solve, however...
  More “unknowns” (parameters) than “knowns” (measurements)
  Infinite number of solutions can explain the data perfectly
  Additional constraints required
Distributed source model
Distributed source model
Distributed source model: linear estimation

Distributed source model with many dipoles throughout the whole brain

estimate the strength of all dipoles

data and noise can be perfectly explained

\[ y = f(x; a_1, a_2, \ldots, a_N) \]
Distributed source model: regularization

\[ V = G \times q + Noise \]

\[ \min_q \{ \| V - G \times q \|^2 \} = 0 !! \]

Regularized linear estimation:

\[ \rightarrow \min_q \{ \| V - G \times q \|^2 + \lambda \times \| D \times q \|^2 \} \]

- mismatch with data
- mismatch with prior assumptions
Scanning methods

Position of the source is not estimated as such
For each (possible) source position, an estimate of the activity is computed

Construct a “spatial filter”

No explicit assumptions about source constraints (implicit: single dipole)
Assumption that sources that contribute to the data should be uncorrelated
Scanning with a beamformer filter
Beamformer: the question

What is the activity of a source $q$, at a location $r$, given the data $y$?

We estimate $q$ with a spatial filter $w$

$$q_r(t) = w(r)^T y(t)$$
Summary 1

Forward modelling
Required for the interpretation of scalp topographies
Different methods with varying accuracy

Inverse modelling
Estimate source location and timecourse from data

Assumptions on source locations
Single or multiple point-like source
Distributed source

Assumptions on source and noise timecourse
Uncorrelated (and dipolar)
Source analysis is not only about the “where” but also about untangling the “what”, the “when” and the “how”.

- **timecourse of activity**
  - $\rightarrow$ ERP

- **spectral characteristics**
  - $\rightarrow$ power spectrum

- **temporal changes in power**
  - $\rightarrow$ time-frequency response (TFR)

- **spatial distribution of activity over the head**
  - $\rightarrow$ source reconstruction
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Independent components are dipolar

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