Forward and Inverse EEG Source Modeling

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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
Differences between EEG and fMRI

- EEG measures post-synaptic potentials
  - related to synchronized neuronal input (phase)
- fMRI measures BOLD
  - related to energy consumption (amplitude)
- Different characteristics in the time domain
- Different generators
- Time course

R. Oostenveld, 2007
Why EEG? Extra information!

- **Timecourse**
  - ERSP
  - ERP
  - Etc.

- **Topography**
  - Scalp distribution
  - Underlying source distribution

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R. Oostenveld, 2007
scalp dynamics \neq source dynamics

Cortex

Skull

Local Synchrony

Local Synchrony

Skin

Equivalent Current Dipole

Relative Independence

Spatial Source Filtering

S. Makeig 2007
Source modeling

forward problem

physiological source electrical current

body tissue volume conductor

observed potential or field

inverse problem
Neuronal currents
Symmetry, orientation and activation

radially symmetric, i.e. randomly-oriented

asynchronously activated

synchronously activated parallel-oriented

R. Oostenveld, 2007
EEG volume conduction

R. Oostenveld, 2007
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 both skull and skin as accurately as possible.

• **Problems with skull**
  – Poorly visible in anatomical MRI (T2)
  – Thickness varies
  – Conductivity is not homogeneous
  – Complex geometry at front and base of skull
  → Individual skull conductivity variable & unknown

R. Oostenveld, 2007
Equivalent current dipole

R. Oostenveld, 2007
Equivalent current dipole

• Physical/mathematical motivation
  – Any current distribution can be written as a multipole expansion
  – First term: monopole (must be 0)
  – Second term: dipole
  – Higher order terms: quadrupole, ...

• Convenience
  – **Dipoles** can be used as building blocks in distributed source models
Volume conductor

- Electrical properties of tissue
- Geometrical description
  - spherical model
  - realistically shaped model

→ Forward model describes how the currents flow, not where they originate

R. Oostenveld, 2007
Volume conductor

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

- Disadvantages of the **spherical** model
  - inaccurate in some regions
  - difficult alignment
Volume conductor

• Advantages of a realistic head model
  – accurate solution for EEG
• Disadvantages of a realistic model
  – more work
  – computationally slower
  – numerically instable?
  – Difficult for inter-individual comparisons

→ The pragmatic (easy, cheap) solution is to use a standard (mean) realistic head model (MNI).

R. Oostenveld, 2007
• Computational methods for volume conduction problem that allow realistic geometries
  – Boundary Element Method (BEM)
  – Finite Element Method (FEM)

• Geometrical description
  – triangles
  – tetrahedra
Volume conductor: BEM

- Boundary Element Method
- Description of geometry by compartments
- Each compartment is:
  - homogeneous
  - isotropic
- Important issues:
  - skin
  - skull
  - brain
  - (CSF)
- Triangulated surfaces as boundaries
- Surfaces should be closed

R. Oostenveld, 2007
Volume conductor: FEM

• Tesselate the 3-D volume into solid tetrahedra
  - Large number of elements
  - Each tetrahedron can have its own conductivity
  - Each tetrahedron can have its own anisotropy

• FEM is most accurate numerical method
  – Computationally expensive
  – Accurate conductivities are not known

R. Oostenveld, 2007
MEG: Electric current $\leftrightarrow$ magnetic field
MEG volume conduction

• Measures sum of fields associated with
  – Primary currents
  – BUT also secondary currents at current distortions !!!
• But only a 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

R. Oostenveld, 2007
Differences between EEG and MEG

- In EEG, scalp distribution more blurred from volume conduction
- MEG is insensitive to radial sources!!
- So EEG sees more sources
- EEG is more noisy (electrode-skin impedance)
- MEG is more sensitive to environmental noise!
- MEG requires no gel
- MEG requires the head to stay fixed !
- MEG MUCH more expensive than EEG!

R. Oostenveld, 2007
Differences between EEG and MEG

• EEG sees potential differences, requires choice of reference electrode
• MEG sensors are measured independently of each other
• MEG can use simple but somewhat accurate volume conduction model
  – E.g. multiple non-concentric sphere model,
  Here, each sensor has its own local sphere fitted to the head position of brain relative to MEG sensors
  – may vary within a long session when head moves
  – is different between sessions

R. Oostenveld, 2007
Inverse methods

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

• **Distributed dipole models**
  – Perfect fit of model to the measured potential/field
  – Minimize an additional constraint on sources
    • LORETA (assume a smooth distribution)
    • Minimum Norm (L2, minimum power at the cortex)
    • Minimum Current (L1, minimum current in the cortex)

R. Oostenveld, 2007
Inverse methods

• Spatial filtering
  – **Scan whole brain** with single dipole and compute the filter output at every location (second-order, covariance)
    • MUSIC
    • *Beamforming* (e.g. LCMV, SAM, DICS)

  – **Perform ICA decomposition** (higher-order statistics)
    • On the scalp maps at individual moments
    • ICA gives the projections of the sources to the scalp surface, i.e., ‘simple’ maps!

→ ICA solves ‘the first half’ of the inverse problem (‘What?’)
Single or multiple dipole models

- Manipulate source parameters to minimize error between measured and model data
  - **Position** 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 by source parameter estimation

R. Oostenveld, 2007
DIPFIT: Dipole scanning: 1. 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
  - BUT two dipoles, 1 cm grid: ~16,000,000

R. Oostenveld, 2007
DIPFIT: Dipole fitting: 2. Nonlinear search

• Start with an initial guess from coarse fitting
  – evaluate the local derivative of goal-function
  – “walk down hill” to the most optimal solution

• Number of evaluations needed ~ 100
Median geometric error in dipole localization from using the MNI template head model warped to recorded electrode positions is 4 mm.

Additional dipole error contributors:
- Electrode co-registration error
- ICA numerical error
- Source model error

Z. Akalin Acar & S Makeig, 2011
Distributed source models

• Position of the source is not estimated as a whole
  – Pre-defined grid (3-D volume or cortical sheet)
  – Strength is estimated at each grid element
  – In principle, a linear problem, easy to solve, BUT...
    • More “unknowns” (parameters) than “knowns” (channels, measurements)
    • An infinite number of solutions can explain the data perfectly (not necessarily physiologically plausible!)

  – So, additional constraints are required ...
Summary

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

• Inverse modeling
  – Model assumption for volume conductor
  – Model assumption for source (i.e. dipole)
  – Additional assumptions on source
• Single point-like sources
• Multiple point-like sources
• Distributed sources
  – Different mathematical solutions
    • Dipole fitting (linear and nonlinear)
    • Linear estimation (regularized)
Electromagnetic source localization using realistic head models (NFT)

Solve the forward problem using realistic head models (BEM)

Mesh generation

EEG/MEG Source Image

Simple Map

Signal Processing

Inverse Problem

Sensor Localization

Electromagnetic source localization using realistic head models (NFT)

Zeynep Akalin Acar, '06
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