Forward and Inverse EEG Source Modeling

using

NFT – The Neuroelectromagnetic Forward Head Modeling Toolbox

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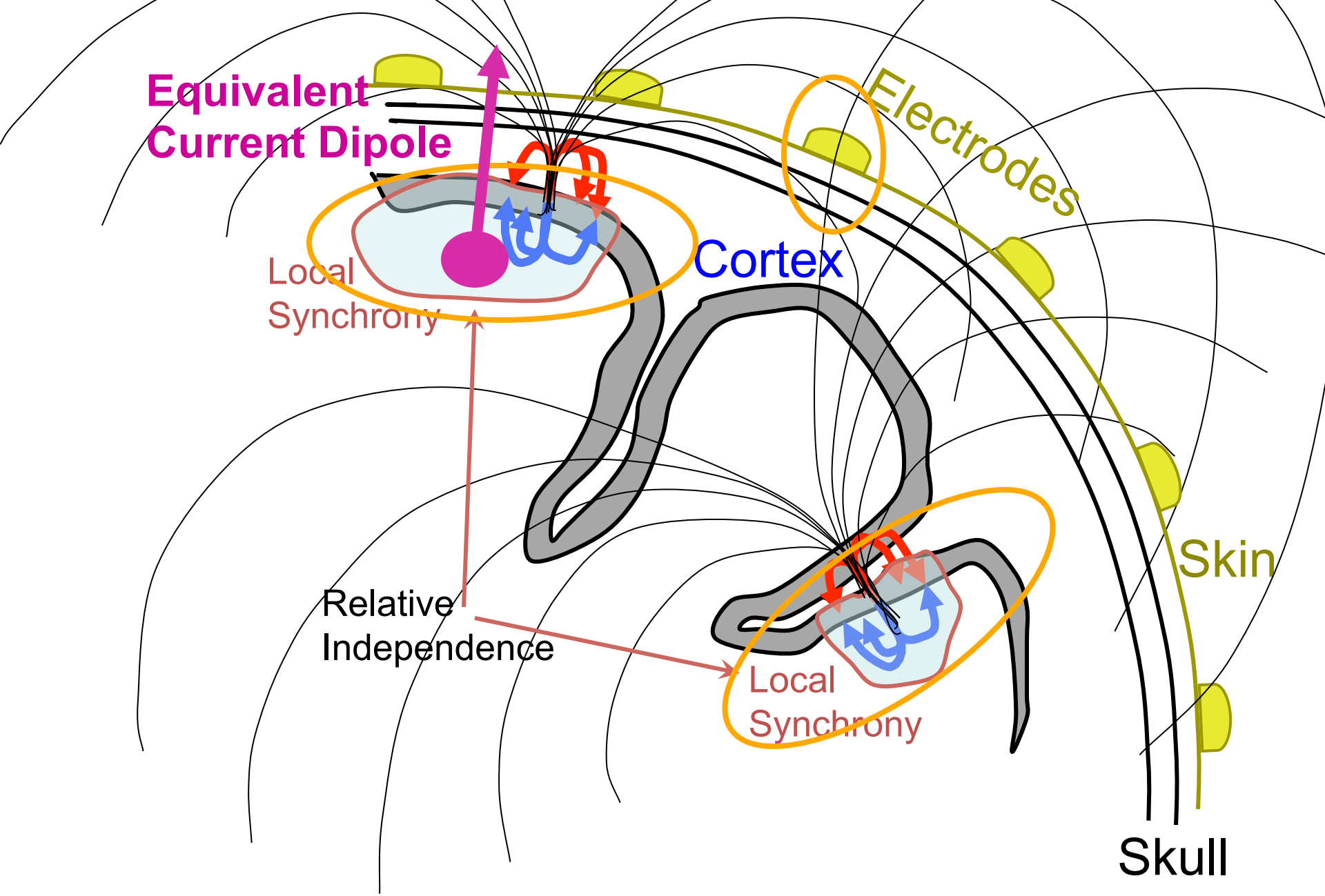
Institute for Neural Computation

UCSD, La Jolla CA

EEGLAB Workshop, University of Sheffield, Sept., 2015



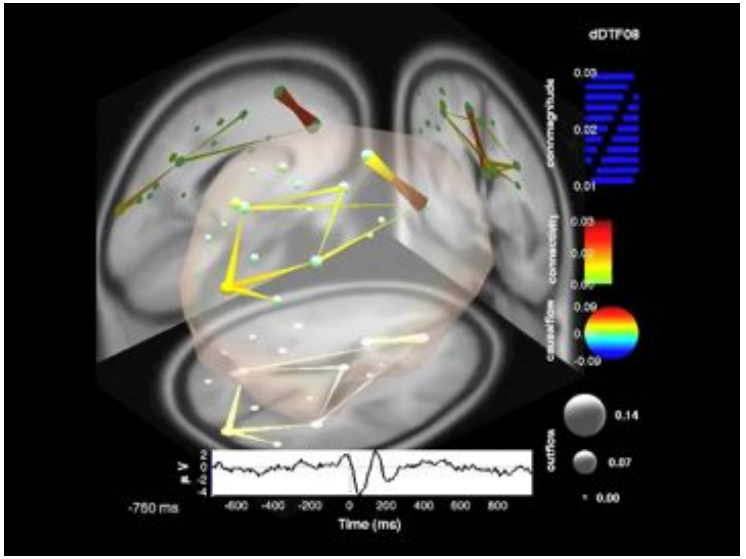
Source-Resolved EEG Brain Imaging

S. Makeig 2007

Source-Resolved EEG Brain Imaging

EEG data collection is

- Non-invasive
- Wearable
- Mobile
- Cheap

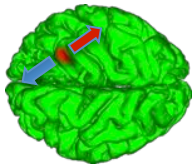


BUT + source imaging requires an electrical head model

- MR head image: ~non-invasive, confining, expensive
- Electrode position measurement: Slow, expensive

Alternatives:

- Template head image: customized (age, race, gender,…)
- Electrode photogrammetry: simple, cheap or free



Source modeling

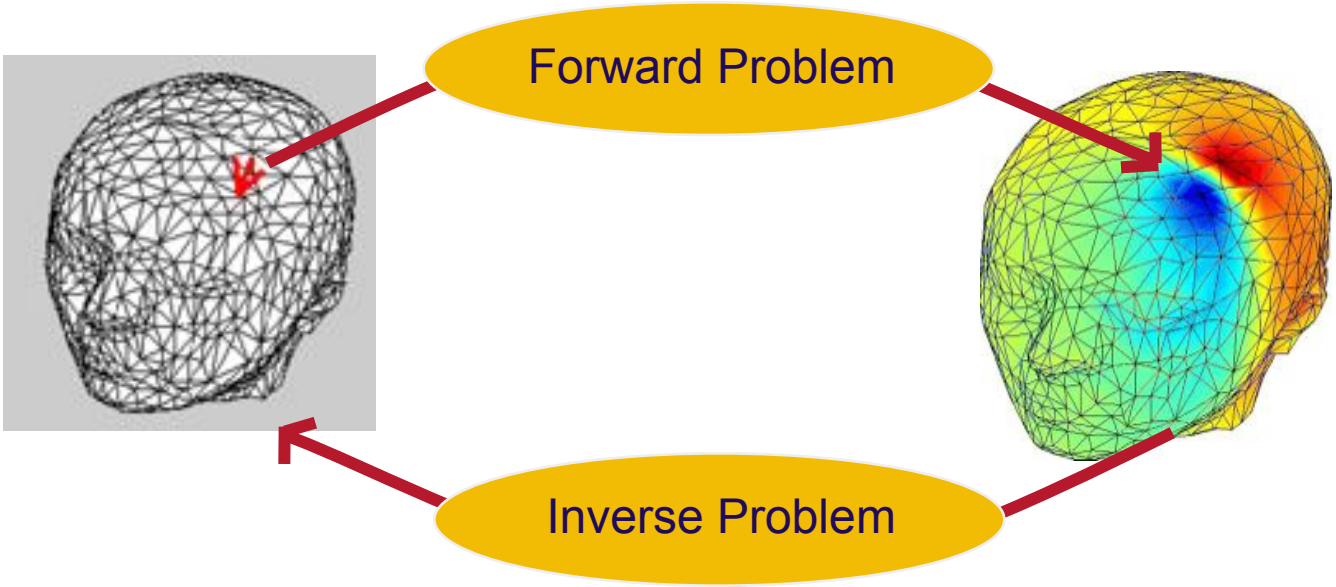
forward problem

physiological source electrical current

body tissue volume conductor

observed potential or field

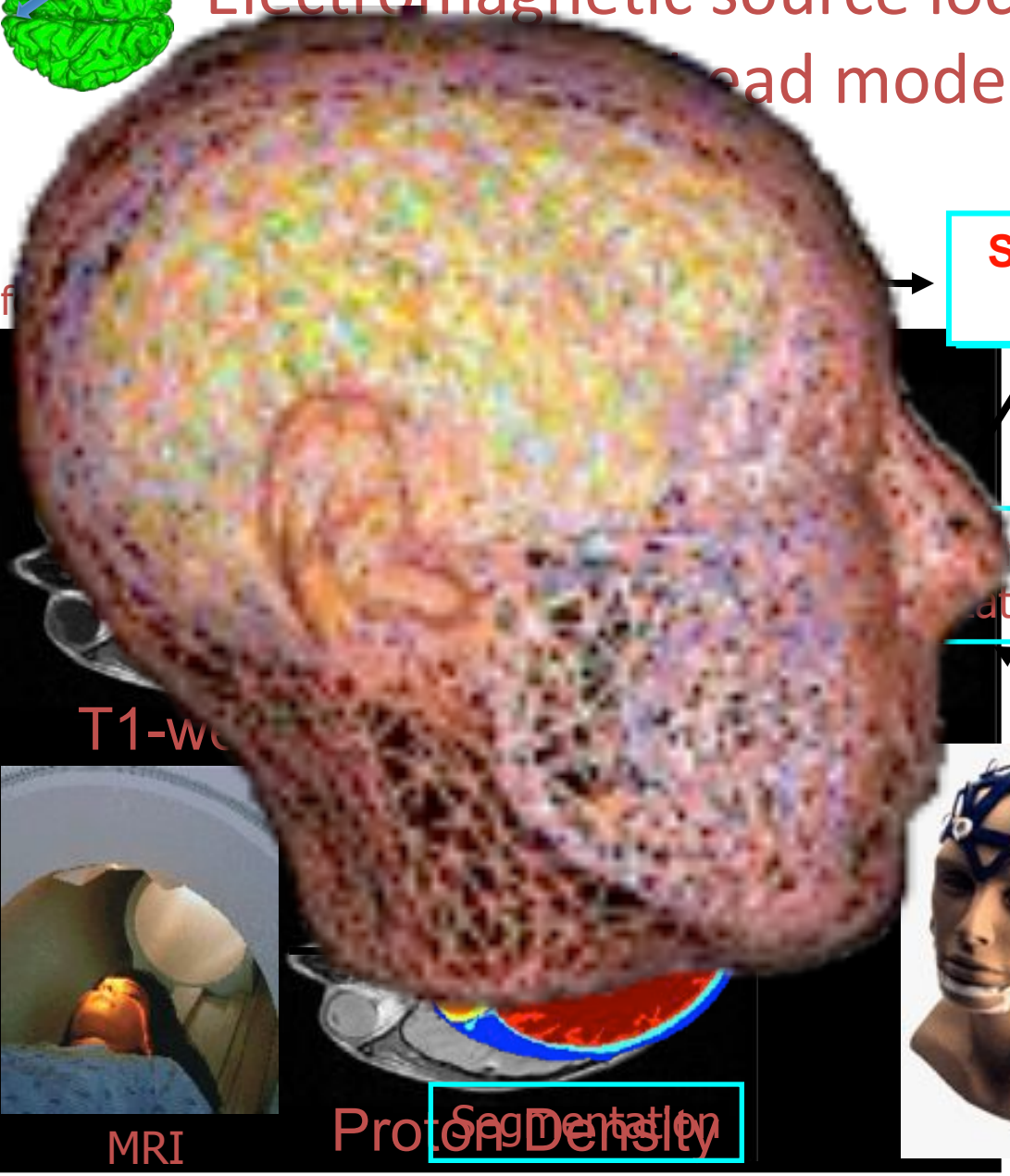
inverse problem



EEG or MEG

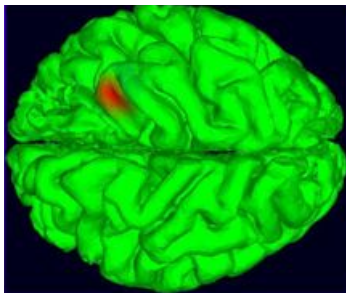
R. Oostenveld, Z. Akalin Acar & S. Makeig, 2010

Electromagnetic source localization using realistic ead models (NFT)



Simple Map

SCS

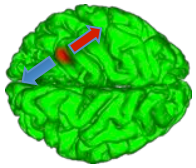


Source Image

Signal Processing

ation

EEG/MEG

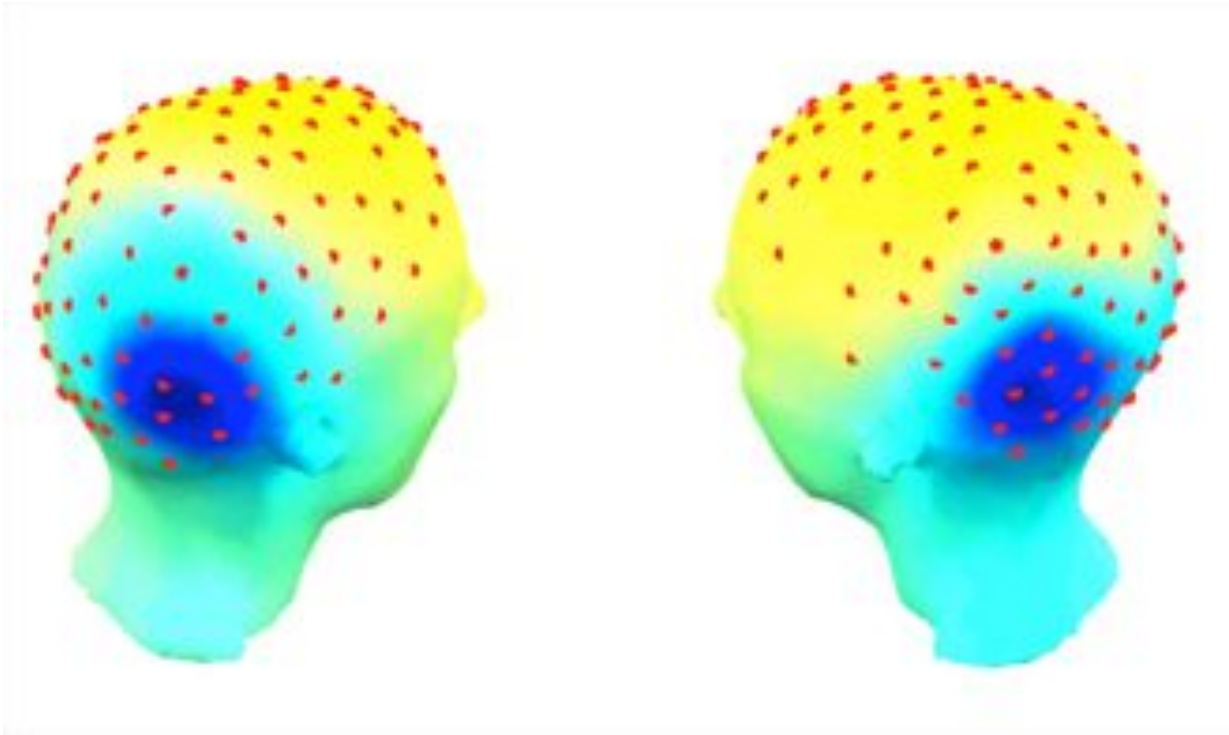


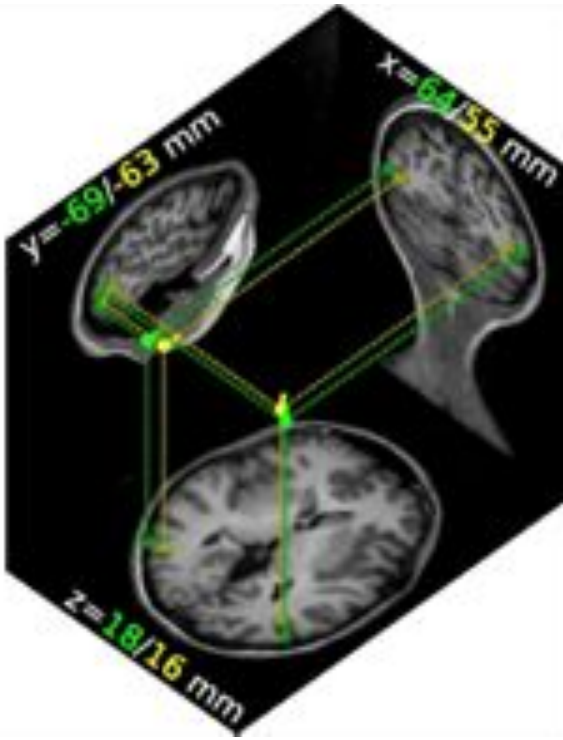
Source Localization Requirements

- Selected/processed EEG signal

  → **Simple single-source scalp map** !
- Number/positions of electrodes on the head surface
- Numerical head model
- Co-registration of EEG electrodes with head model
- Evidence/assumptions about the source space
- Choice of inverse model
- Choice of numerical method

3- and 4-layer MR-based realistic head model





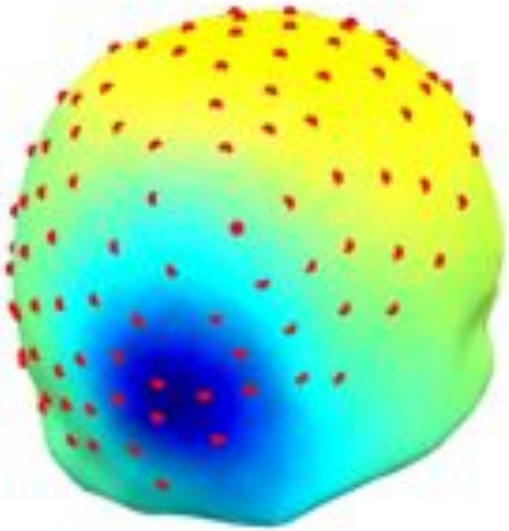
Scalp maps of 2 components

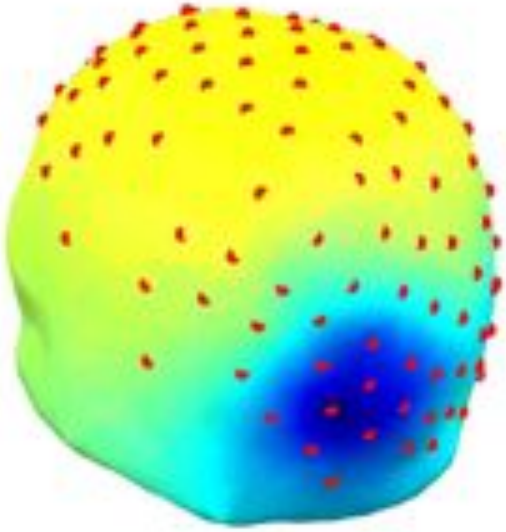
Sources of 2 components

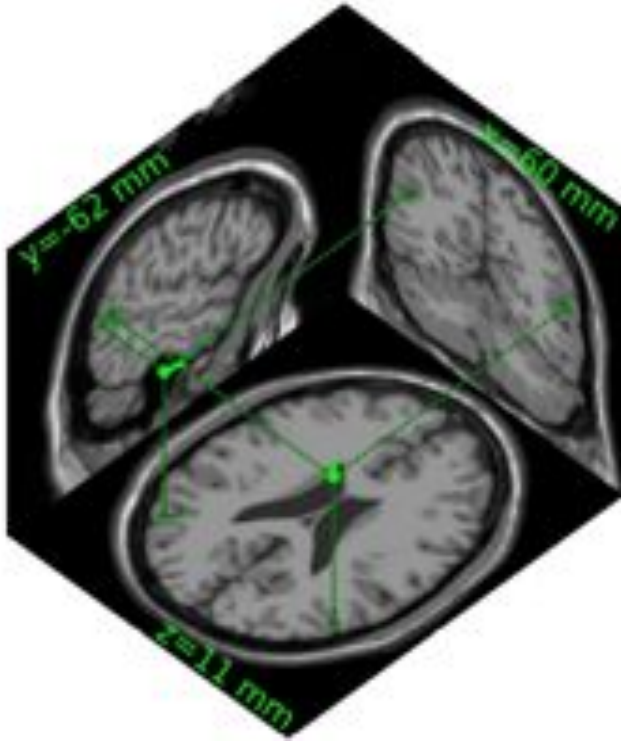
green dipoles - 4-layer

yellow dipoles - 3-layer

MNI template head model



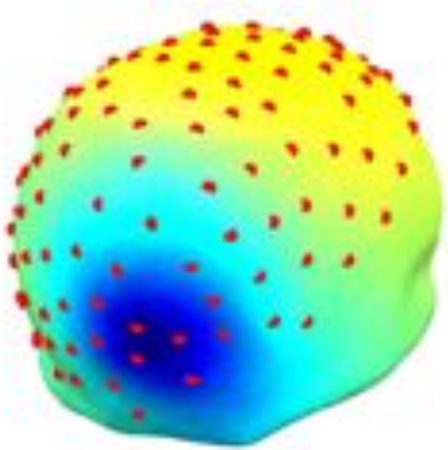


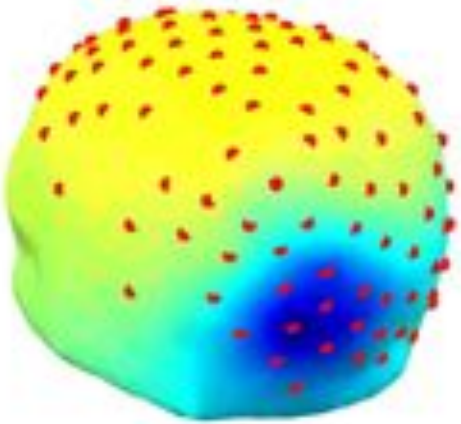


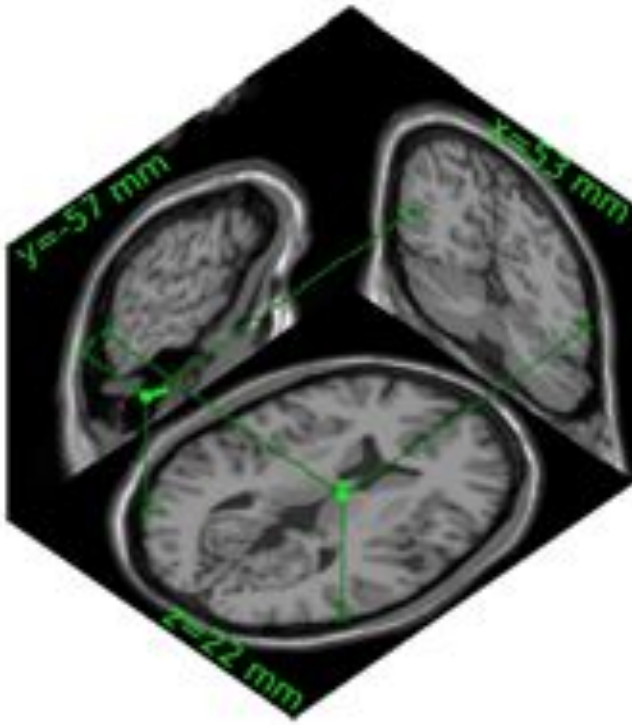
Scalp maps of 2 components

Sources of 2 components

Electrode-position warped MNI template head model



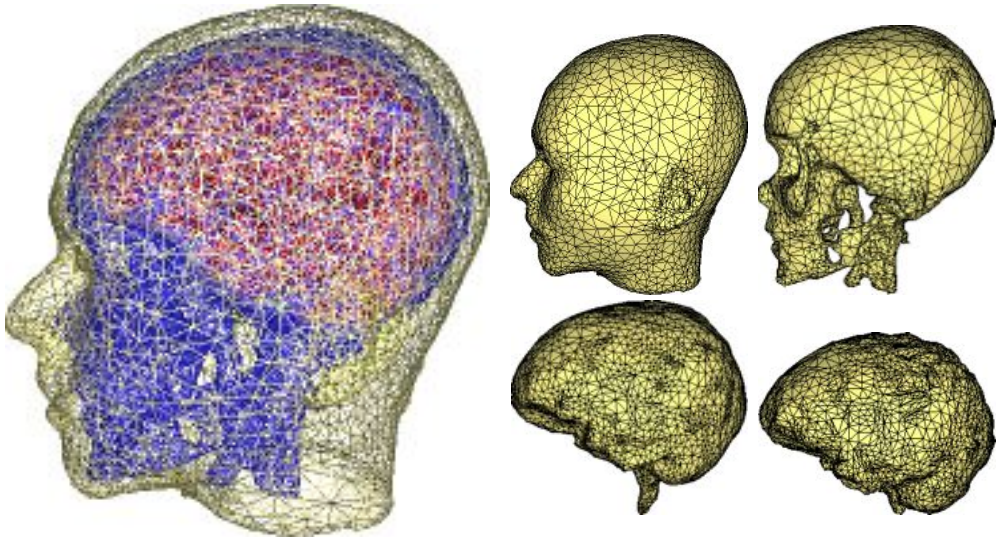




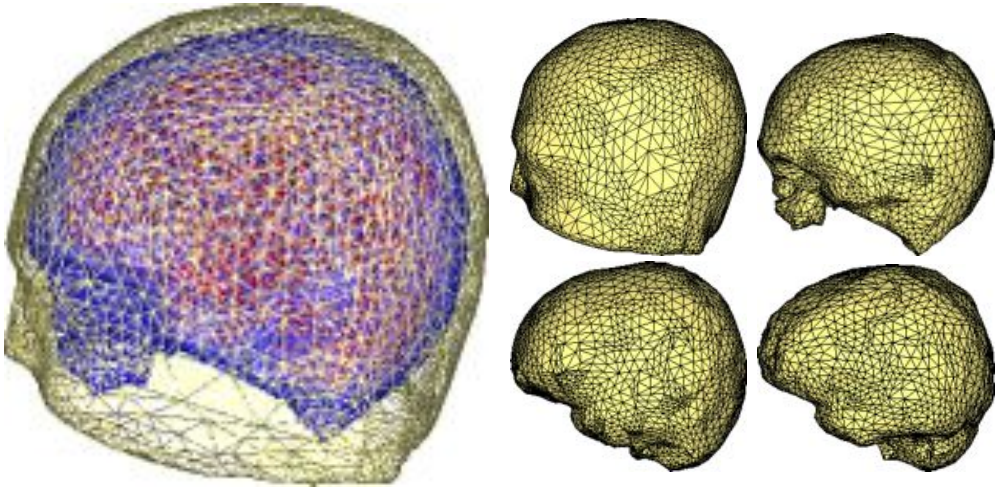
Scalp maps of 2 components

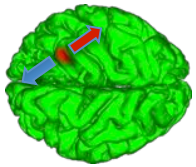
Sources of 2 components

Four-layer individual BEM head model



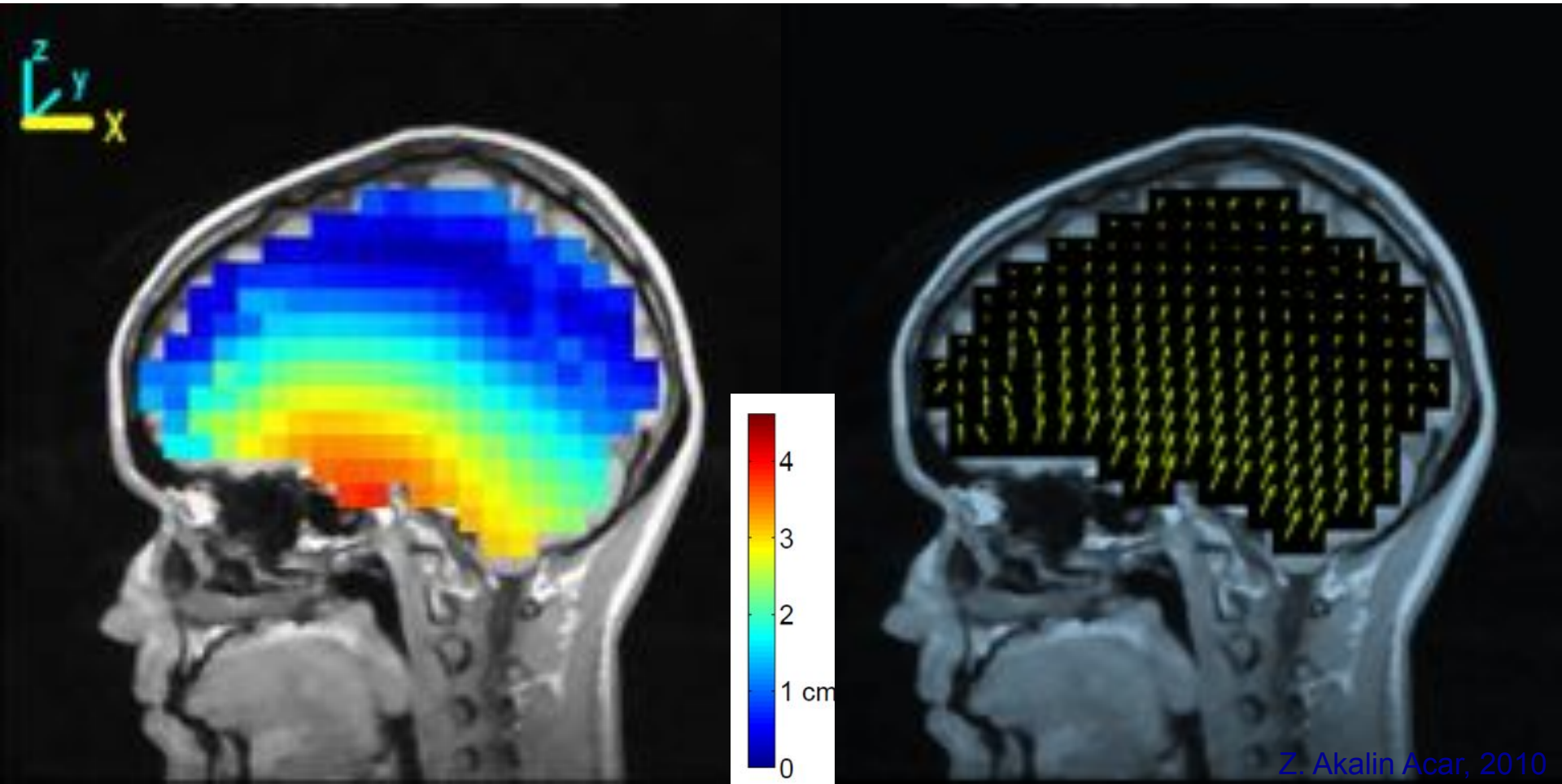
Four-layer MNI template BEM head model





Source Localization Error

- Using a simple **3-layer spherical** head model
- Instead of a good 4-layer **individual BEM** head model…



Z. Akalin Acar, 2010

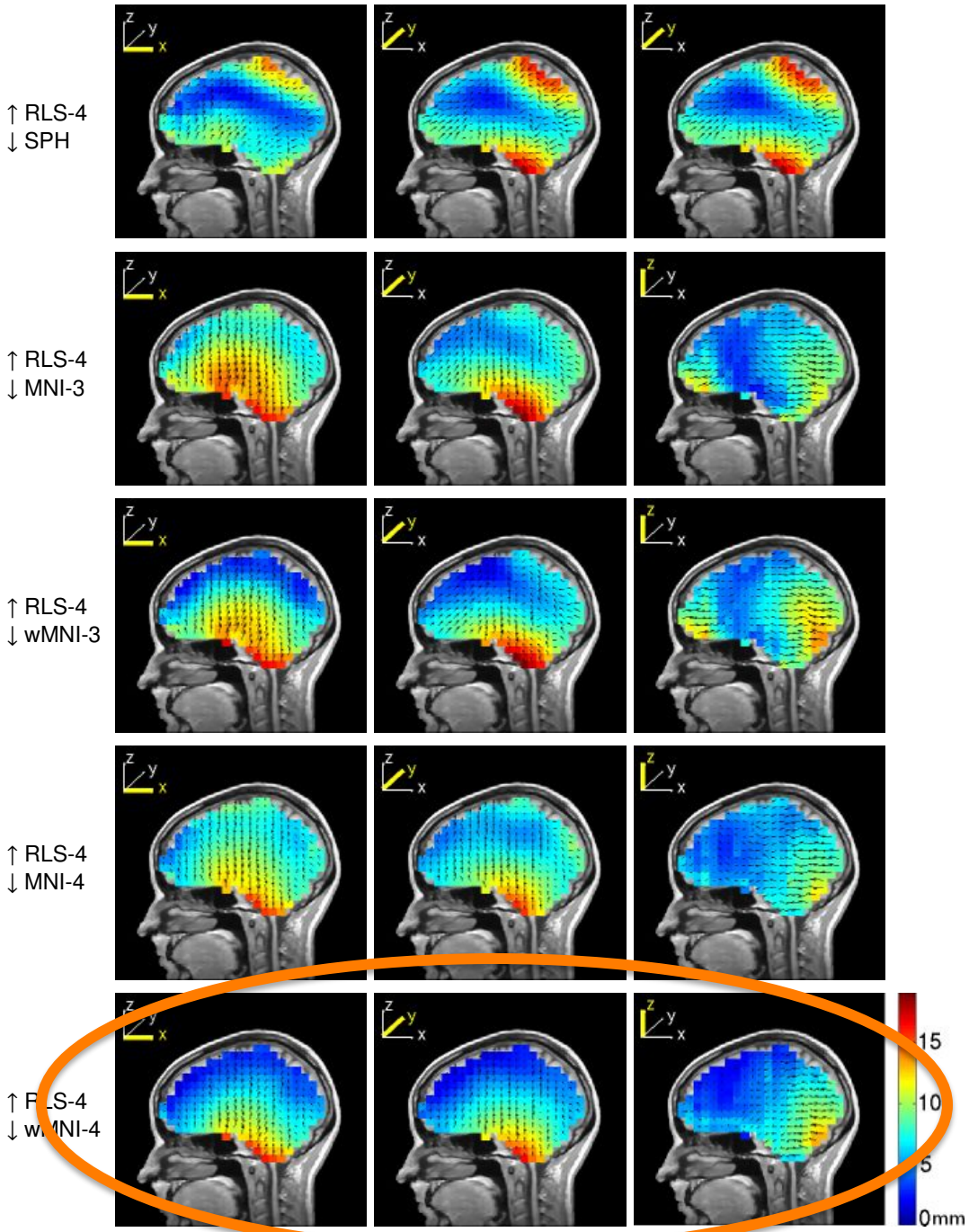


Fig. 9
Mean of 4 Ss

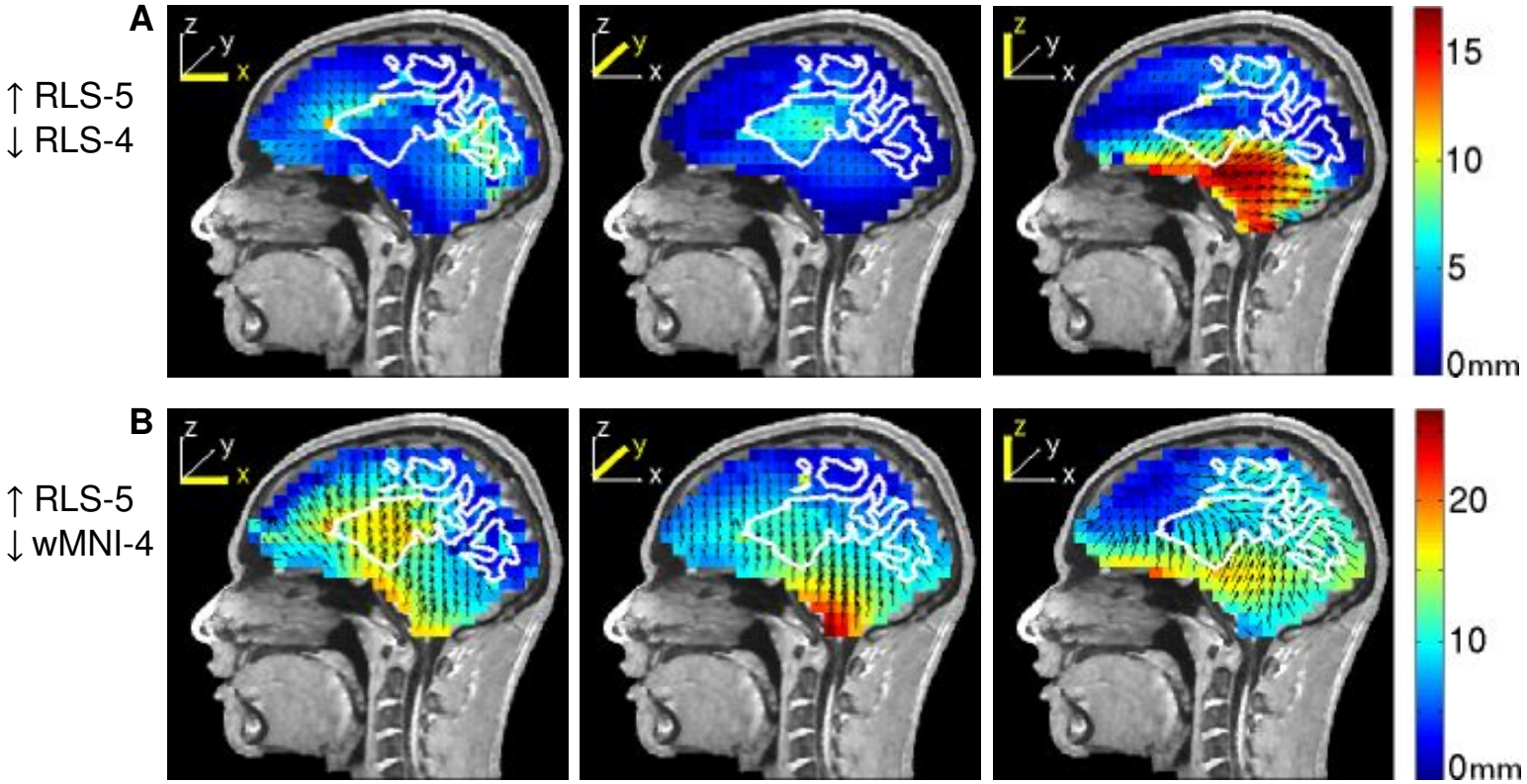


Fig. 11
5 → 4-layer

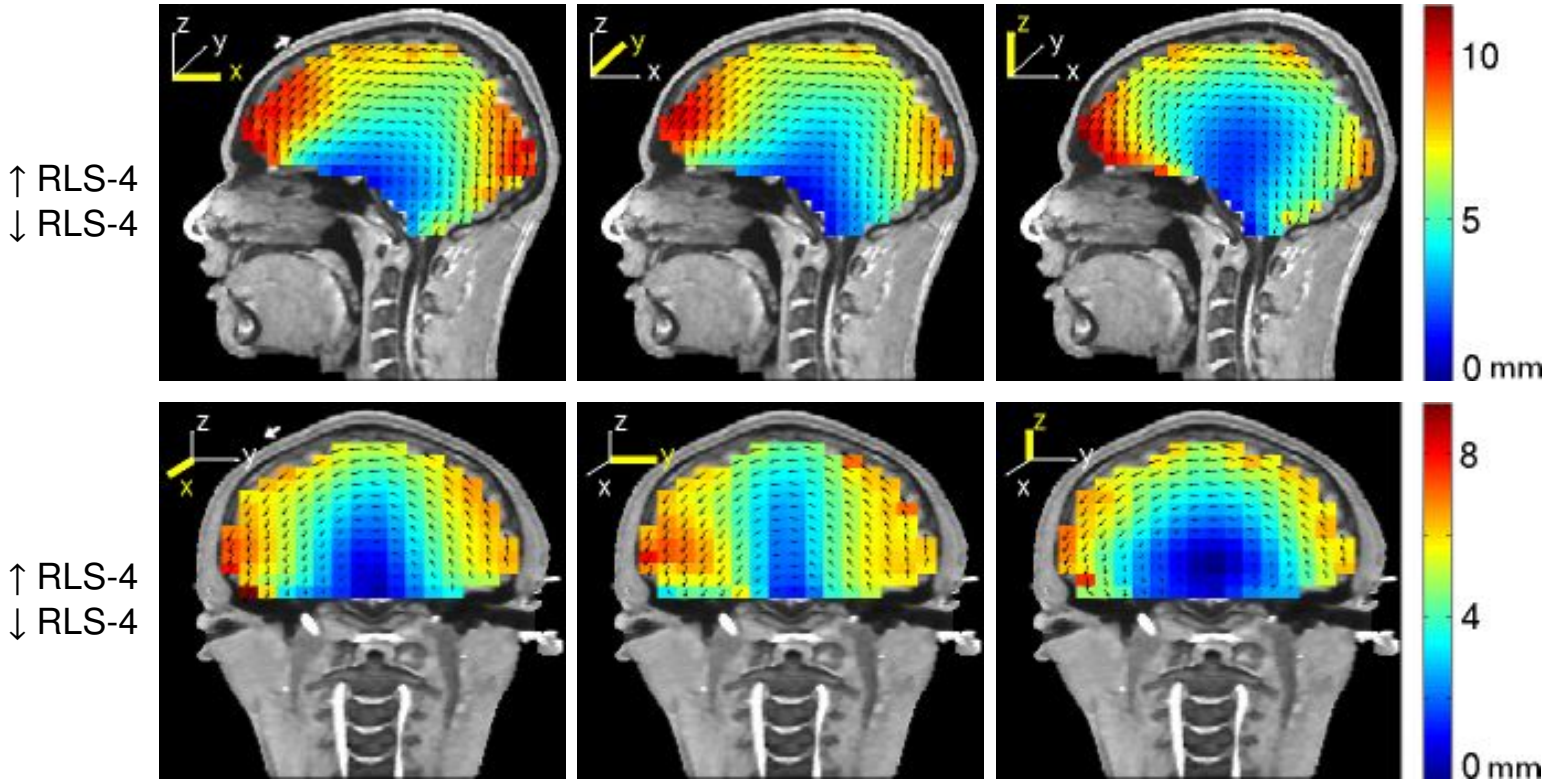
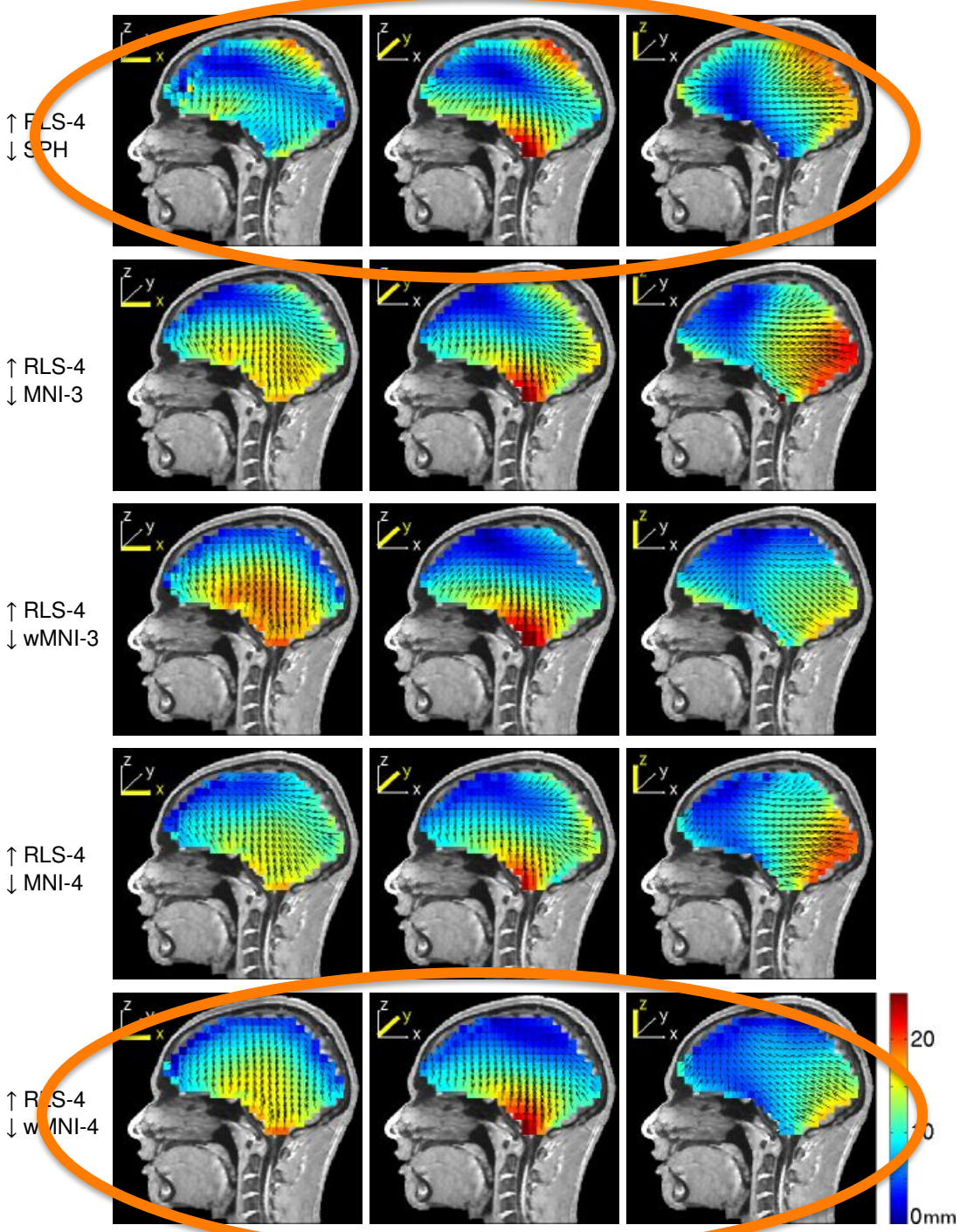


Fig. 12
Cap shifts



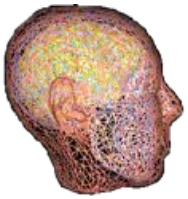


Fig. 4
Subject S1

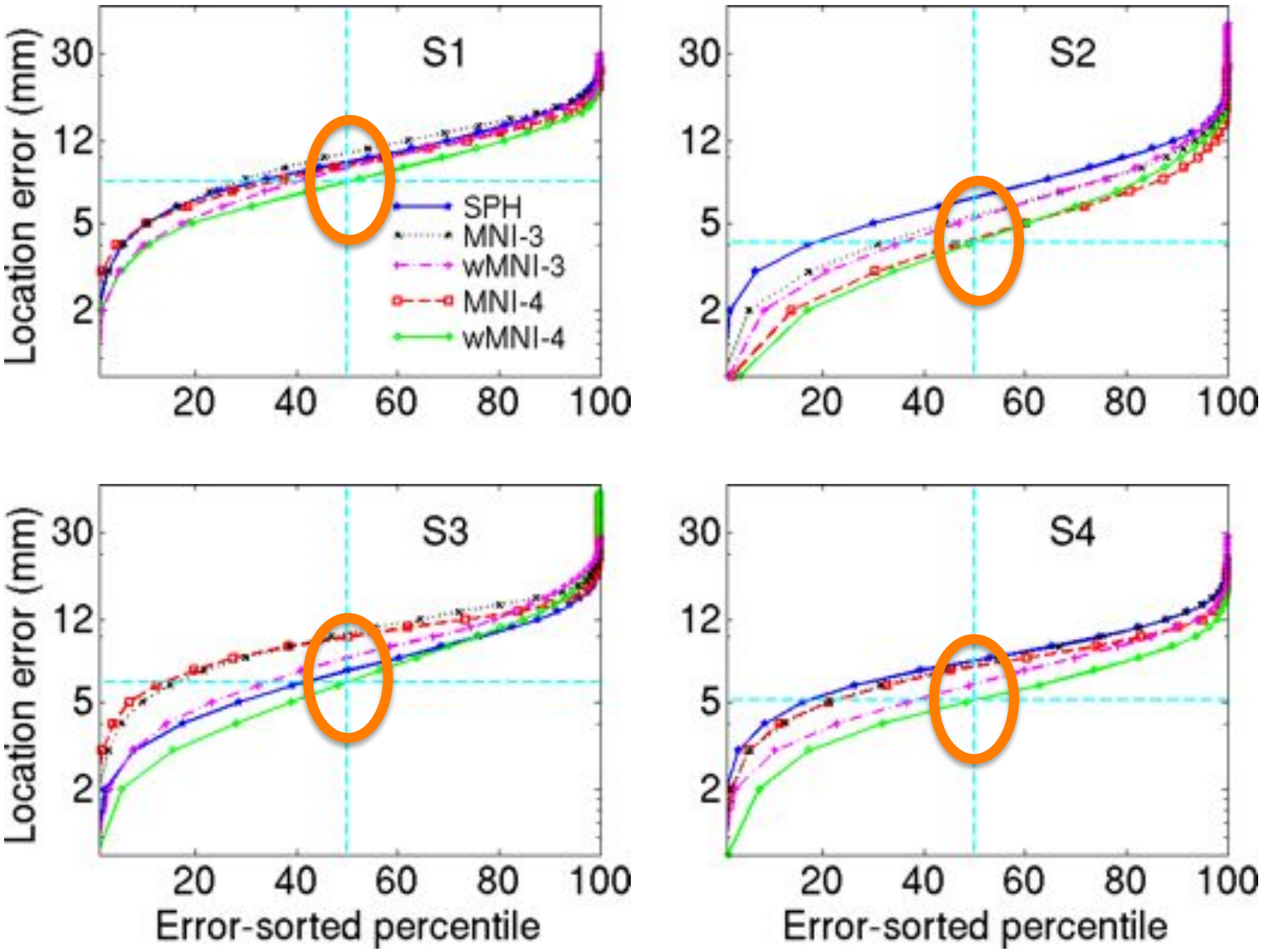
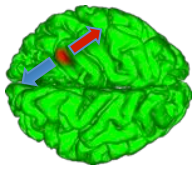
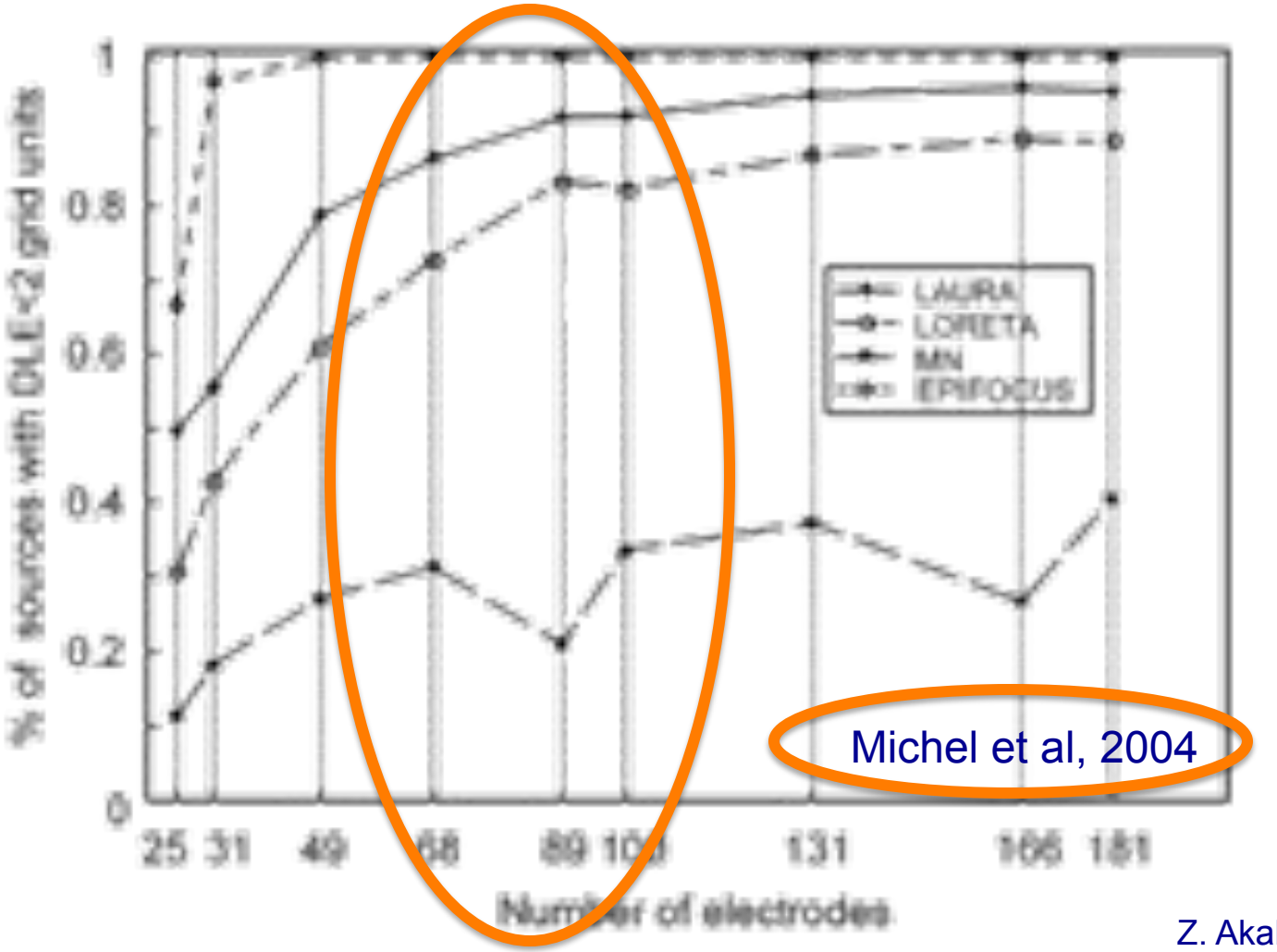

S1
S2
S3
S4
Location error (mm)
30
12
5
2
20
40
60
80
100
Error-sorted percentile
SPH
MNI-3
wMNI-3
MNI-4
wMNI-4

Fig. 7



Effect of Number of Electrodes

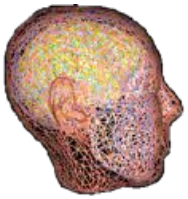
- Single dipole source
- 3-layer spherical head model
- 1152 solution points

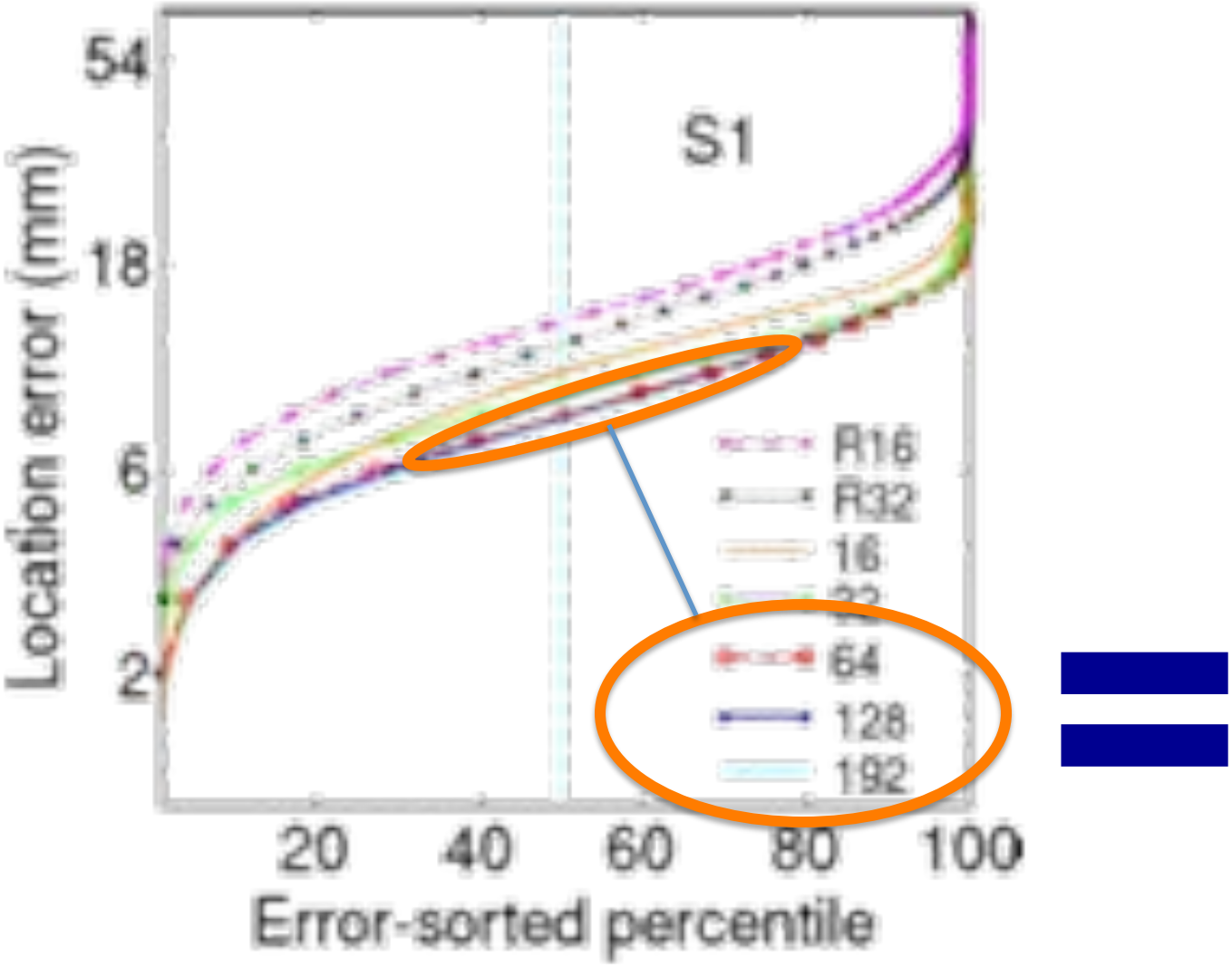


Michel et al, 2004

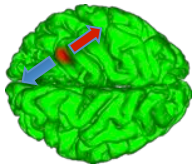
Z. Akalin Acar, 2010

Effect of Number of Electrodes

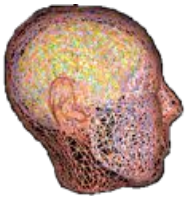




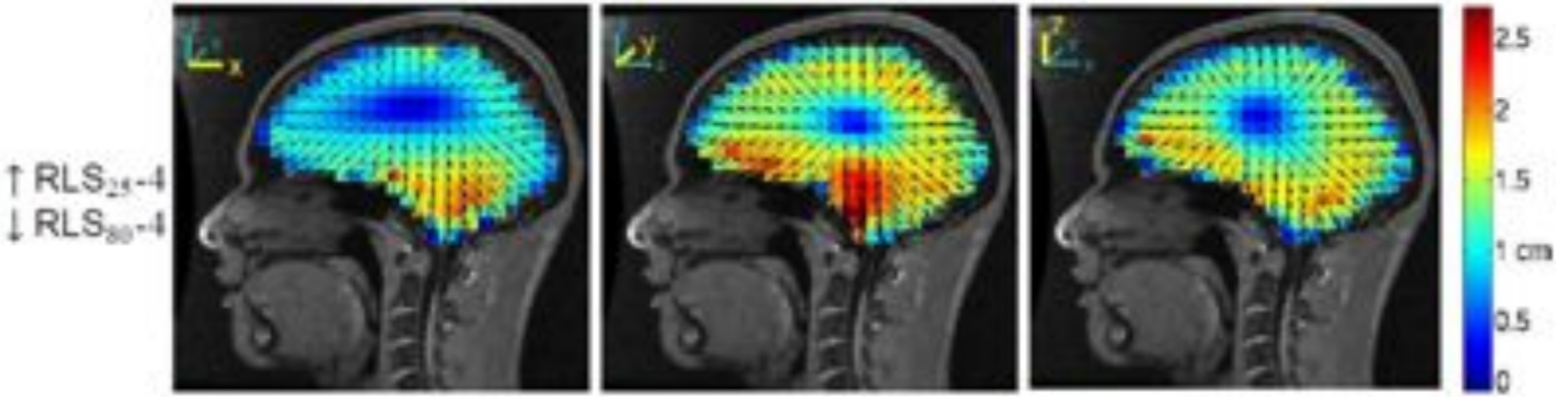
Akalin Acar & Makeig, 2013



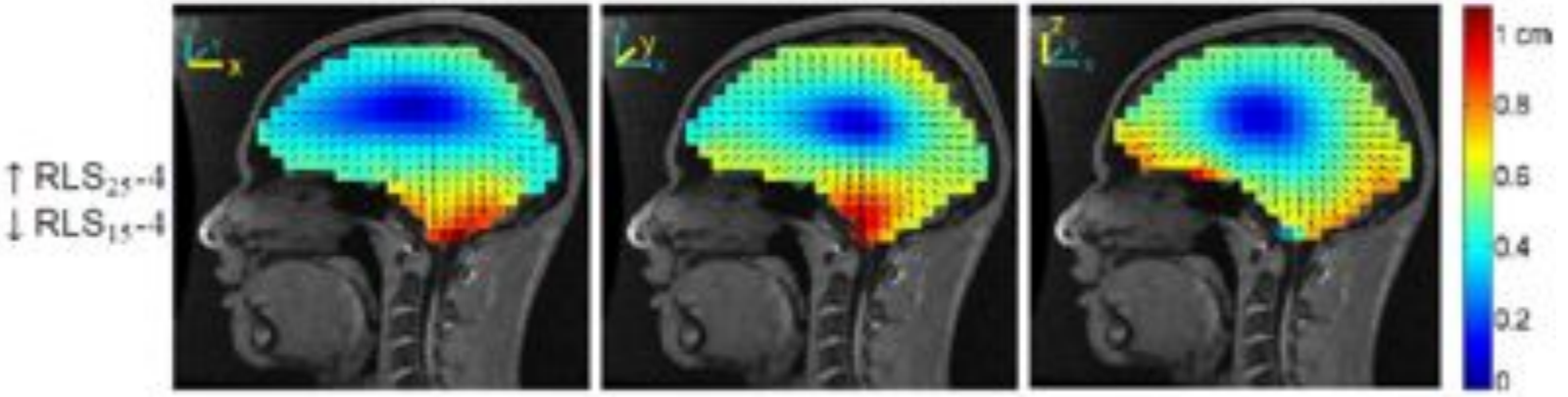
Source Localization Errors



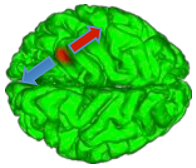
- Forward simulation – BSCR 25
- Inverse model – BSCR 80



- Forward simulation – BSCR 25
- Inverse model – BSCR 15



Z. Akalin Acar, 2010



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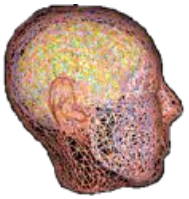
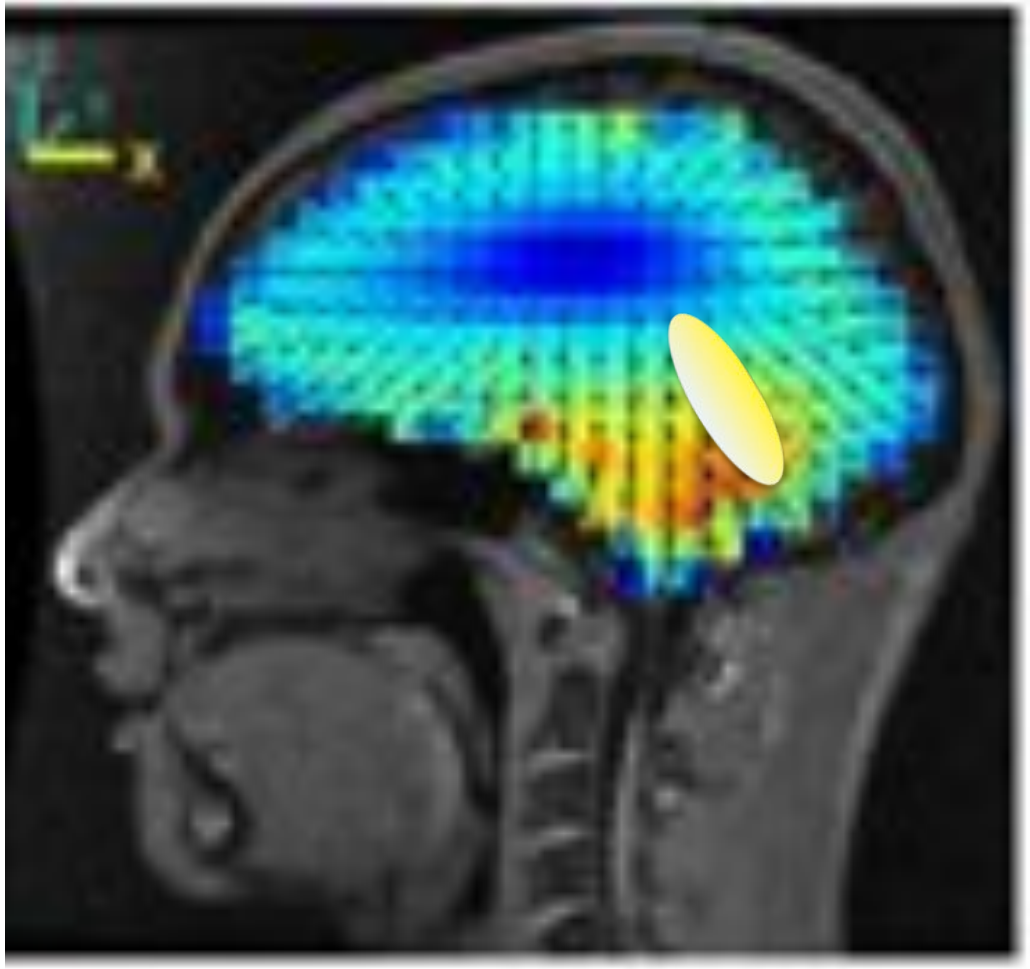
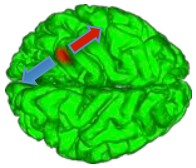




Z. Akalin Acar, 2010



Effect of reference electrode

"The choice of a particular reference electrode … does not change in any way the biophysical information contained in the potential distribution. It does not in any way change the relation between source and potential, except for an additive constant of no physical significance."

- Geselowitz, 1998

NFT Download

sccn.ucsd.edu/nft

NFT Reference Paper (2010)

Contents lists available at ScienceDirect

Journal of Neuroscience Methods

journal homepage: www.elsevier.com/locate/jneumeth

Neuroelectromagnetic Forward Head Modeling Toolbox☆

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ARTICLE INFO

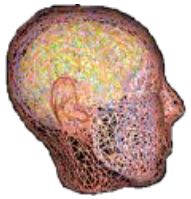
Article history:
Received 10 September 2009
Received in revised form 28 April 2010
Accepted 29 April 2010

Keyword:

ABSTRACT

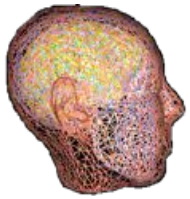
This paper introduces a Neuroelectromagnetic Forward Head Modeling Toolbox (NFT) running under MATLAB (The Mathworks, Inc.) for generating realistic head models from available data (MRI and/or electrode locations) and for computing numerical solutions for the forward problem of electromagnetic source imaging. The NFT includes tools for segmenting scalp, skull, cerebrospinal fluid (CSF) and brain tissues from T1-weighted magnetic resonance (MR) images. The Boundary Element Method (BEM) is used for the numerical solution of the forward problem. After extracting segmented tissue volumes, surface

NFT: Introduction



- ***A MATLAB toolbox for realistic head modeling and forward problem solving.***
- **Can use available subject information:**
  - T1-weighted 3-D MR images ***and/or***
  - Digitized sensor (electrode) locations
- **Implements all head modeling steps:**
  - Segmentation of MR images
  - Mesh generation
  - Warping a template head model to the sensor positions
  - Sensor/head image co-registration
  - Lead field matrix: Source space → Sensors

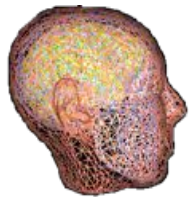
Forward Problem Solver



- MATLAB interface to numerical solvers
- Boundary Element Method
  - No MEG (yet)
  - Supports IPA and Accelerated BEM
  - Interfaces to the Matrix generator written in C++
- Other computations in MATLAB
- Generated matrices are stored on disk for future use.
- Other solvers:

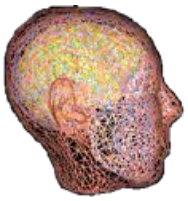
  Finite Element Method (FEM)

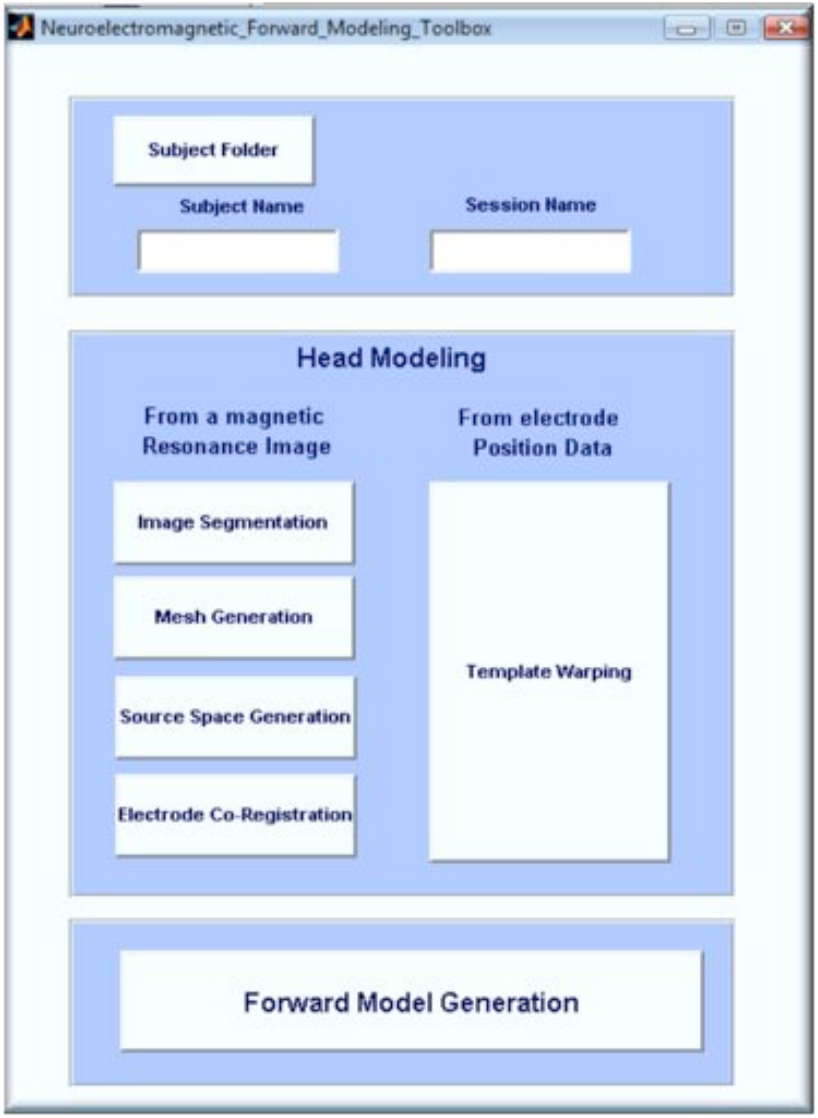
NFT: Operation



- **T1 MR Images**
  - Choose subject
  - Generate subject head model
  - Segmentation
    - Mesh generation
  - Register sensors to mesh
    - Sensor set = session
  - Generate forward model
  - Generate Lead Field Matrix
- **Template Mesh**
  - Choose subject
  - Select sensors
  - Warp Template to sensors
  - Generate forward model
  - Generate LFM for sensors

NFT Main Menu



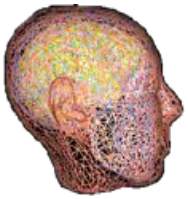


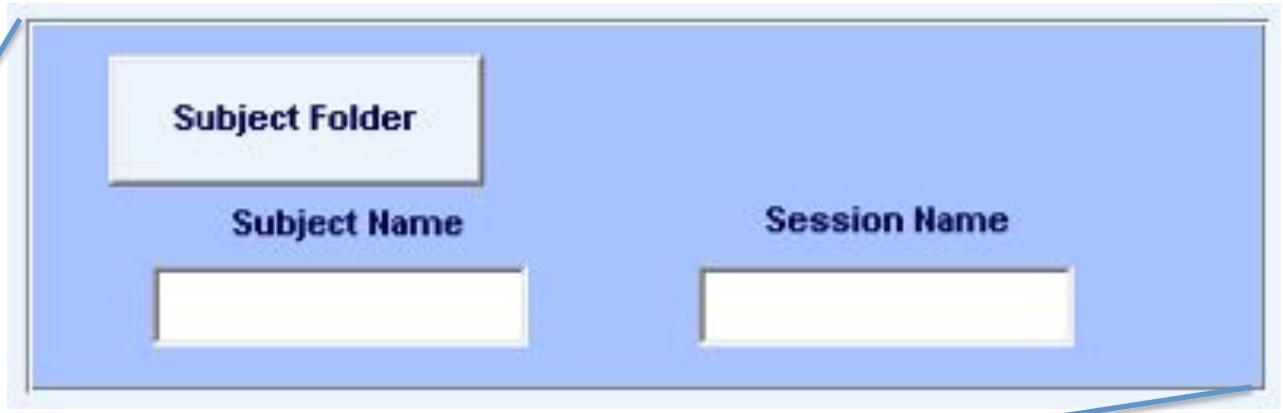
Subject Selection

Head Modeling

Forward Modeling

Subject Selection





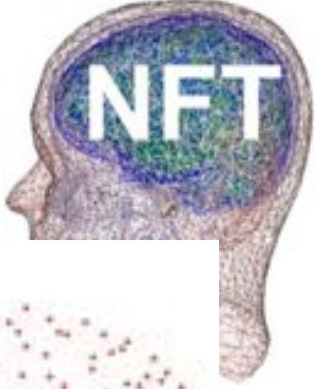
- Select subject folder name
- Specify subject code
- Specify session name

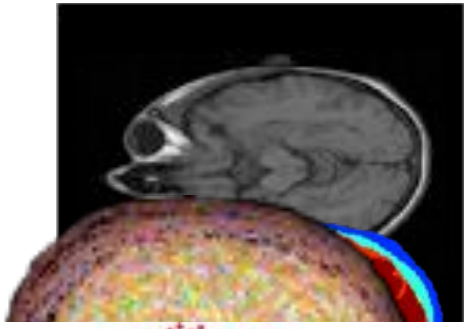
Neuroelectromagnetic Forward Head Modeling Toolbox

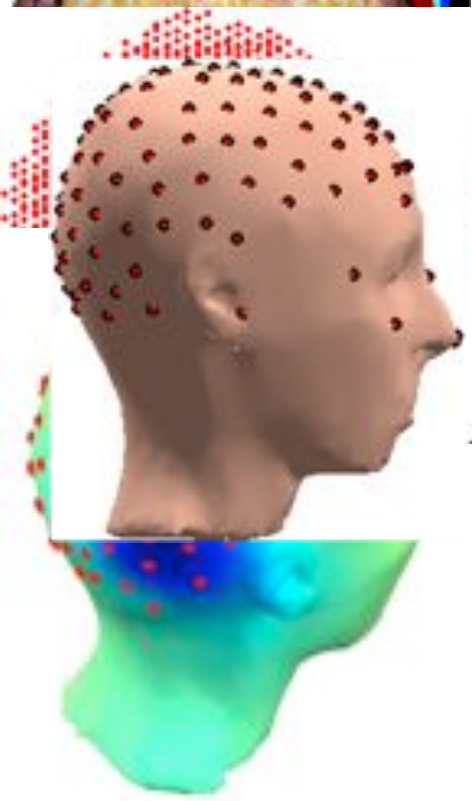
Akalin Acar and Makeig, J. Neurosci. Methods, 2010

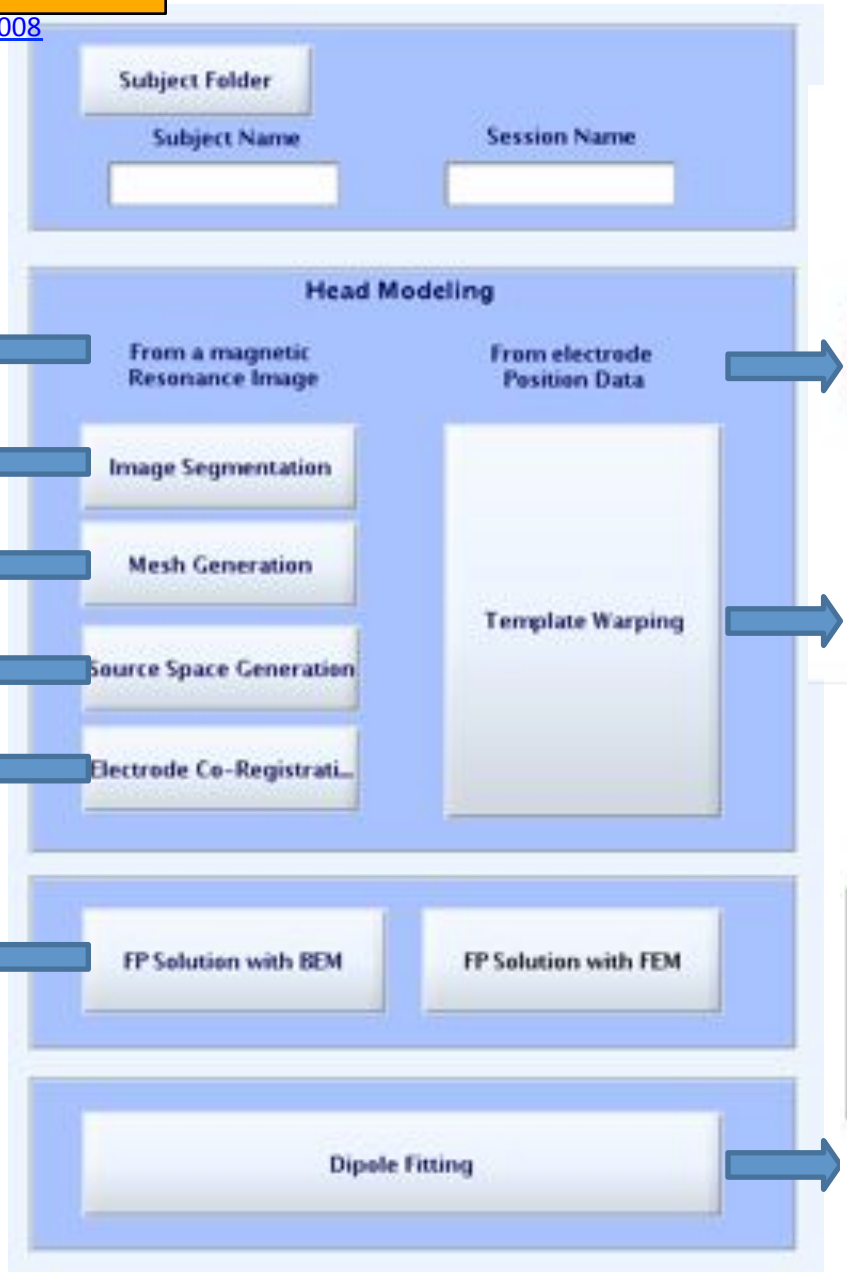
Akalin Acar and Makeig, IEEE EMBC, 2008

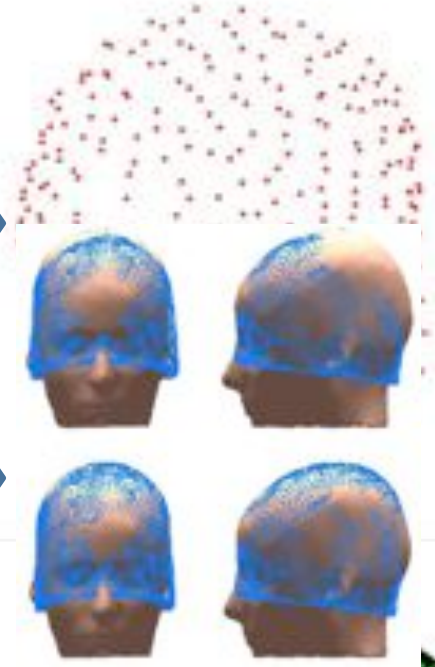
http://sccn.ucsd.edu/nft

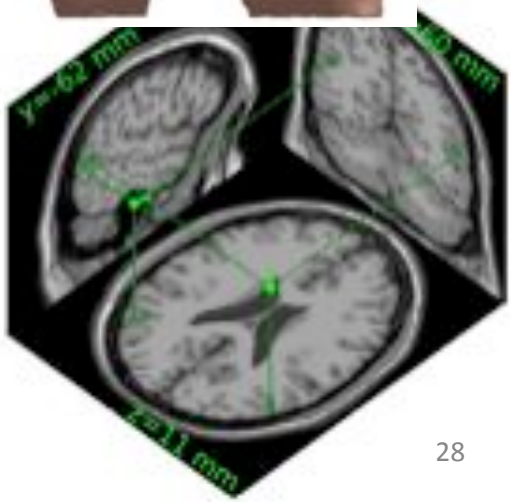






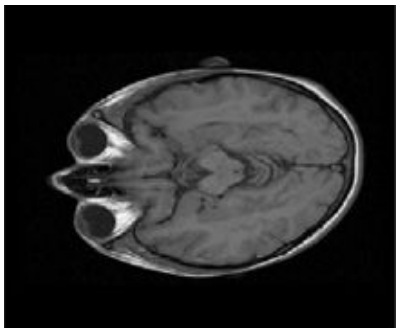






Head modeling from an MR head image

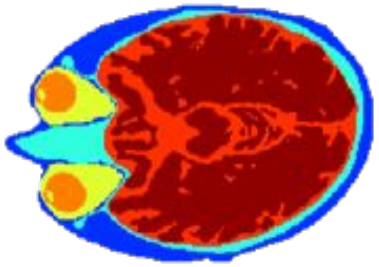
MR image



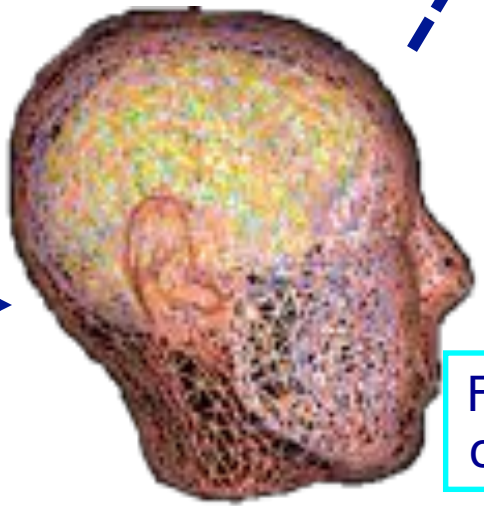
T1-weighted

From a magnetic Resonance Image

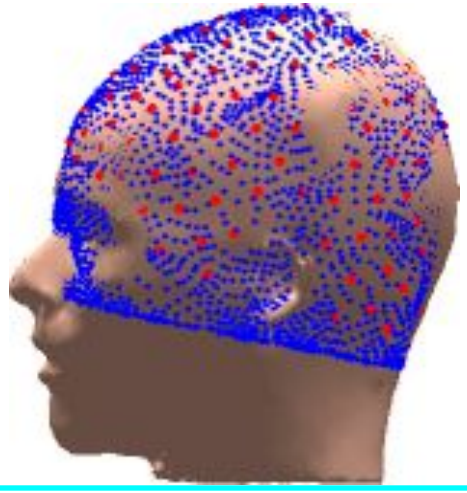
- Image Segmentation
- Mesh Generation
- Source Space Generation
- Electrode Co-Registration



Tissue Segmentation

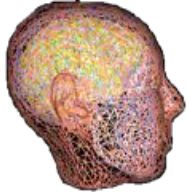


F/BEM mesh construction



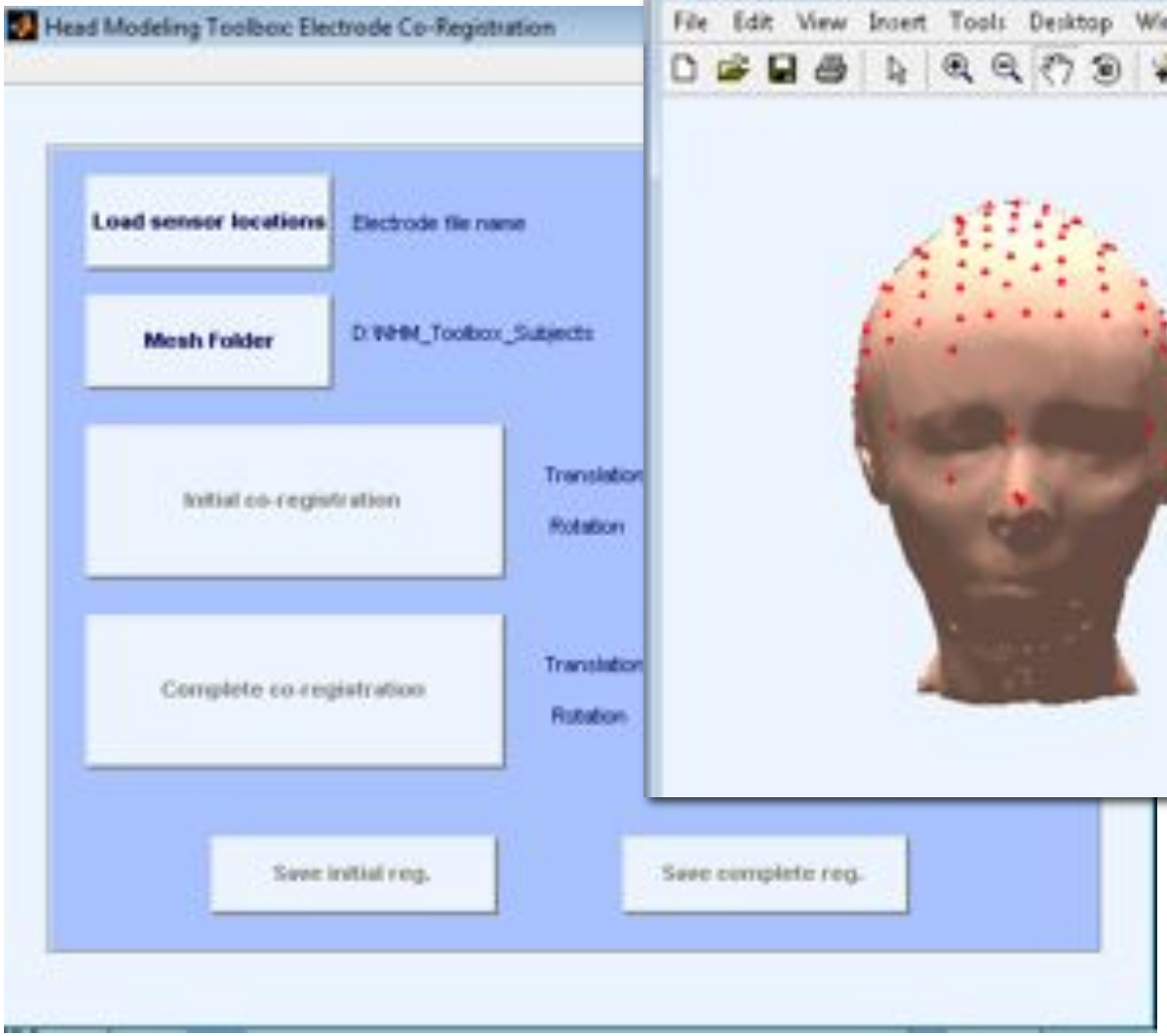
Electrode Registration

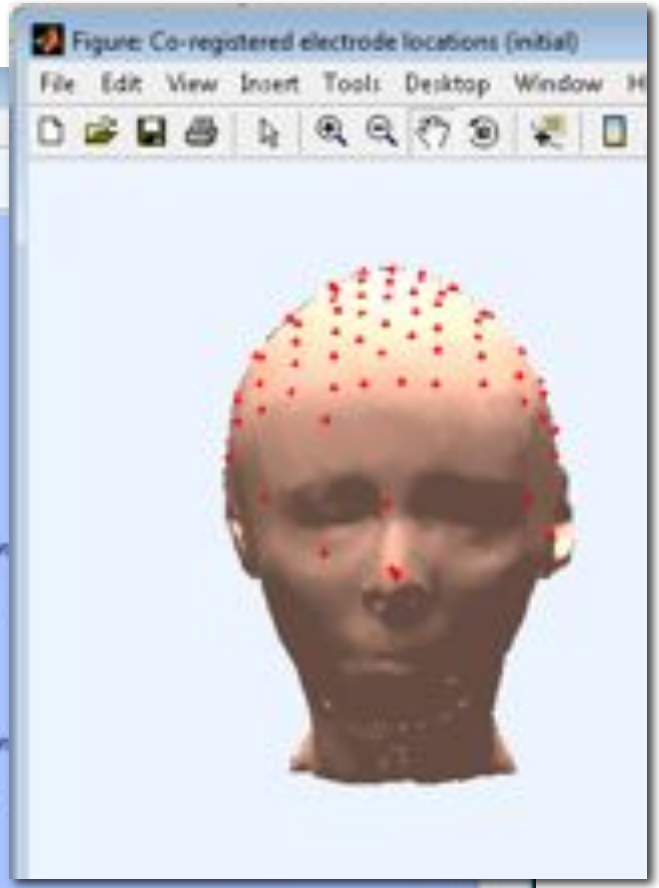
Electrode Co-Registration



From a magnetic Resonance Image

- Image Segmentation
- Mesh Generation
- Source Space Generation
- Electrode Co-Registration



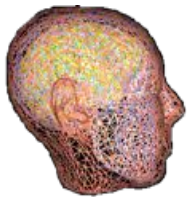


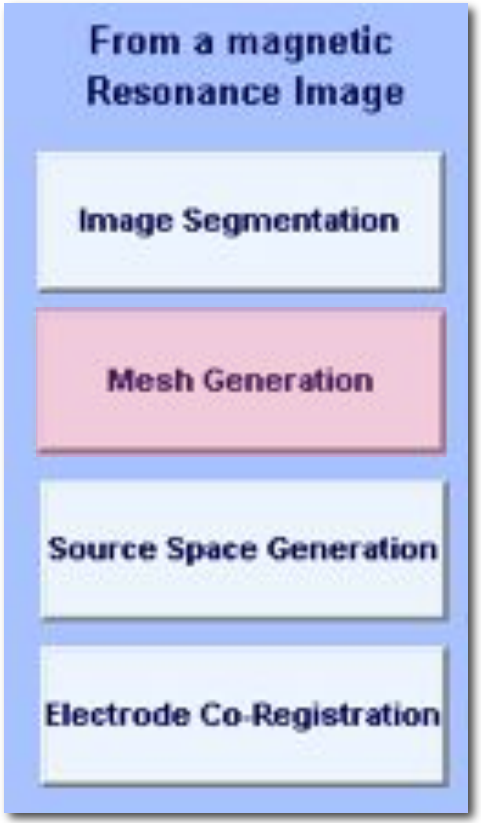
Preparing the MR image for segmentation

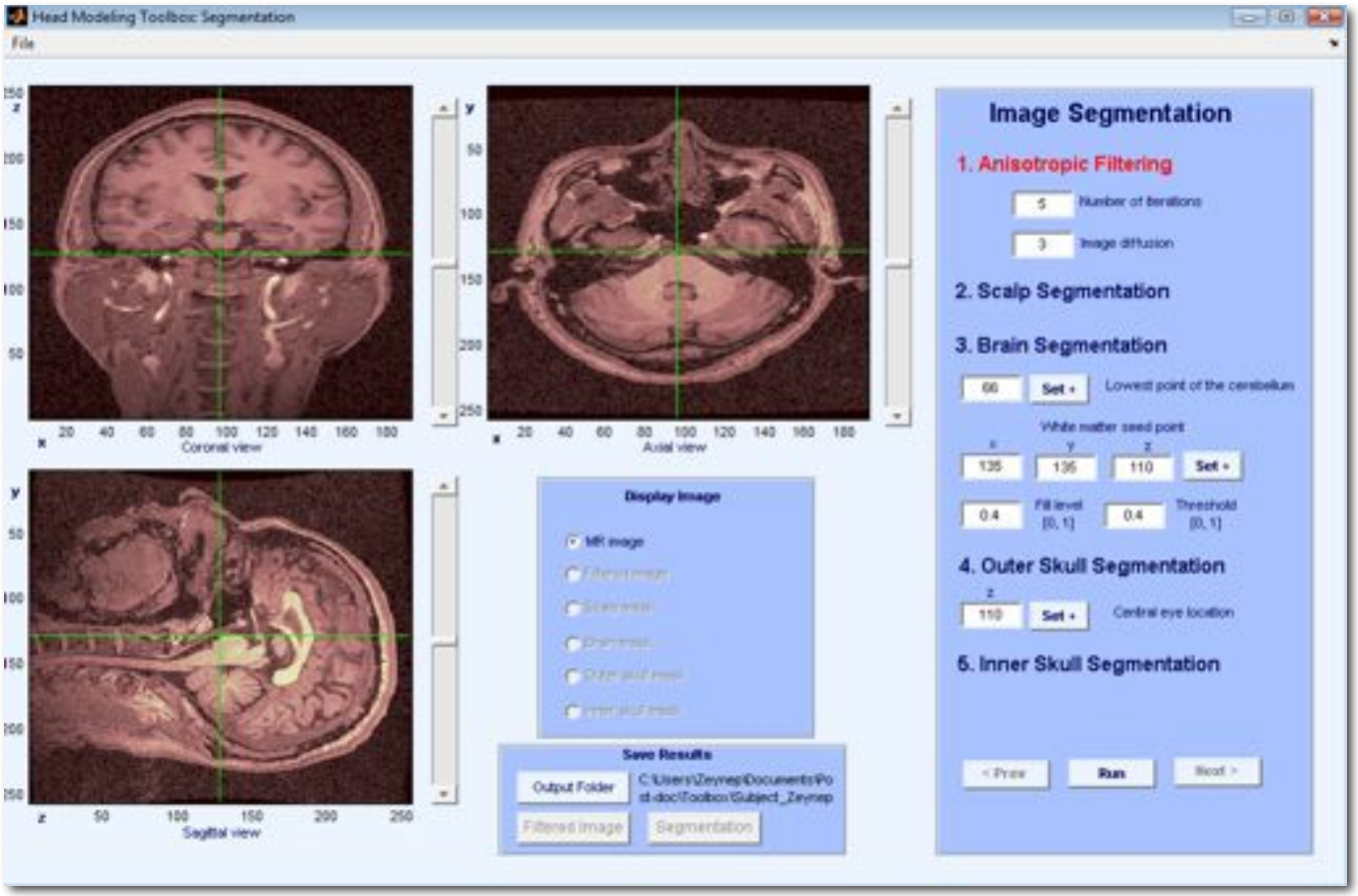
Use FREESURFER to

- Perform inhomogeneity correction
- Convert to 1x1x1 pixels
- Arrange direction of the image
- Save in Analyze format

Image Segmentation

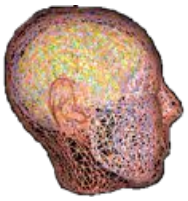


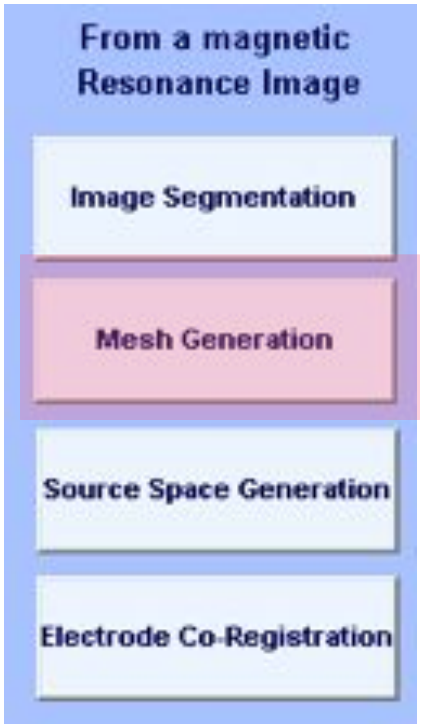


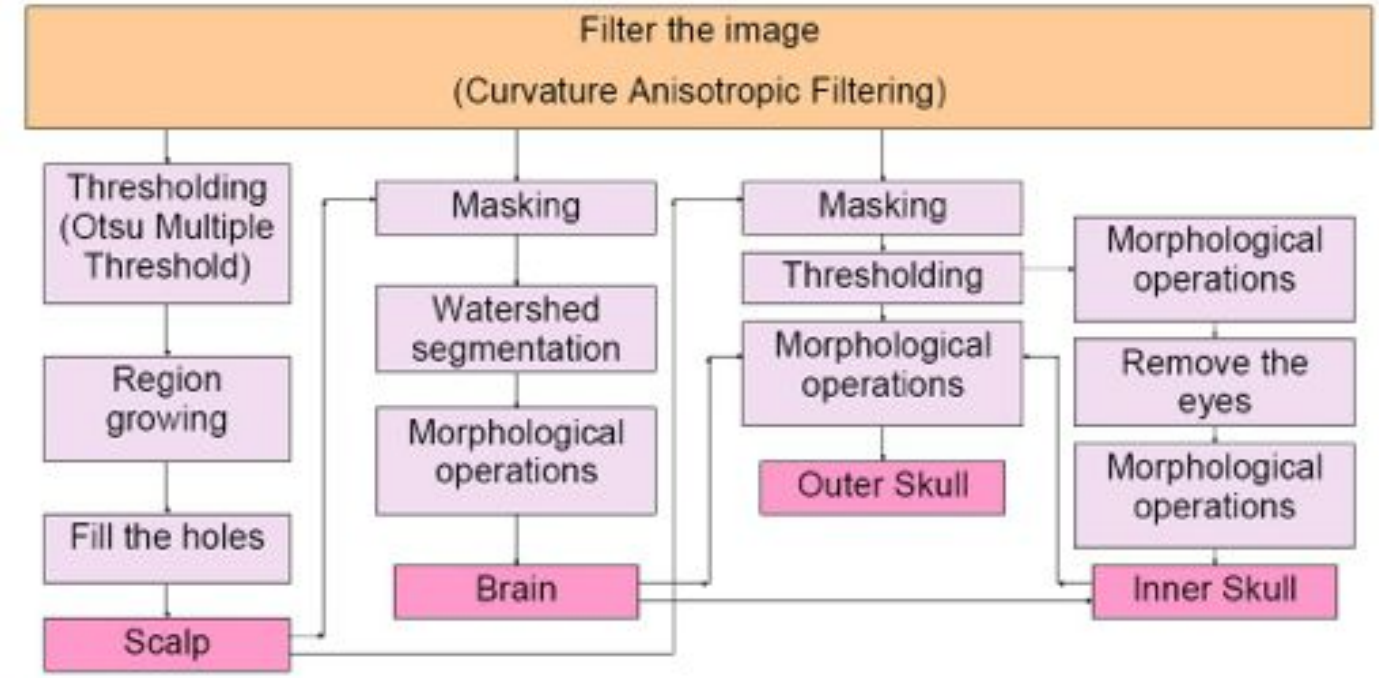


- Interface for Segmenting the MR image

Image Segmentation Flowchart

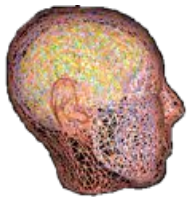


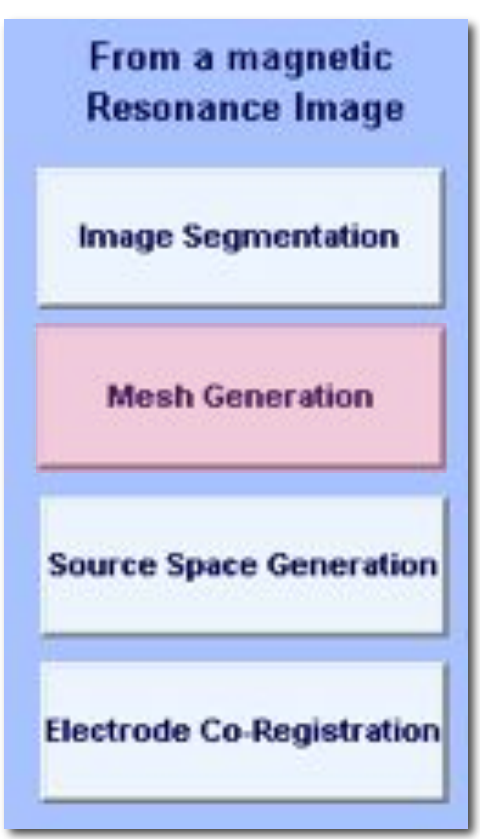


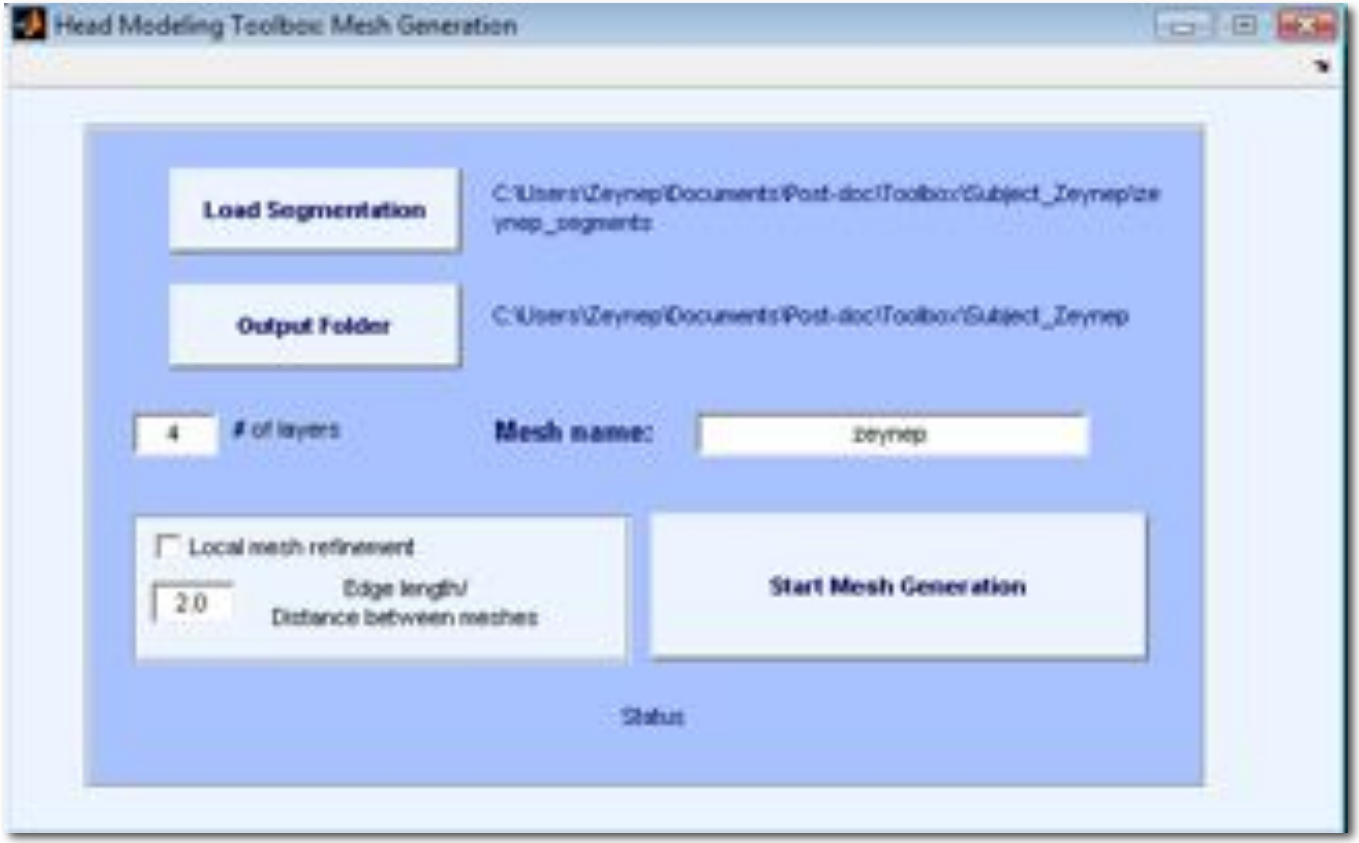


- Classifies four tissues from T1-weighted images
  - (Scalp, Skull, CSF and Brain)

Mesh Generation

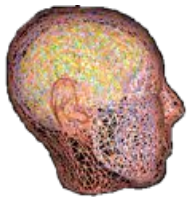


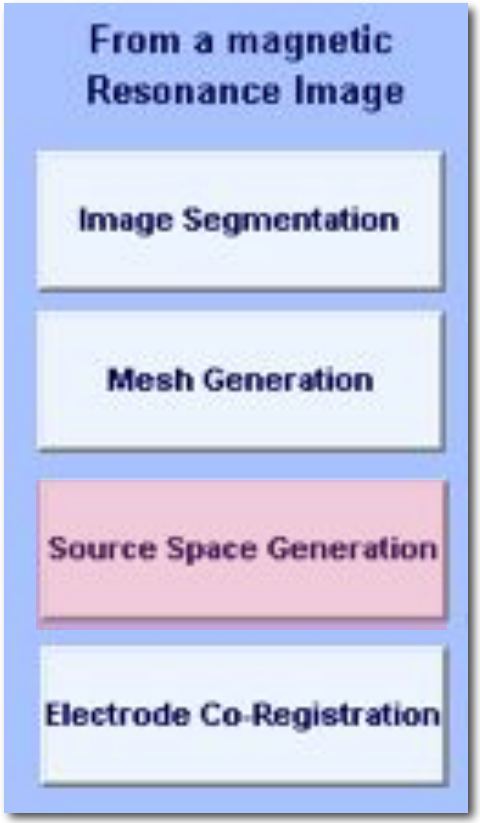


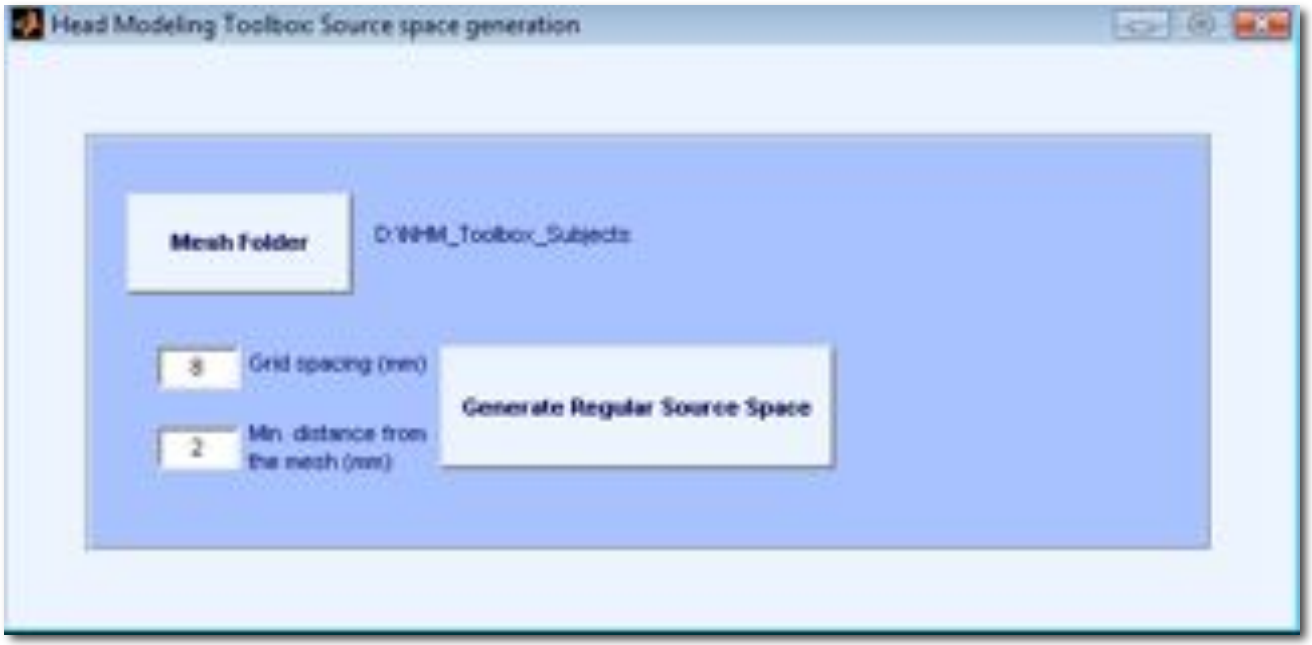


- Generate a mesh for a 3- or 4-layer BEM head model
  - (triangulation, correction, coarsening, refinement)

Source Space Generation

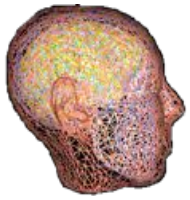






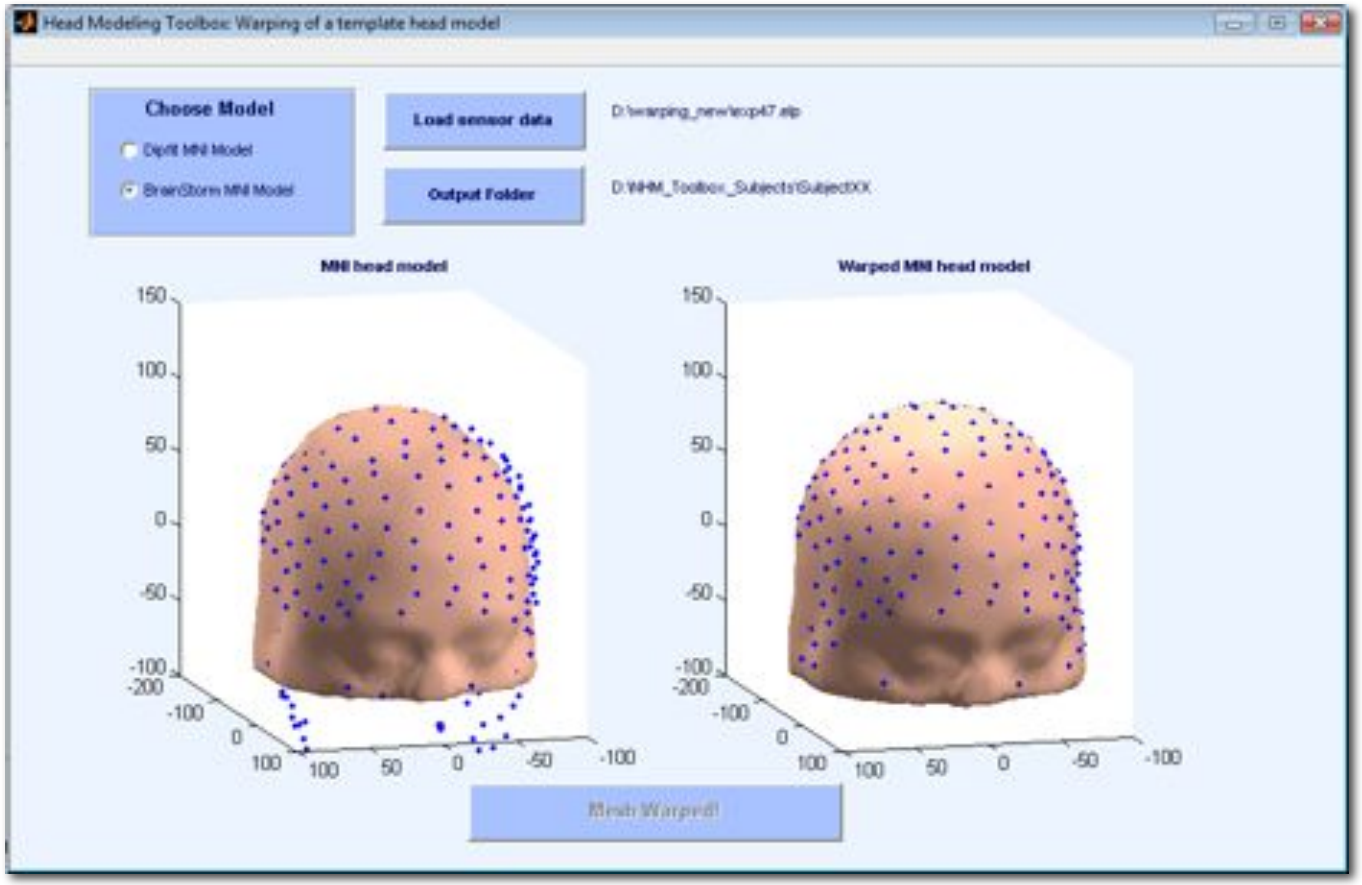
- Here, generate a simple source space:
  - A regular grid within the brain space
    - with a given spacing & min. dist. to the mesh

Electrode Position-Based Template Head Warping

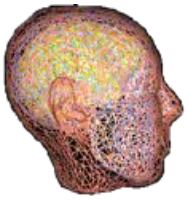


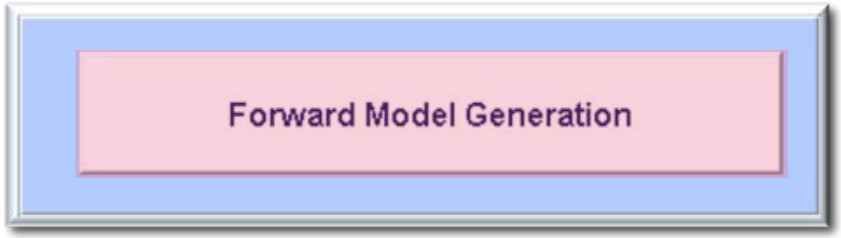
From electrode Position Data

Template Warping



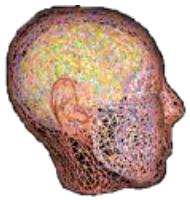
Forward Model Generation

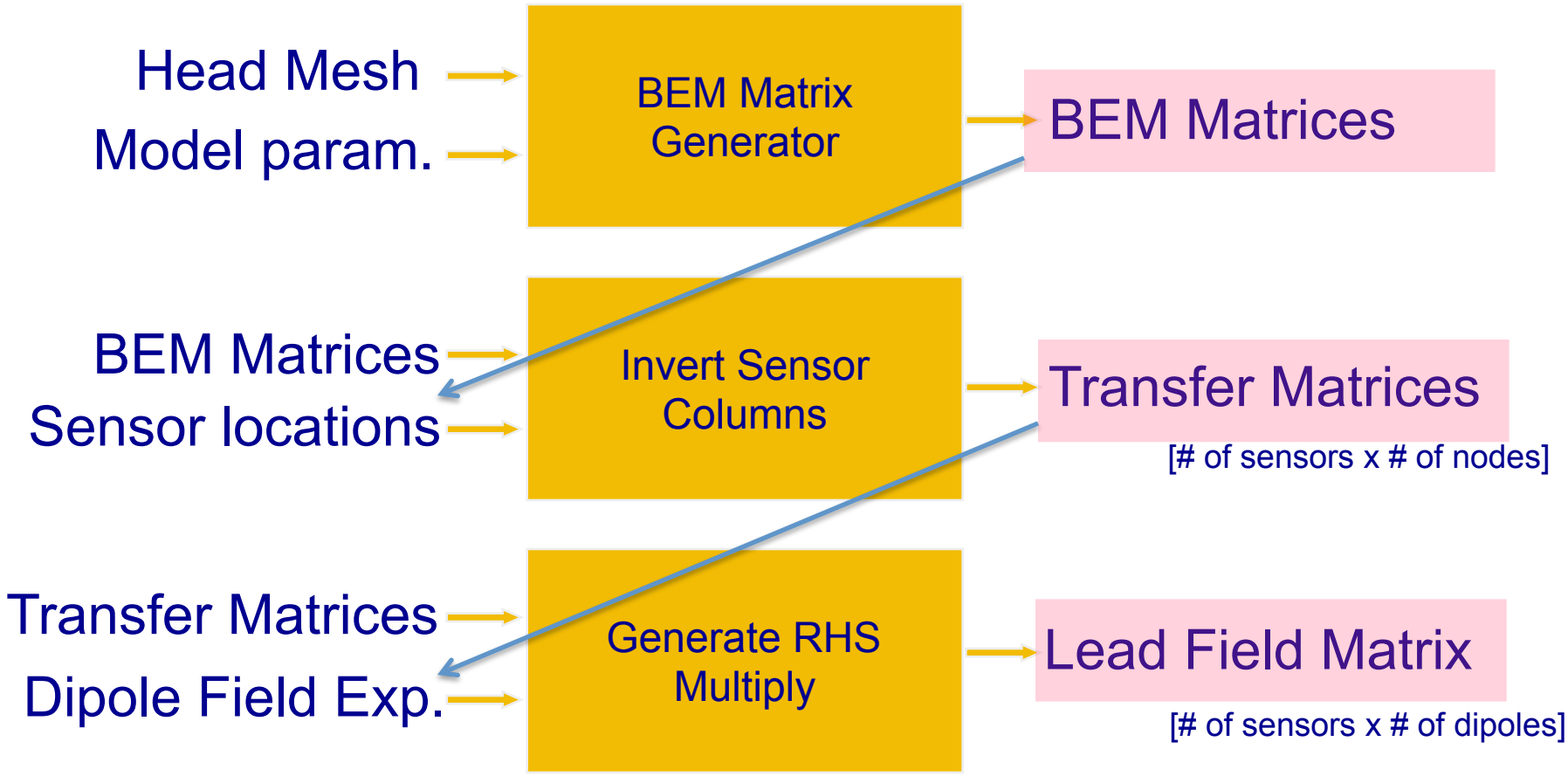




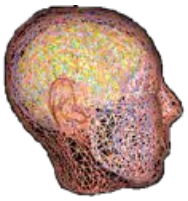
- Generates the Forward Model from meshes
  - BEM or FEM
- Generates three structures:
  - Mesh
  - Model (Mesh + Electrical Properties)
  - Session (Model + Sensors)

Forward Problem Solution





Forward Problem Solution



Forward Model Generation

Forward Problem Solution

File

BEM Mesh Info

Mesh Name

Show Mesh

Number of Layers

Number of Nodes

Number of Elements

Number of Nodes/Element

BEM Model

Model Name

Enter conductivity values:

0.33 Scalp 0.0042 Skull

0.33 Brain

Modified (Isolated Problem Approach)

Create Model

No Model

Session

Session Name

Load Sensors

Mesh Node List

Mesh Coordinates

Load

Show Sensors

Generate transfer matrix

No Session

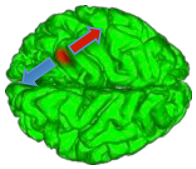
Forward Problem Solution

Load Source Space

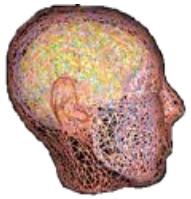
Compute Lead Field Matrix

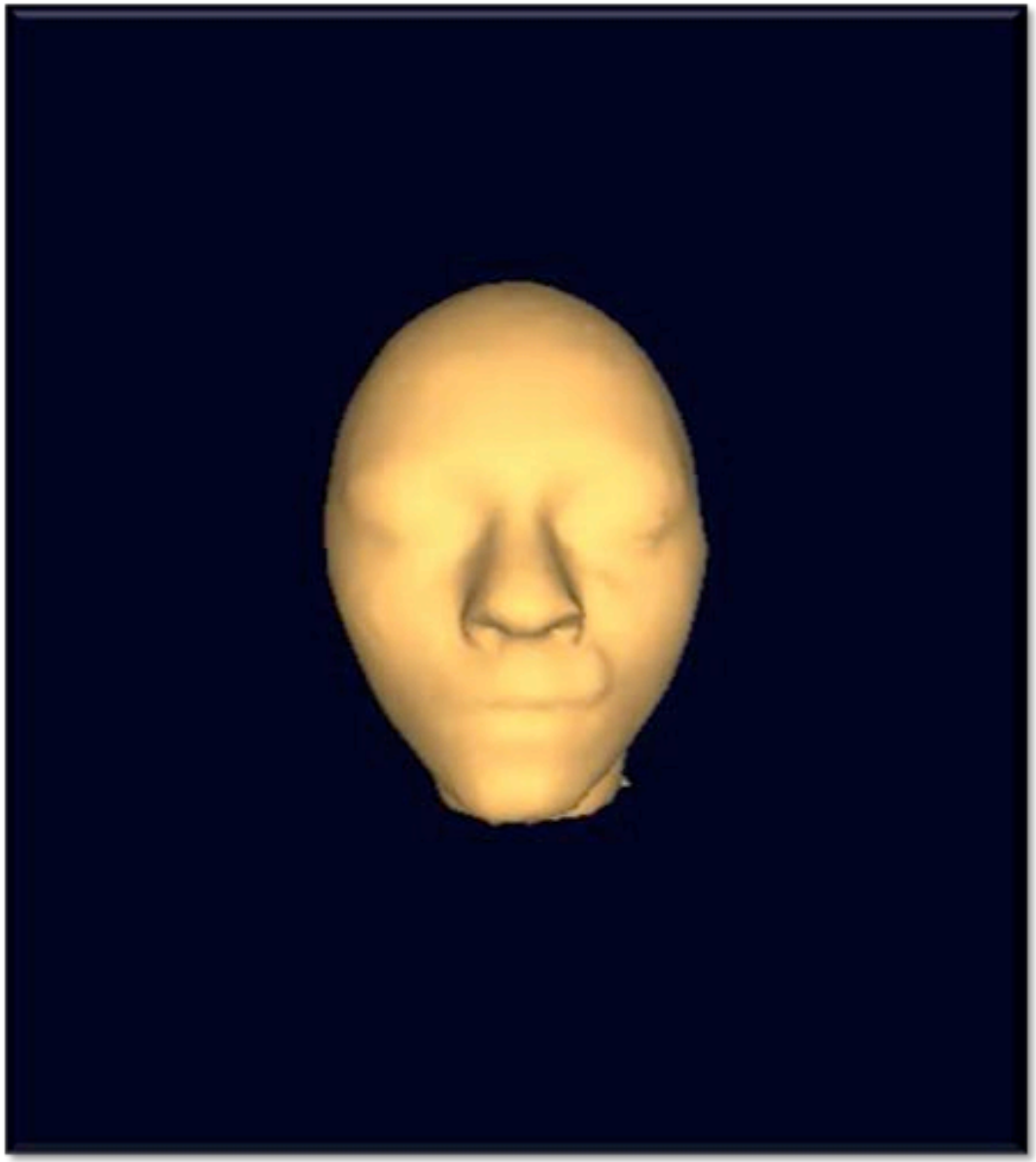
Plot Potential Distribution

For Dipole



A Four-Layer BEM Head Model





Neuroelectromagnetic

Forward head modeling

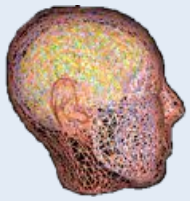
Toolbox (**NFT**)

# of elements

Scalp:	6,900
Skull:	6,800
CSF:	9,000
Brain:	8,800
Total	31,500

Z. Akalin Acar, 2010

Source localization error comparisons



BEM Head Models:

- **4-layer MR-based realistic BEM head model**
- 3-layer MR-based realistic BEM head model
- MNI template head model
- Electrode-warped MNI template head model
- Spherical BEM head model

Brain Topogr
DOI 10.1007/s10548-012-0274-6

ORIGINAL PAPER

Effects of Forward Model Errors on EEG Source Localization

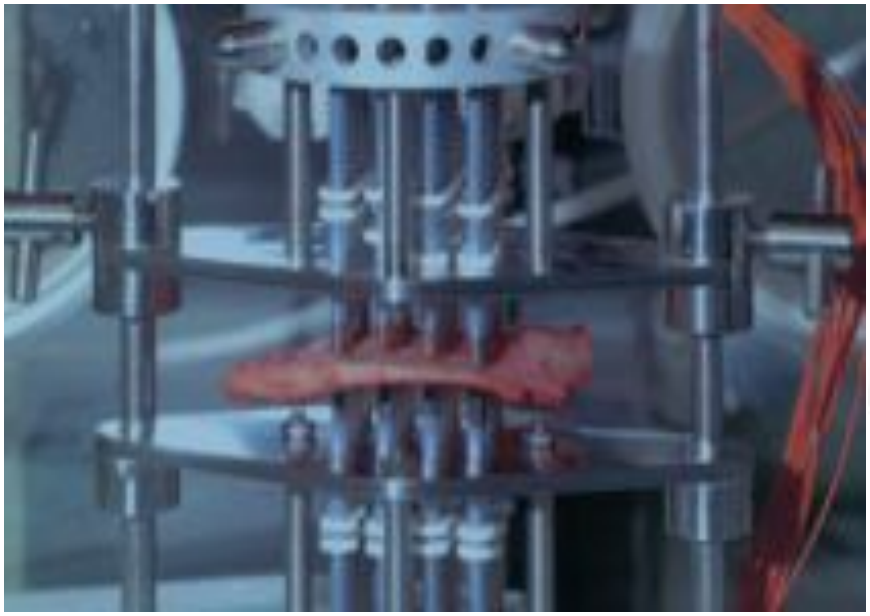
Zeynep Akalin Acar · Scott Makeig

Effects of Skull Conductivity Estimation

Measurements of skull conductivity:

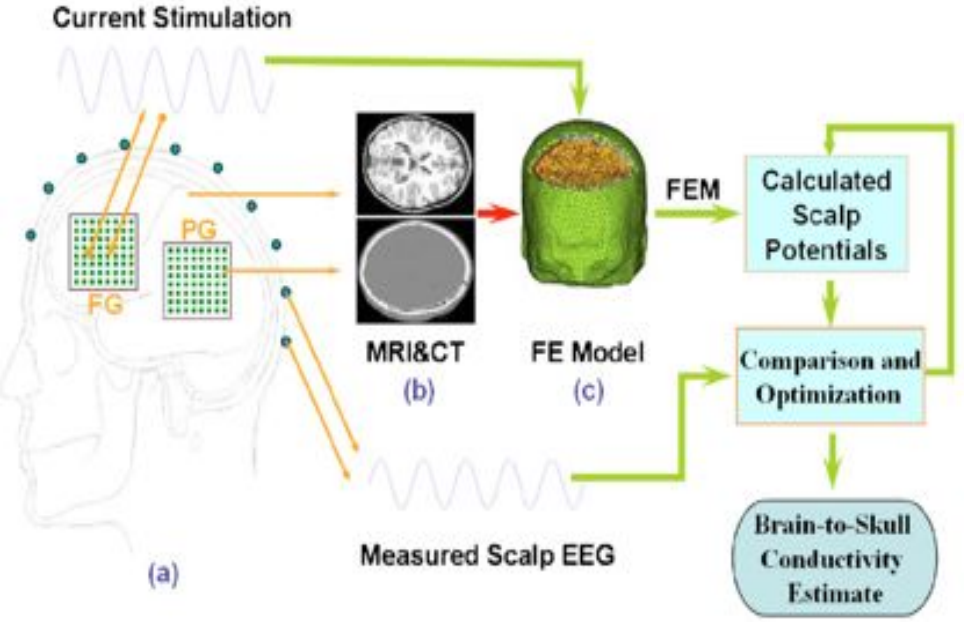
- MR-EIT
- Magnetic stimulation
- Current injection

In vivo



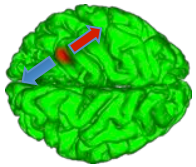
Hoekama et al, 2003

In vitro

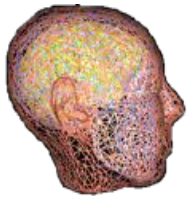


He et al, 2005

Z. Akalin Acar, 2010



Skull Conductivity Measurements



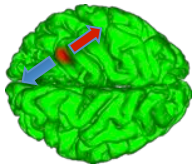
Brain to skull ratio		
Rush and Driscoll	1968	80
Cohen and Cuffin	1983	80
Oostendorp et al	2000	15
Lai et al	2005	25

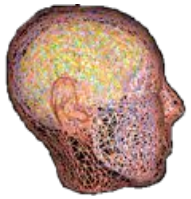
Measurement	Age	σ (mS/m)	Sd (mS/m)
Agar-agar phantom	–	43.6	3.1
Patient 1	11	80.1	5.5
Patient 2	25	71.2	8.3
Patient 3	36	53.7	4.3
Patient 4	46	34.4	2.3
Patient 5	50	32.0	4.5
Post mortem skull	68	21.4	1.3

Skull conductivity by age

Hoekama et al, 2003

Z. Akalin Acar, 2010





Summary I

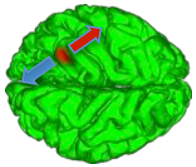
- **Forward modeling**

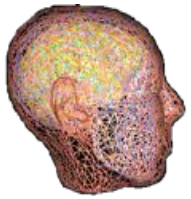
  is required to interpret the scalp topographies
- Interpreting scalp topographies means

  inverse modelling or "**source estimation**"
- Mathematical techniques are available

  to aid in interpreting scalp topographies

  → These are **inverse source models**



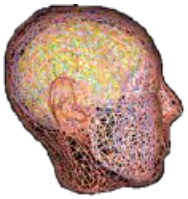


Summary II

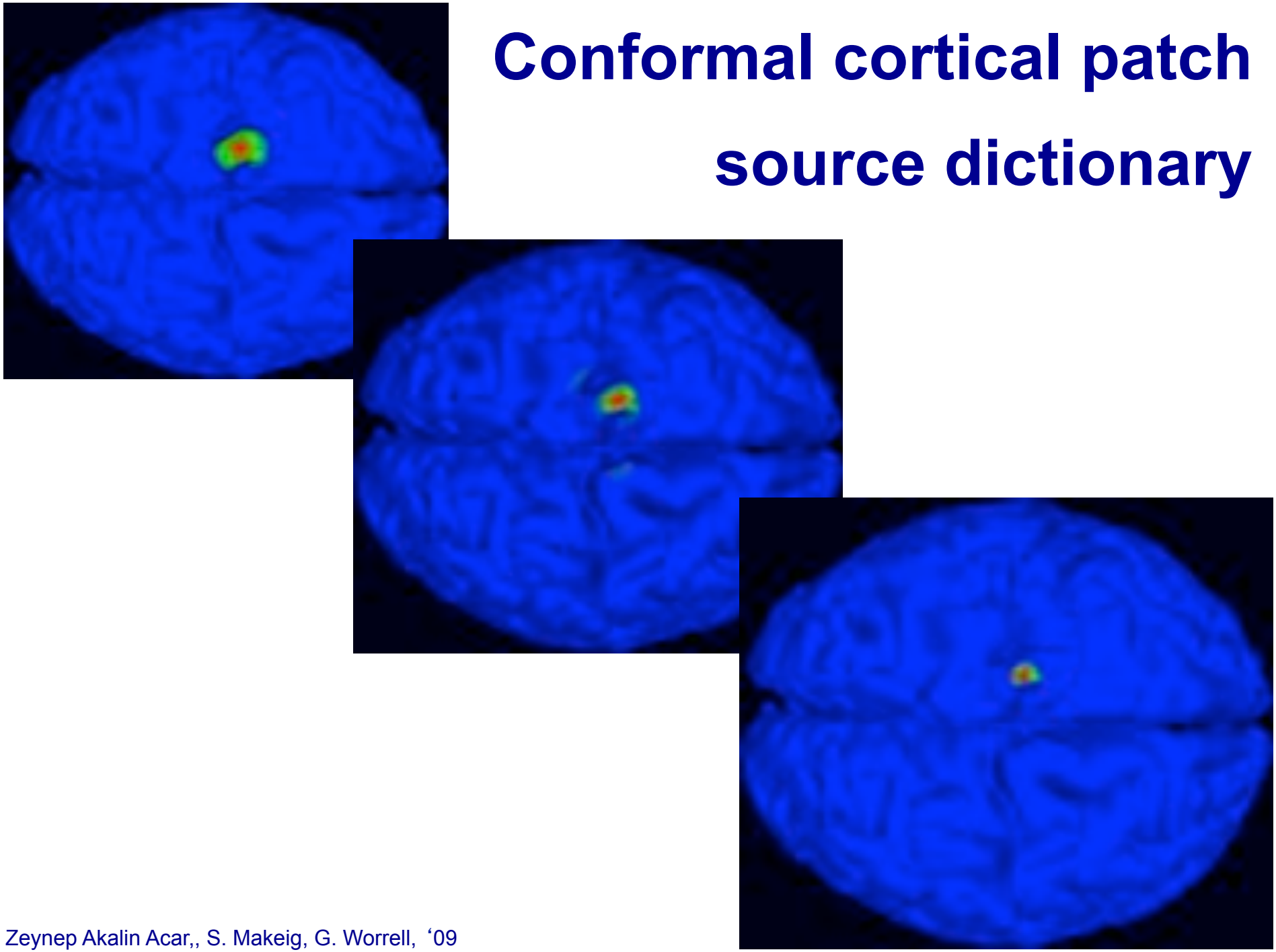
- **Inverse modeling**
  - Model assumptions for the (volume conductor) head
  - Model assumptions for source (equiv. dipole source)
  - Additional assumptions on source location/orientation
- **Single point-like sources**
- **Multiple point-like sources**
- **Distributed sources**
  - Different mathematical solutions
    - Dipole fitting (linear and nonlinear)
    - Linear estimation (regularized)
- **For EEG inverse modeling, conductivity is key!**

R. Oostenveld & S. Makeig, 2010

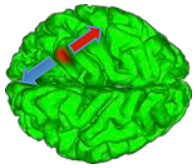
Solving inverse problems → NIST



Conformal cortical patch source dictionary

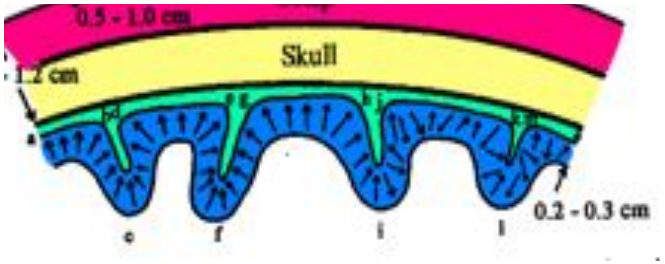


Zeynep Akalin Acar,, S. Makeig, G. Worrell, ‘09



Conformal cortical patch basis model

→ Model a source as a sum of overlapping patches

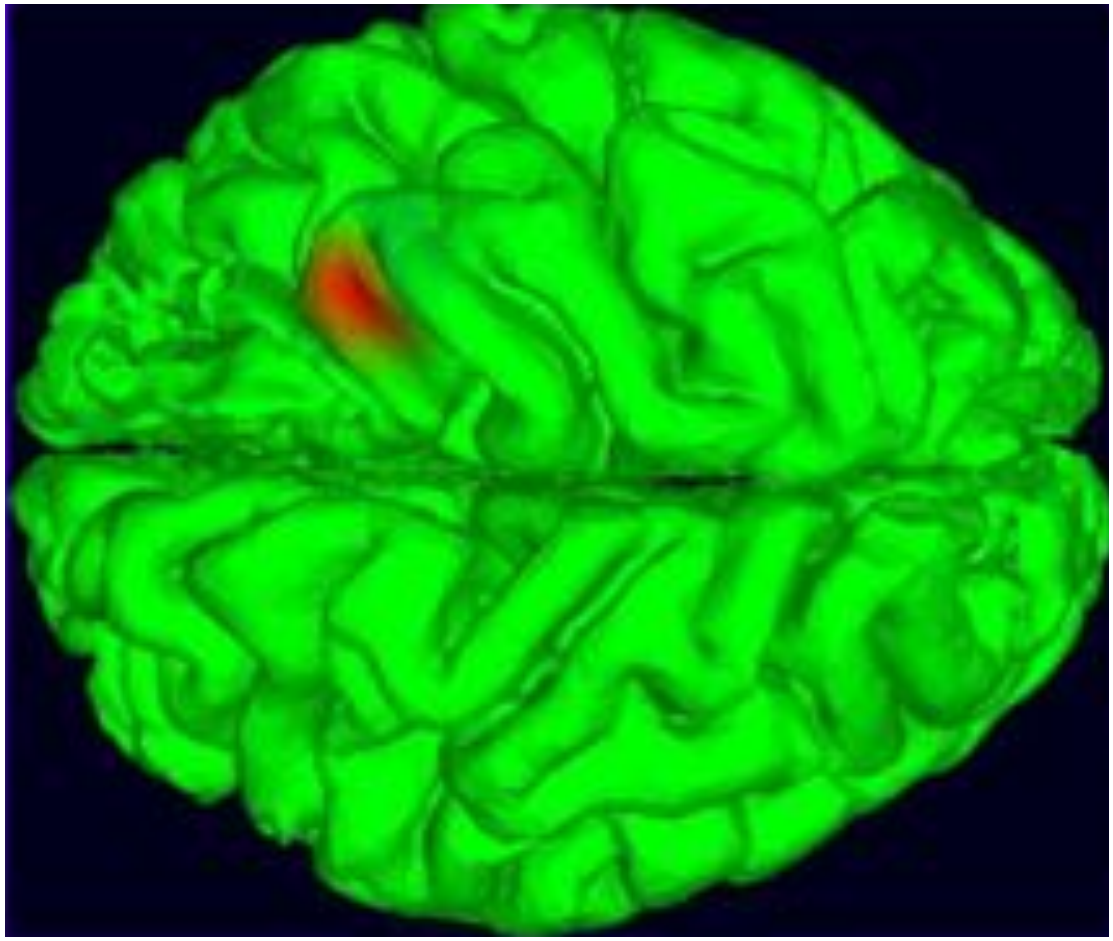


Sparse

Compact

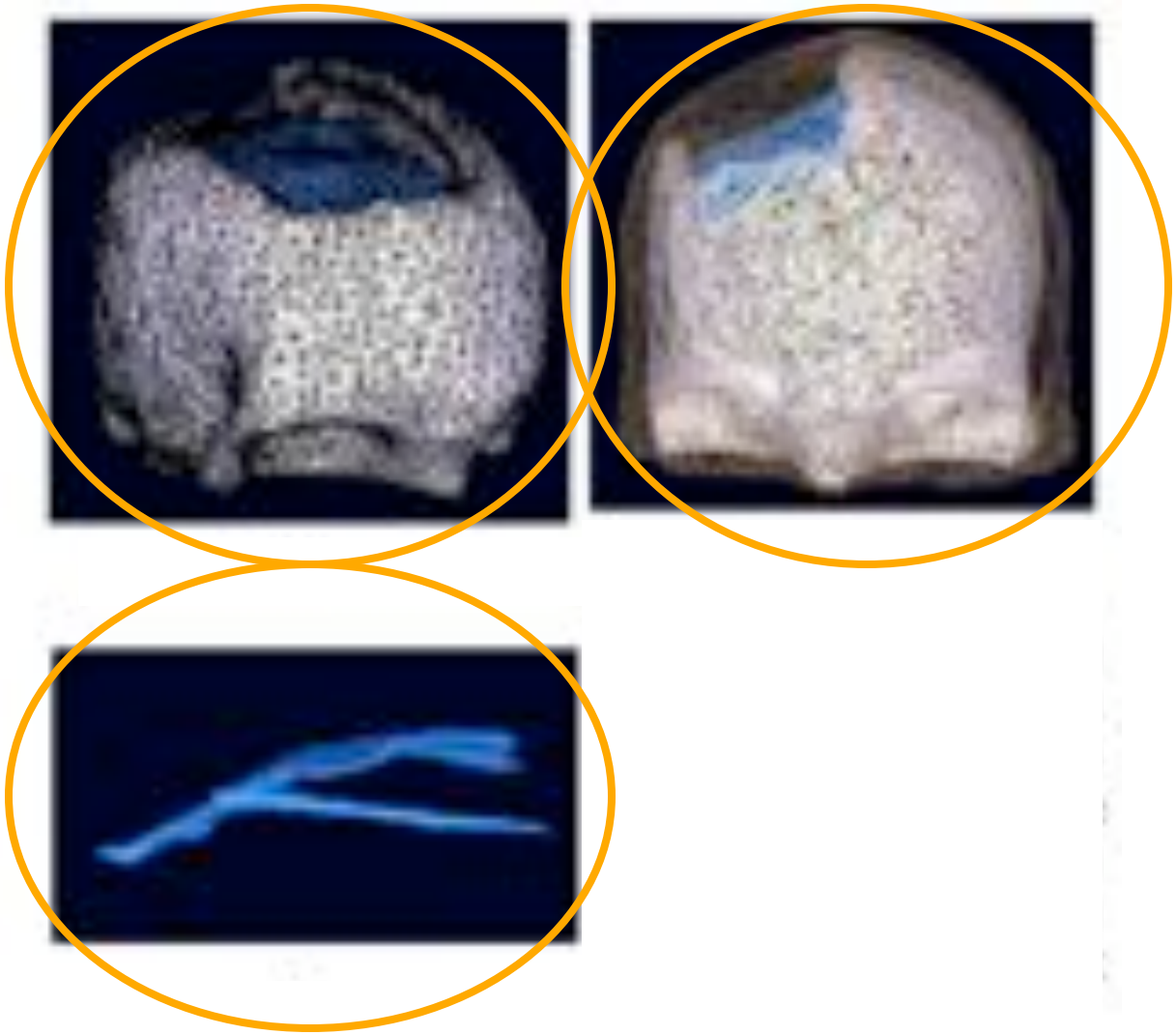
Smooth

- Cheng Cao 2011

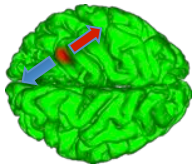


Z. Akalin Acar, 2010

Electromagnetic source localization using realistic head models – an intracranial monitoring model



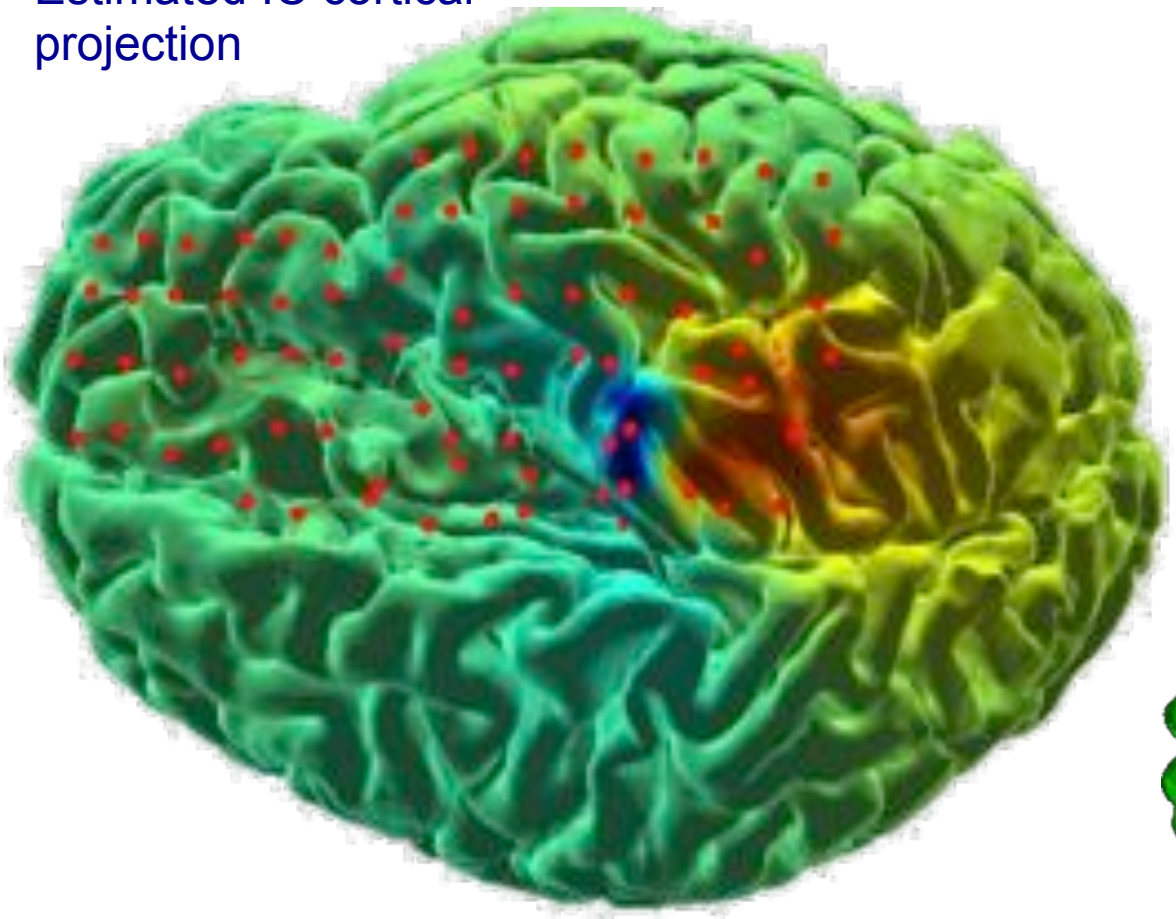
Zeynep Akalin Acar,, S. Makeig, G. Worrell, ‘09



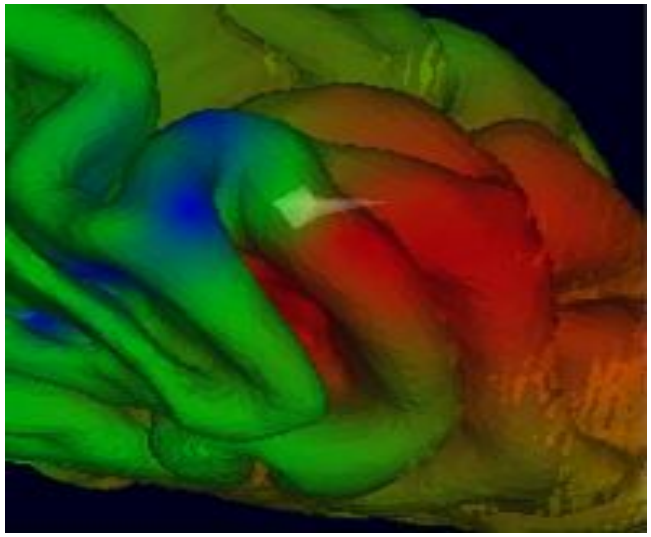
Source models

of an IC from an intracranial data set

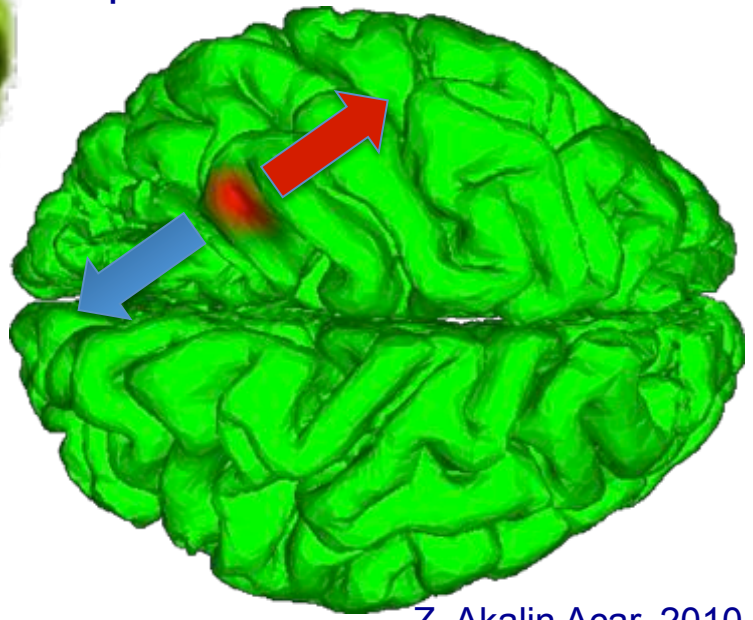
Estimated IC cortical projection



Equivalent Current Dipole Model



Sparse Patch Basis Model



Z. Akalin Acar, 2010

NFT

Neuroelectromagnetic Forward Head Modeling Toolbox

Zeynep Akalin Acar