Influence of anisotropic conductivities in EEG source estimation in patients with epilepsy

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Introduction: Epilepsy

• Epilepsy
  – Neurological disorder
  – Seizure: abnormal synchronous brain activity
  – Prevalence: 0.5 – 1 %

• Epileptic onset zone in partial epilepsy
  – One or multiple region(s) in the brain responsible for the seizures
Introduction: Epilepsy treatment

- Epilepsy: ~75%
- Refractory epilepsy: ~25%
- Medication: 30-40%
- Surgery: 60-70%
- Nervus vagus stimulation: ~1%
- Deep brain stimulation

Goal of presurgical evaluation: determining the epileptic onset zone

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Content

• Introduction

• Source localization
  – Forward problem
  – Inverse problem

• Incorporating anisotropic conductivities

• Influence of anisotropic conductivities

• Future work
Source Localization

Forward problem

calculation of the electrodepotentials
given a source and head model

Inverse problem

quantitative estimation of the source parameters
in the head model given an EEG fragment
- Dipole model

- Cortical patch of 5 by 5 mm generates a measurable potential

- Currents have to be aligned orthogonally to the cortex: pyramidal neurons
Source Localization

Forward problem
calculation of the electrodepotentials
given a source and head model

Inverse problem
quantitative estimation of the source parameters
in the head model given an EEG fragment
Source Localization: Head model

- Spherical head models
  - Simple, but unrealistic

- Realistic head models
  - Medical imaging
  - Requires segmentation
Source Localization

Forward problem
Calculation of the electrodepotentials given a source and head model

Source model
Head model
Measurements

Inverse problem
Quantitative estimation of the source parameters in the head model given an EEG fragment
Source Localization: Forward problem

- Solving Poisson’s equation in head model due to a dipole source

\[ \nabla \cdot (\sigma(x, y, z) \cdot \nabla V(x, y, z)) = \nabla \cdot \mathbf{J}(x, y, z) \]

- Spherical head models
  - Analytical solution
    - De Munck, Zhang

- Realistic head models
  - Numerical methods
    - BEM, FEM, FDM
Source Localization

Forward problem
calculation of the electrodepotentials
given a source and head model

Source model

Head model

Measurements

Inverse problem
quantitative estimation of the source parameters
in the head model given an EEG fragment
Source Localization: Inverse problem

- Fits the dipole parameters to a measured set of potentials

- Minimization of the Relative Residual energy:

\[
RRE = \frac{\| V_{electrodes} - V_{model}(r,d) \|}{\| V_{electrodes} \|}
\]

- Nelder-mead simplex method
Content

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• Future work
Anisotropic conductivities: skull

- Layered structure

\[
\frac{\sigma_{\text{tangential}}}{\sigma_{\text{normal}}} = \frac{10}{1}
\]

[Akhtari M. et al., Brain Topography, 2002; Marin G. et al, Human Brain Mapping 1998]
Anisotropic conductivities: skull

- Derive normal vector of a skull segment using medical imaging

\[
\frac{\sigma_{\text{tangential}}}{\sigma_{\text{normal}}} = \frac{10}{1}
\]

- Cartesian tensors and transformations

\[
\Sigma = R \begin{bmatrix} \sigma_n & 0 & 0 \\ 0 & \sigma_t & 0 \\ 0 & 0 & \sigma_t \end{bmatrix} R^T
\]

\(R = \) matrix indicating the rotation from local to global reference frame
Anisotropic conductivities: white matter

- Fiber structure

\[
\frac{\sigma_{\text{longitudinal}}}{\sigma_{\text{transversal}}} = \frac{9}{1}
\]

[Nicholson, P.W., Experimental Nuerology, 1965]
Anisotropic conductivities: white matter

- Diffusion Tensor Imaging
  - The fiber direction in white matter
  - Conductivities can be derived

- Fractional Anisotropy
  » mainly in white matter
  » Also in grey matter
Anisotropic conductivities

• From the diffusion to conductivity

Isotropic conductivities from literature

\[ \sigma_{\text{isotropic \ brain}} = 0.33 \frac{S}{m} \]

\[ \sigma_{\text{isotropic \ skull}} = \sigma_{\text{isotropic \ brain}} \div 16 = 0.021 \frac{S}{m} \]

Anisotropic conductivities: forward problem

- Incorporating anisotropic conductivities in the forward problem
  - Finite Difference Method
  - For every center node:
    \[ \sum_{i=1}^{18} A_i \varphi_i - \left( \sum_{i=1}^{18} A_i \right) \varphi_0 = I \]
  - System of equations
    \[ A \varphi = I \]
  - Head model (1mm resolution):
    approx. 4500000 elements => approx. 4500000 unknowns in the system

[Saleheen et al., 1998 & Hallez et al., 2005]
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• Source localization
• Incorporating anisotropic conductivities
• Influence of anisotropic conductivities
  – Estimation errors due to different anisotropic conductivity models of white matter (method B vs method A)
  – Estimation errors due to neglecting anisotropic conductivities
  – Estimation errors due to neglecting anisotropic conductivities in the presence of noise
• Future work
Influence of anisotropic conductivities

- Estimation errors due to different anisotropic conductivity models of white matter (method B vs method A)

\[ \vec{V}_{\text{electrodes}} \]

Forward Problem
Method B with variable anisotropic conductivity values

Dipole estimation
Method A with fixed anisotropic conductivity values

Error on dipole location

\[ \| \hat{\vec{r}} - \vec{r} \| \]

Error on dipole orientation

\[ \angle (\hat{\vec{d}}, \vec{d}) \]
**Influence of anisotropic conductivities**

- Estimation errors due to different anisotropic conductivity models (method B vs method A)
  - Dipole location error

![Diagram showing dipole location error in axial, coronal, and sagittal views.](image)
Influence of anisotropic conductivities

- Estimation errors due to different anisotropic conductivity models (method B vs method A)
  - Dipole orientation error
Influence of anisotropic conductivities

- Estimation errors due to neglecting anisotropic conductivities

\[ \hat{\mathbf{r}}, \hat{\mathbf{d}} \]

Forward Problem

Head model with anisotropic conductivities

\( \mathbf{V}_{\text{electrodes}} \)

Dipole estimation

Head model with isotropic conductivities

- Skull, white matter and grey matter
- Skull only
- White and grey matter

Error on dipole location

\[ \| \hat{\mathbf{r}} - \mathbf{r} \| \]

Error on dipole orientation

\[ \angle (\hat{\mathbf{d}}, \mathbf{d}) \]
Influence of anisotropic conductivities

- Dipole location errors due to not incorporating anisotropic conductivities
  - Error is largest when skull anisotropy is neglected
  - Error is largest at the edges than in center
  - Error due to neglecting white matter anisotropy is very small
Influence of anisotropic conductivities

- Estimation errors due to neglecting anisotropic conductivities in the presence of noise

\[ \text{Error on dipole location} \quad \| \hat{r} - r \| \]

\[ \text{Error on dipole orientation} \quad \angle (\hat{d}, d) \]

- Skull, white matter and grey matter
- Skull only
- White and grey matter
Influence of anisotropic conductivities

- Estimation errors due to neglecting anisotropic conductivities in the presence of noise

\[
\text{noise level} = \frac{\text{RMS}_{\text{noise}}}{\text{RMS}_{\text{dipole}}}
\]

Dipole estimation over
- 1 time sample
- 20 time samples by first component of SVD
Influence of anisotropic conductivities

- Average dipole location error due to noise in anisotropic and isotropic head model
  - Error due to noise only is larger in anisotropic head-model than in isotropic one

![Graph showing dipole location error vs. noise level for anisotropic and isotropic head models.](image)

Dipole location error (mm) vs. noise level.

- Error in anisotropic head model is greater than in isotropic head model at all noise levels.

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Influence of anisotropic conductivities

- Anisotropic conductivity makes the problem more illposed

- Potentials are more attenuated and smeared out over the surface

- Incorporating anisotropic conductivities will provide a more accurate estimation, but the illposedness will make it more difficult
Influence of anisotropic conductivities

• Application of an averaged epileptic spike
  – left hippocampus (manually segmented)
  – Surgery outcome: seizure free
Content

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• Future work
  – Incorporation of functional imaging as a priori knowledge
  – Multi-level approaches on solving the inverse problem
  – Brain Connectivity
Future work

- Incorporate functional activation (SPECT or fMRI) boundaries as a priori knowledge

**EEG-MR coregistration**

**SPECT-MR coregistration**

**EEG source localization**

**MR image**

**SPECT**

**SPECT-MR**

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*Hallez et al., 2009*
Future work

- Multilevel techniques to efficiently solve the inverse problem in a discrete non-convex search space

Collaboration with prof. Luc Dupré and Guillaume Crevecoeur (EELAB)
Future work

- Multilevel techniques to efficiently solve the inverse problem in a discrete non-convex search space

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Brain Connectivity

- Use EEG source localization to estimate location and time series of dipoles

- Use connectivity to estimate causal relationship
Brain Connectivity

• Intracranial recordings during

The functional connectivity pattern between the brain regions through energy weighted Adaptive Directed Transfer Function:

Between LH contact points:

The information flow spreads from LH4 and LH5 symmetrically to the other contact points
References


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Future Work: Event related potentials

- Functionality of the brain
  - How does the brain work when doing certain tasks?

- Diagnosis of Dyslexia
  - Which brain regions are involved?