Electromagnetic inverse problems in biomedical engineering

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Overview

1. Introduction
2. Localization of magnetic markers in the alimentary tract
3. The influence of forward model conductivities on EEG/MEG source reconstruction
4. Optimization of magnetic sensor arrays for magnetocardiography
5. Validation of source reconstruction procedures
Introduction

Genesis of bioelectromagnetic fields and potentials

Cortical column

Pyramidal cell

EPSP

intracellular current
Genesis of bioelectromagnetic fields and potentials

(a) and (c): tangential direction

(b) and (d): radial direction
Measurement of biomagnetic fields

Argos 200
ATB (Chieti, Italy)

Vectorview
Neuromag
(Helsinki, Finland)
Comparison of typical amplitudes of the magnetic induction B

Environmental fields
- Earth magnetic field
- Urban noise
- Car @ 50 m
- El. screw driver @ 5m
- IC-Chip @ 2m
- Transistor @ 1m

Biomagnetic fields
- Brain (spontaneous)
- Brain (evoked)
- Heart
- Muscles
- Fetal heart
- Eye
Magnetometer and Gradiometer

Reference coil

Pick up coil

B + ΔB

SQUID

L

L_i
Magnetic shielding

**Goal:**
Shielding against external disturbances

**Design criteria:**
Compromise between costs and shielding

**Realization:**
Passive
Active
Source reconstruction overview

Measurements

Data

Models

Results and Interpretation
Solution of the inverse problem

Problem

Measurement data

Forward problem      Inverse problem

Sources
Overview

1. Introduction

2. Localization of magnetic markers in the alimentary tract
   1. Multipole method
   2. Simulations
   3. Phantom measurements
   4. Clinical study

3. The influence of forward model conductivities on EEG/MEG source reconstruction

4. Optimization of magnetic sensor arrays for magnetocardiography

5. Validation of source reconstruction procedures
Localization of magnetic markers in the alimentary tract

- Motivation:
  - Analysis of tract motion (peristalsis)
  - Passage / throughput times
  - Targeted disposal of drugs

- Methods:
  - Magnetically marked capsules
  - Fast and robust method for (online) localization

- Problem:
  - Interferences

- Solution:
  - Multipole approach for simultaneous localization and external noise compensation
State of the art

- Noise suppression with various methods
- Marker localization with non-linear search methods (Simplex, Levenberg-Marquardt, Gauss-Newton)
Multipole method

- Multipole expansion of the measured magnetic field with inner and outer components (multipoles)
- Comparison of coefficients of the Taylor series expansion of the magnetic dipole field with inner multipoles yields a system of equations for the determination of the dipole location and moment from the inner multipole of 1\textsuperscript{st} and 2\textsuperscript{nd} order
- Noise cancelation by elimination of outer components
- Iterative usage in time series analysis

Hilgenfeld & Haueisen, Biomagnetic Research and Technology, 2004
Inner components

Dipole
First order tensor
3 linearly independent components

Quadrupole
Second order tensor
Symmetric
5 linearly independent components
Outer components

First order tensor

- 3 linearly independent components
- Homogeneous disturbing field of 0th order

Second order tensor

- Symmetric
- 5 linearly independent components
- Gradient disturbing field of 1st order
Localization and noise separation

Inner components

location and place of the marker are reconstructed from the dipole and quadrupole at coordinate center

Separation of outer components as noise.
Multipole expansion

Multipole expansion for the field of a magnetic marker close to \((0,0,0)\):

\[
\vec{B}_m(\vec{r}) = \frac{\mu_0}{4\pi} \sum_{j=1}^{3} \left( F^{i,j}_m(\vec{r}) \right)_{i=1}^3 c_j^m + \frac{\mu_0}{4\pi} \sum_{k=1}^{3} \sum_{j=1}^{3} \left( F^{i,j,k}_m(\vec{r}) \right)_{i=1}^3 c_{j,k}^m
\]

\[
+ \frac{\mu_0}{4\pi} \sum_{l=1}^{3} \sum_{k=1}^{3} \sum_{j=1}^{3} \left( F^{i,j,k,l}_m(\vec{r}) \right)_{i=1}^3 c_{j,k,l}^m + \ldots
\]

Form functions \(F\) can be treated as Taylor series expansion:

\[
F^i_m = \frac{x_i}{r^3}, \quad F^{i,j}_m = -\frac{\partial F^j_m}{\partial x_i},
\]

\[
F^{i,j,k}_m = -\frac{\partial F^{j,k}_m}{\partial x_i}, \quad F^{i,j,k,l}_m = -\frac{\partial F^{j,k,l}_m}{\partial x_i}.
\]
Multipole expansion

Multipole expansion for the field of distant external noise sources:

\[
\vec{B}_{\text{ex}}(\vec{r}) = \frac{\mu_0}{4\pi} \sum_{j=1}^{3} (F_{\text{ex}}^{i,j}(\vec{r}))_{i=1}^{3} c_{j}^{\text{ex}} + \frac{\mu_0}{4\pi} \sum_{k=1}^{3} \sum_{j=1}^{3} (F_{\text{ex}}^{i,j,k}(\vec{r}))_{i=1}^{3} c_{j,k}^{\text{ex}} \\
+ \frac{\mu_0}{4\pi} \sum_{l=1}^{3} \sum_{k=1}^{3} \sum_{j=1}^{3} (F_{\text{ex}}^{i,j,k,l}(\vec{r}))_{i=1}^{3} c_{j,k,l}^{\text{ex}} + \ldots
\]

Form functions for external sources derived from the inner sources:

\[
F_{\text{ex}}^{i,j} = \frac{\partial (F_{\text{m}}^{j} r^3)}{\partial x_i}, \quad F_{\text{ex}}^{i,j,k} = \frac{\partial (F_{\text{m}}^{j,k} r^5)}{\partial x_i}, \quad F_{\text{ex}}^{i,j,k,l} = \frac{\partial (F_{\text{m}}^{j,k,l} r^7)}{\partial x_i}
\]
Start search location $r_s$

Shift coordinate system to $r_s$

Set up Matrix of form funktions $F$

Compute moments of inner and outer fields
\[ c = (F^T \cdot F)^{-1} \cdot F^T \cdot B_{\text{meas}} \]

Compute moments and position of marker
\[ \vec{m} = c_{q}^{m|\text{ex}} \quad \vec{r}' = \left( m^T \cdot m \right)^{-1} \cdot m^T \cdot c_{q}^{m} \]

Marker position becomes new search location
\[ r_{s \text{ new}} = r_s + \vec{r}' \]

Measurement values $B_{\text{meas}}$

Position and moment of Marker: $r_s + \vec{r}'$, $\vec{m}$

Control of step width $|\vec{r}'|$
Simulation setup

Aims:
• Localization error as a function of noise
• Localization error after one step, as function of starting distance
• Convergence distance depending on noise level

Set up:
• Dipole with 20µAm², 300mm below sensor level
• Gaussian noise
• Variation of multipole expansion order
Simulation setup
Simulations
Localization error as a function of noise

Marker strength 20µAm²
Marker pos  z = -300mm
100 repeated runs per data point
2 ... Dipole, 3 ... Dipole and Quadrupole,
4 ... Dipole, Quadrupole und Octupole
1st number: inner 2nd number: outer multipole
Simulations

Localization error depending on the starting point distance $d_s$ for one iteration

Marker strength $20\mu$Am$^2$
Marker pos $z = -300$mm

100 repeated runs per data point

2 ... Dipole, 3 ... Dipole and Quadrupole, 4 ... Dipole, Quadrupole und Octupole
1st number: inner  2nd  number: outer multipole
Simulations
Convergence distance depending on noise level

Marker strength 20µAm²
Marker pos  z = -300mm

100 repeated runs per data point

2 ... Dipole, 3 ... Dipole and Quadrupole,
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Measurement with glass phantom

Marker in fluid (sucrose) under measurement system
Measurement with glass phantom
Clinical study with magnetically marked tablets
Clinical study with magnetically marked tablets

- Determination of drug disposal in the intestine
- Test- and reference tablets
- Two sets of measurement on 12 probands
- 10-min for single measurement, 30 min inter-measurement time, total time about 12 hours
- 2 probands per day, blood control every 30 min
Localization results

- one measurement, 1S/s
- Respiratory movements
- larger movement in the colon
Marker moment for one series
Summary

- Fast online method: max. 3 iterations for each localization
- SNR better 100 is recommended
- Inner oktupole not used because of high sensitivity to noise
- Starting point within about 10 cm of true location
Overview

1. Introduction
2. Localization of magnetic markers in the alimentary tract
3. The influence of forward model conductivities on EEG/MEG source reconstruction
   1. Finite Element Modeling
   2. Animal sensitivity analysis
   3. Human sensitivity analysis
4. Optimization of magnetic sensor arrays for magnetocardiography
5. Validation of source reconstruction procedures
Introduction

• How does volume conduction influence source estimation?
• How does anisotropy influence source estimation?
SimBio and NeuroFEM

Image Registration (T1, T2, PD) → Segmentation → Mesh Generation BEM/FEM → Forward toolbox, Inverse toolbox → Visualisation
Galerwin

T1 weighted MR data:
• 1.6 mm slice thickness,
• 102 slices,
• 1 mm x 1 mm pixel size

FEM model cross section:
• resolution of 1 mm x 1 mm x 3.2 mm,
• 1,456,069 hexahedral elements (voxels)
• adaptive JCG solver

Schimpf, Haueisen et al., Parallel Computing, 1998
Conductivity and anisotropy data

Human Diffusion Tensor Imaging

Anisotropy map (FA)

Anisotropy map color coded

Diffusion tensor as ellipsoid

Fiber tracking (main direction of strong anisotropic tensors)

Böhr, Güllmar, Knab, Reichenbach, Witte, Haueisen: Brain Res, 2007
Conductivity and anisotropy data

Rabbit imaging

Flash3D T1
(isotropic resolution 0.625 mm)

TSteam - DTI

633172 cubic elements (0.6mm)
Animal sensitivity analysis
Simulations with a block of white matter

Sagittal slice with 4 tissue types:
- skin
- skull
- gray matter
- artificial white matter block

- source space with 3 layers of dipoles around the anisotropic block
- dipole orientation left/right, rostral/caudal, and inferior/superior
- anisotropic conductivity of 1:10 in caudal-rostral orientation
Animal sensitivity analysis

Differences in the forward computations

RDM

MAG
Simulations with a block of white matter

Values above the 0.8 percentile for RDM*, MAG, dipole shift, magnitude change and orientation change are visualized by red surfaces.

Güllmar, Haueisen et al.
IEEE TBME 2006
Experimental validation

Anisotropic block in a torso phantom

Experimental validation

Anisotropic block in a torso phantom

Sengül, Haueisen et al. submitted, 2008
Experimental validation

Anisotropic block in a torso phantom

Sengül, Haueisen et al. submitted, 2008
Animal sensitivity analysis
Simulations with measured conductivity tensors

Source localization error
Forward computation: anisotropic model
Inverse: isotropic model

1360 dipoles

Dipole shift in mm

Histogram of the dipole shift
Animal sensitivity analysis
Simulations with measured conductivity tensors

Magnitude change (relative to 1)

Dipole magnitude estimation error

Histogram of the dipole magnitude errors
Animal sensitivity analysis
Simulations with measured conductivity tensors

Dipole orientation estimation error

Orientation change in deg

Histogram of the dipole orientation errors
Sensitivity analysis

Forward simulations with isotropic and anisotropic human head models

Results:
Correlation: above 0.98
Magnitude: more than 50% change

Tissue anisotropy seems to have a minor influence on source localization but a major influence on dipole strength estimation.

Haueisen et al., The influence of brain tissue anisotropy on human EEG and MEG. Neuroimage 15:159-166, 2002
Sensitivity analysis

Simulations with conductivity changes of single voxels

Results:

Correlation:
Change in A: 0.98
Change B-F: >0.999

Magnitude:
Change in A: 2 - 60%
Change B-F: < 1%

Conductivity changes in the vicinity of the dipole influence source estimation.

Haueisen et al., The influence of local conductivity changes on MEG and EEG. Biomed. Tech. 45 (7-8), 211 – 214, 2000
Human sensitivity analysis

- 5 tissue types
- 3.2 million cubic elements (1mm)
- 130 electrodes
- 25,000 dipoles perpendicular to cortical surface
- Anisotropies of 1:2, 1:5, 1:10 and 1:100

Comparison of isotropic and anisotropic model output by RDM and MAG mapped to each dipole position
Human sensitivity analysis

right hemisphere

left hemisphere

Relative Difference Measure – outside view
Human sensitivity analysis

right hemisphere

left hemisphere

Relative Difference Measure – inside view
Conclusions

• Anisotropic volume conduction influences source strength and source orientation estimation more than source location estimation.

• Local conductivity properties in the vicinity of the source crucially influence source estimation.

• Model errors both on a local and a global scale are not Gaussian.