DIPFIT: localizing dipoles

Robert Oostenveld

r.oostenveld@fcdonders.ru.nl
DIPFIT: localizing dipoles

• Motivation
• Ingredients
  – Source model
  – Volume conductor model
    • Analytical (spherical model)
    • Numerical (realistic model)
  – Comparison EEG and MEG
• Inverse modeling
  – Single and multiple dipole fitting
  – Distributed source models
DIPFIT: localizing dipoles

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Motivation

• Why fit dipoles?
• Why measure EEG?
• Why do ICA?

• Get extra information about brain processes
  – Time course of activity ----> EEG
  – Location of activity ----> fMRI
Difference between EEG and fMRI

• EEG measures post-synaptic potentials
  – related to neuronal input
• fMRI measures BOLD
  – related to energy consumption
• Different characteristics in the time domain
• Different generators
• Timecourse and location
Why EEG: extra information

- Timecourse
  - ERSP
  - ERP

- Topography
  - Scalp distribution
  - Underlying generators
Source modelling

- forward problem
  - physiological source electrical current
  - body tissue volume conductor
  - observed potential or field

- inverse problem
Overview

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Neuronal currents
Symmetry, orientation and activation

radial symmetric

random oriented

asynchronously activated

synchronously activated

parallel oriented
Motivation for current dipoles

• Neurophysiological motivation
Equivalent current dipoles
Motivation for current dipoles

- Neurophysiological motivation

- Physical/mathematical motivation
  - Any current distribution can be written as a multipole expansion
  - First term: monopole (must be zero)
  - Second term: dipole
  - Higher order terms: quadrupole, octupole
Motivation for current dipoles

• Neurophysiological motivation

• Physical/mathematical motivation
  – Any current distribution can be written as a multipole expansion
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  – Second term: dipole
  – Higher order terms: quadrupole, octupole

• Convenience
  – Dipoles can be used as building block in distributed source models
Overview

• Motivation and background

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  – Spatial filtering
Volume conductor

• electrical properties of tissue
• geometrical description

• spherical model
• realistic shaped model

→ Describes how the currents flow, not where they originate from
Volume conductor

- Advantages spherical model
  - mathematically accurate
  - reasonably accurate
  - computationally fast
  - easy to use

- Disadvantages spherical model
  - inaccurate, esp. in some regions
  - difficult alignment with anatomy
Volume conductor

- Advantages realistic model
  - accurate solution for EEG

- Disadvantages realistic model
  - more work
  - individual anatomical MRI required
  - computationally slow(er)
  - numerically instable
  - difficult in interindividual comparison

→ The pragmatic solution is to use a standard realistic headmodel for EEG
Realistic volume conductor

- Computational methods for volume conduction problem that allow realistic geometries
  - Boundary Element Method (BEM)
  - Finite Element Method (FEM)

- Geometrical description
  - triangles
  - tetraeders/voxels
Volume conductor: BEM

- **Boundary Element Method**
  - description of geometry by compartments
  - each compartment is
    - homogenous
    - isotropic
  - important tissues
    - skin
    - skull
    - brain
    - (CSF)
  - triangulated surfaces as boundaries
  - surfaces should be closed
Volume conductor: FEM

- Tessellation of 3D volume in tetraeders
- Large number of elements
- Each tetraeder can have its own conductivity

- FEM is most accurate numerical method
- Computationally expensive
- Accurate conductivities are not (well) known
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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 skull and skin as accurately as possible
- Problems with skull
  - Not visible in anatomical MRI
  - Thickness varies
  - Conductivity is not homogeneous
  - Complex geometry at base of skull
Electric current $\rightarrow$ magnetic field
MEG volume conduction

- Measures sum of fields associated with
  - Primary currents
  - Secondary currents !!!
MEG volume conduction

- Only tiny fraction of current passes through the poorly conductive skull
- Therefore skull and skin can be neglected in the MEG model
- Local conductivity around dipole important
  - geometry
  - conductivity
Differences between EEG and MEG

- scalp distribution more blurred due to volume conductor in EEG
- MEG is insensitive to radial sources
- EEG sees more, making source characterization more difficult
- EEG more noisy in itself (electrode-skin impedance)
- MEG more sensitive to environmental noise
Differences between EEG and MEG

- EEG potential differences, requires choice of reference electrode
- MEG sensors are measured independent of each other
- MEG can use simple but accurate volume conduction model
  - multiple non-concentric sphere model, i.e. each sensor has its own local sphere fitted to the head
- position of brain relative to MEG sensors
  - may vary within a long session
  - is different between sessions
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Source modelling

Forward problem

physiological source
electrical current

body tissue
volume conductor

observed
potential or field

Inverse problem
Inverse methods

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

• Distributed dipole models
  – Perfect fit of model to the measured potential/field
  – Minimize additional constraint on sources
  – LORETA (smoothness)
  – Minimum Norm (L2)
  – Minimum Current (L1)

• Spatial filtering
  – Scan whole brain with single dipole and compute the filter output at every location
  – MUSIC
  – Beamforming (e.g. LCMV, SAM, DICS)
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Single or multiple dipole models

• Manipulate source parameters to minimize error between measured and model data
  – Location of each source
  – Orientation of each source
  – Strength of each source

• Orientation and strength together correspond to the “dipole moment” and can be estimated linearly

• Position is estimated non-linearly

• Source parameter estimation
Parameter estimation

\[ Y = f(X; a, b) = a \times X + b \]

\[ \xi = a, b, c, \ldots \]
Parameter estimation: model

forward model
volume conductor
source
measured potential
model for the data
select “optimal” model

\[ \Psi_i = \Psi(r_i) = \Psi(r_i; \xi) \]

\[ V_i = V(r_i) + \text{Noise} \]

\[ V_i = \Psi(r_i; \xi) + \text{Noise} \]

\[ \min_{\xi} \left\{ \sum_{i=1}^{N} (\Psi_i(r_i; \xi) - V_i)^2 \right\} \]
Select optimal model

$$\text{error}(\xi) = \sum_{i=1}^{N} (Y_i(\xi) - V_i)^2 \Rightarrow \min_{\xi} (\text{error}(\xi))$$

$$\xi = a, b, c, ...$$
Dipole *scanning*: grid search

- define grid with allowed dipole locations
- compute optimal dipole moment for each location
- compute value of goal-function
- plot value of goal-function on grid

- number of evaluations:
  - single dipole, 1 cm grid: ~4 000
  - single dipole, ½ cm grid: ~32 000
  - two dipoles, 1 cm grid: ~16 000 000
Dipole fitting: nonlinear search

- start with an initial guess
- evaluate the local derivative of goal-function
- “walk down hill” to the most optimal solution

- number of evaluations: ~100
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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
  – Linear estimation problem
Distributed source model

- Linear estimation

\[
\vec{\Psi} = q_1 \vec{\Psi}_1 + q_2 \vec{\Psi}_2 + \ldots = \begin{bmatrix} \Psi_{1,1} & \Psi_{2,1} & \ldots \\ \Psi_{1,2} & \Psi_{2,2} & \ldots \\ \vdots & \vdots & \ddots \\ \Psi_{1,N} & \Psi_{2,N} & \ldots \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ \vdots \end{bmatrix} = L \cdot \vec{q}
\]

\[
\vec{q} = L^{-1} \cdot \vec{\Psi}
\]
Distributed source model

\[ V = L \cdot q + \text{Noise} \]

\[
\min_q \{ \| V - L \cdot q \|^2 \} = 0
\]

- Regularized linear estimation:

\[
\min_q \{ \| V - L \cdot q \|^2 + \lambda^2 \cdot \| D \cdot q \|^2 \}
\]

- Constrained linear estimation:

\[
\min_q \{ q^T \cdot W \cdot q \} \quad \text{while} \quad \| V - L \cdot q \|^2 = 0
\]
Summary 1

• Forward modelling
  – Required for the interpretation of scalp topographies
  – Interpretation of scalp topography is “source estimation”
  – Mathematical techniques are available that aid in interpreting scalp topographies -> inverse modeling
Summary 2

- Inverse modeling
  - Model assumption for volume conductor
  - Model assumption for source (i.e. dipole)
  - Additional assumptions on source
    - Single point-like source
    - Multiple point-like sources
    - Distributed source
  - Different mathematical solutions
    - Dipole fitting (linear and nonlinear)
    - Linear estimation (regularized)