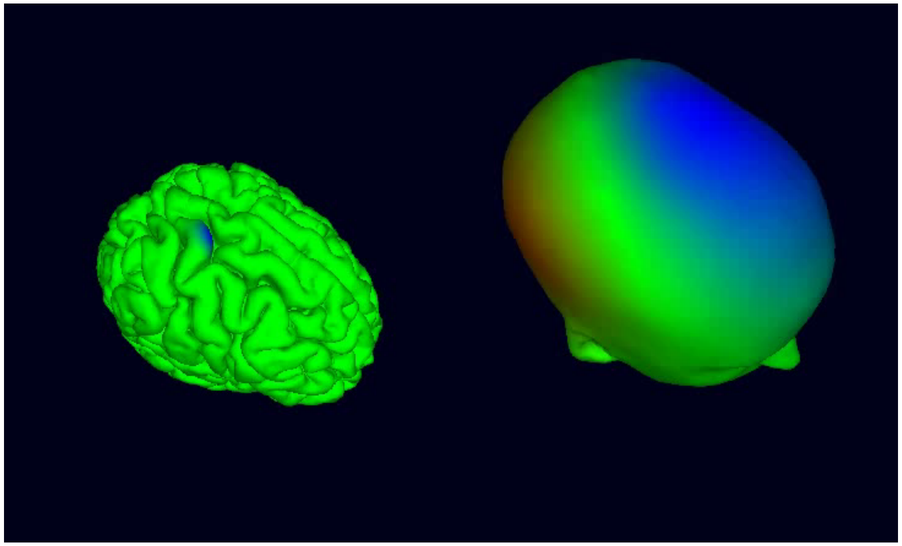


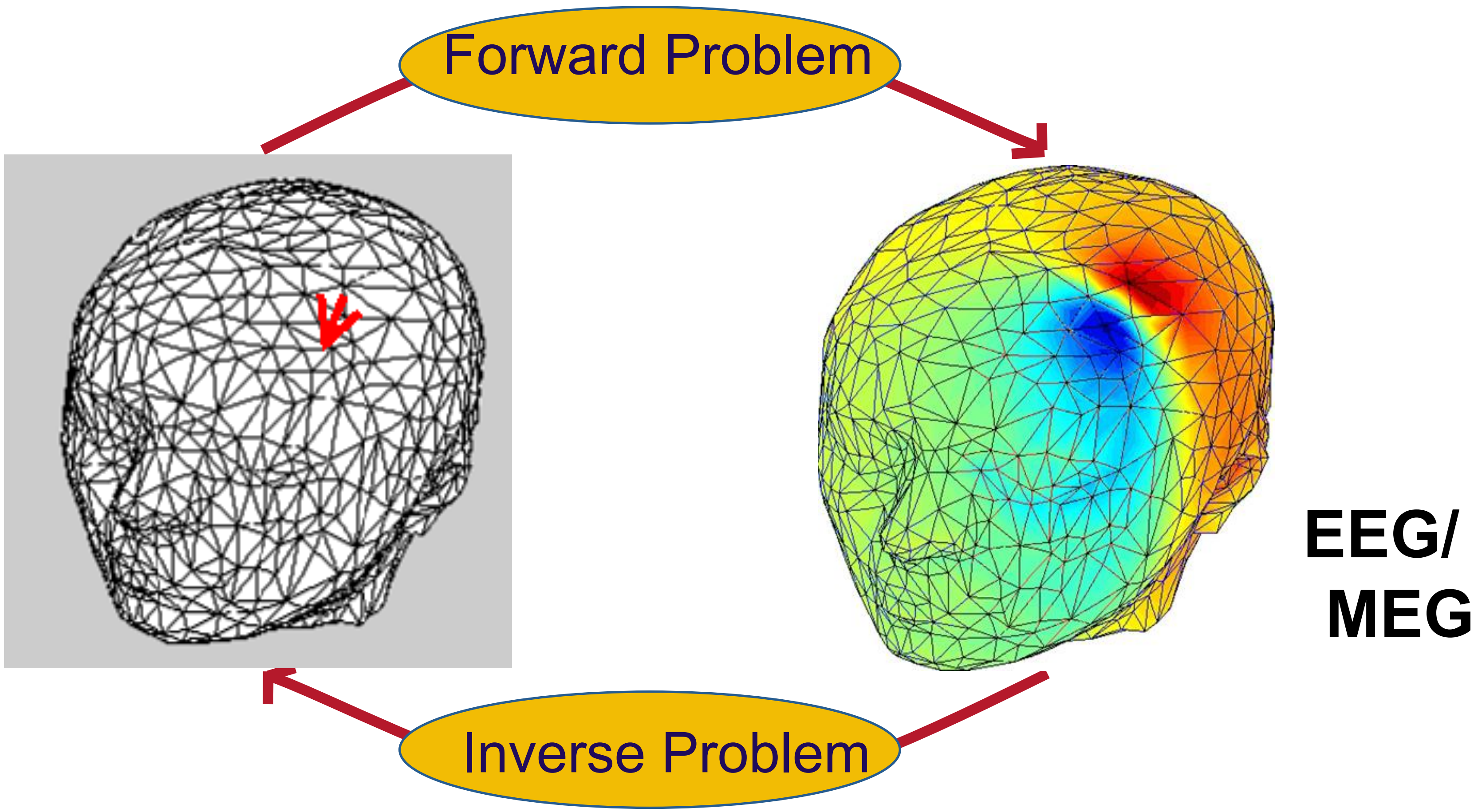
Forward Problem of EEG

Zeynep AKALIN ACAR

14th EEGLAB Workshop, Mallorca

September, 2011

Forward and inverse problem

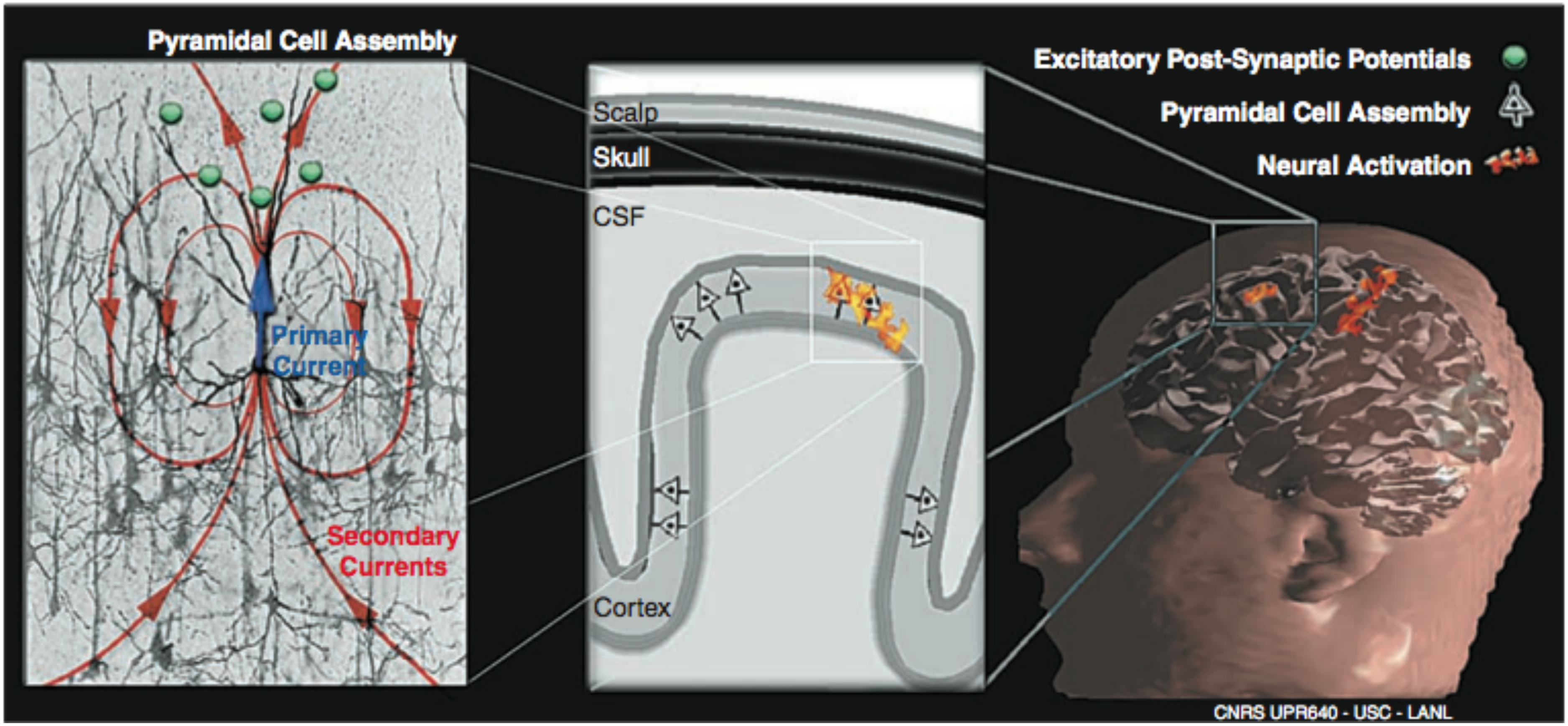


= 1000s of FP solution

Components of source localization

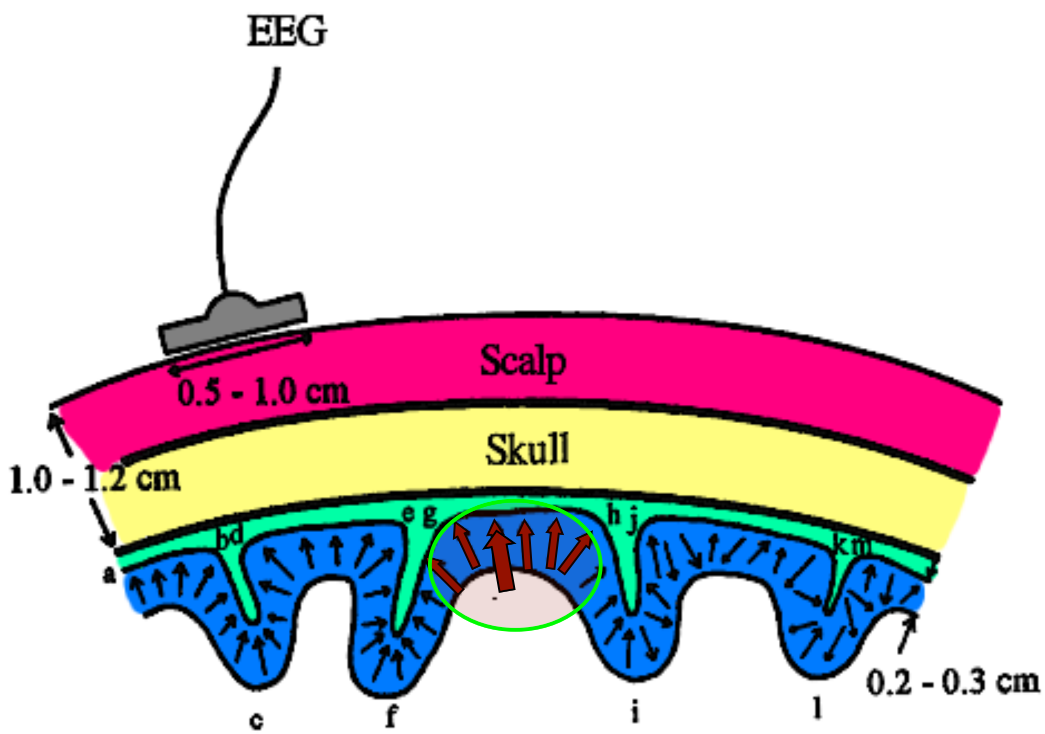
- Numerical head model
- Choice of numerical method
- Conductivity distribution in the head
- Co-registration of EEG electrodes with MRI
- Number/position of electrodes on the head surface
- A priori information of source space
- Processing of EEG signals
- Choice of inverse model

Generators of EEG

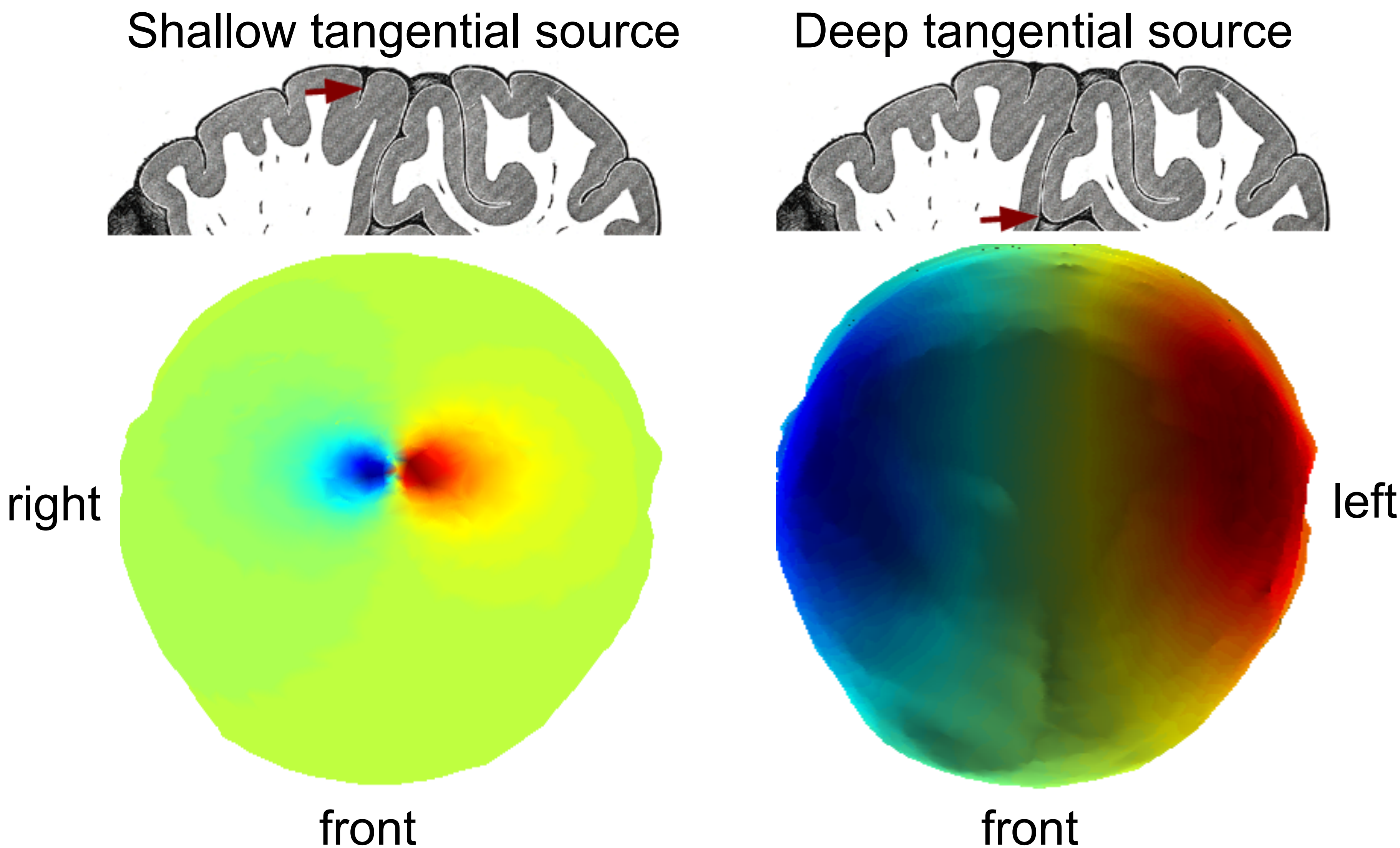


Baillet et al, 2001

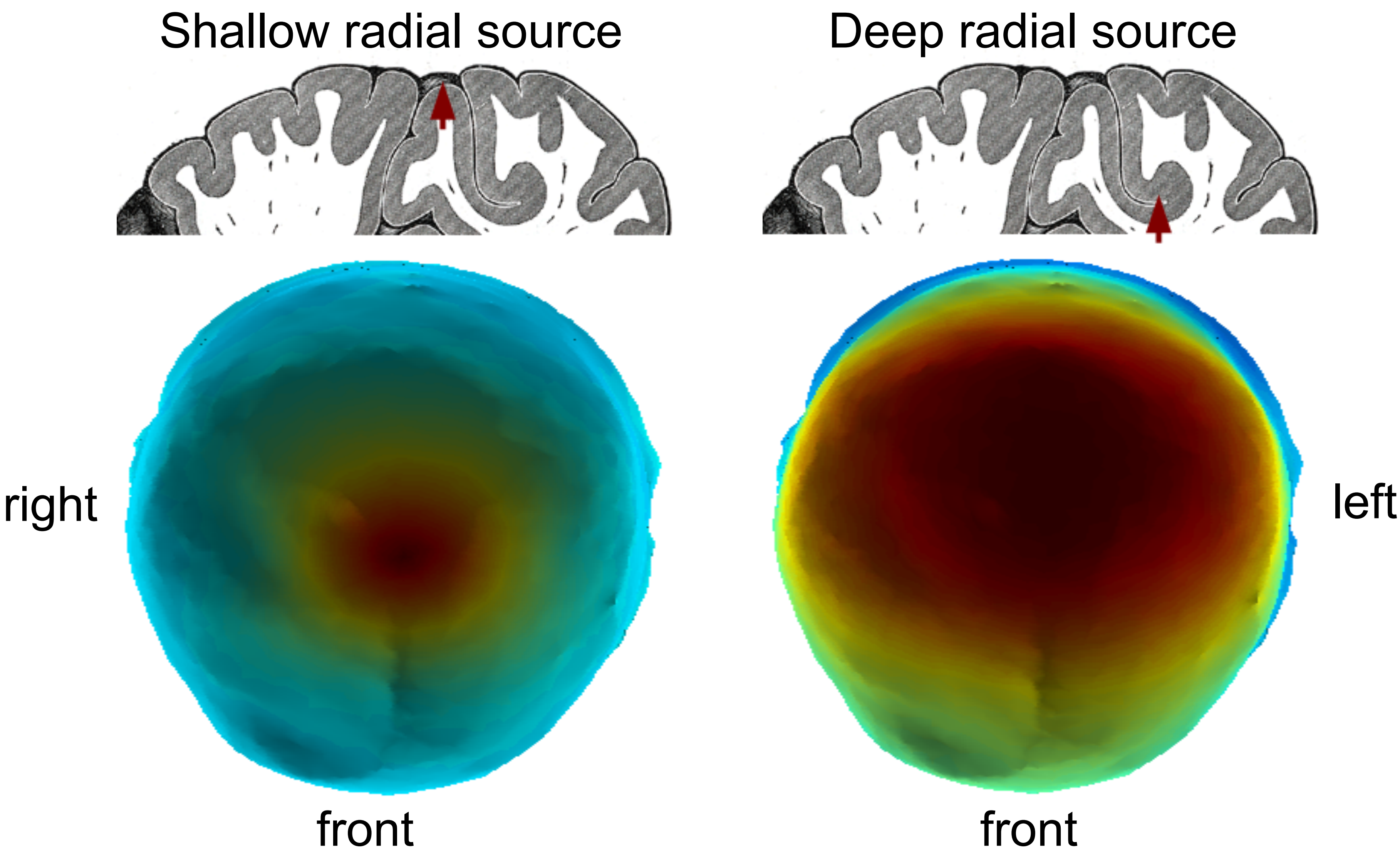
Equivalent cortical dipoles



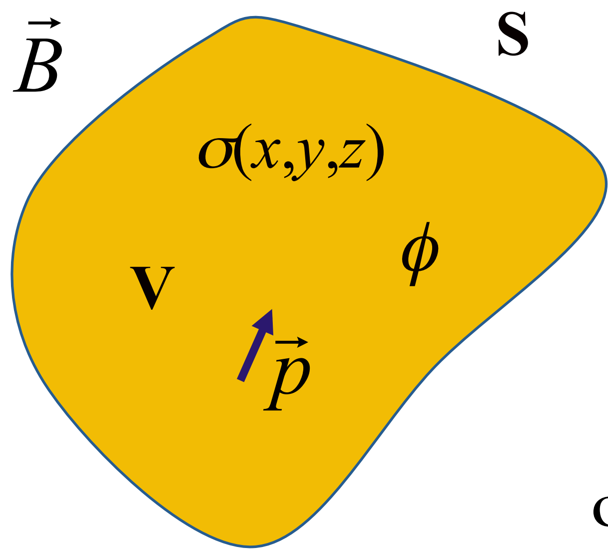
Potential fields on the scalp



Potential fields on the scalp



Formulation of the FP



$$\nabla \cdot \left(\sigma \nabla \Phi\right) = -\nabla \cdot J^{P} \quad \text{inside } V$$

$$\sigma \frac{\partial \Phi}{\partial n} = 0 \qquad \text{on } S$$

$\sigma(x,y,z)$: conductivity distribution

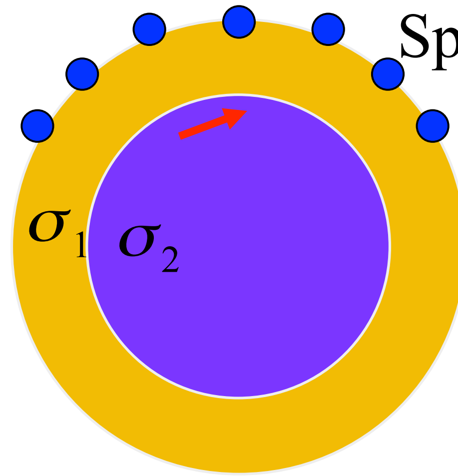
$\vec{p}$: current source

Reference: Gulrajani, R., Bioelectricity and biomagnetism

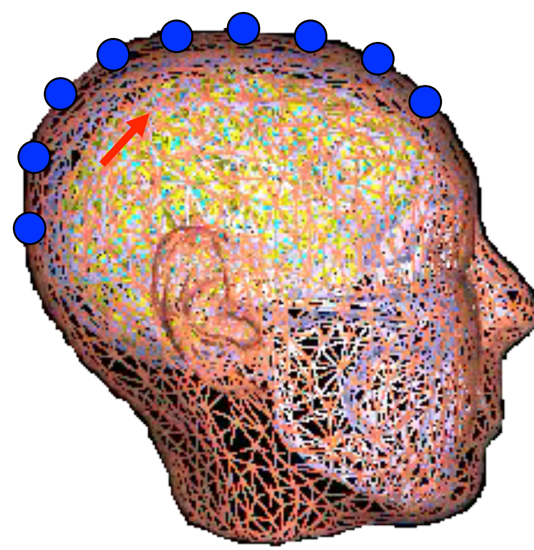
To Solve the Forward Problem

WE NEED

- Head Model
  - Conductivity values
  - Geometry
- Source distribution
  - Magnitude
  - Location
  - Direction
- Field Locations
- Solver



Spherical Model



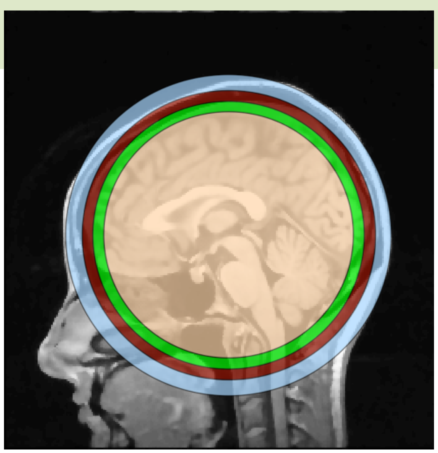
Numerical Model

Head Modeling Comparison

Simple Head Models

- Single layer sphere, spheroid
- 3-4 layer sphere

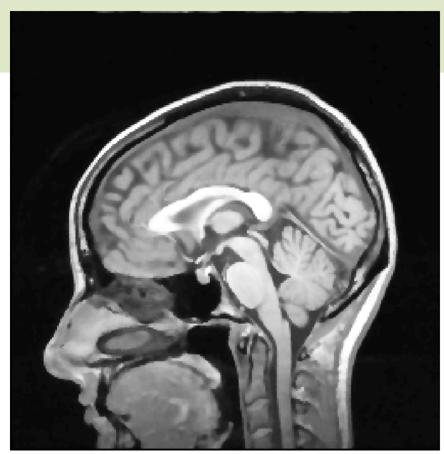
ANALYTICAL SOLVER
Simple, fast, but not accurate

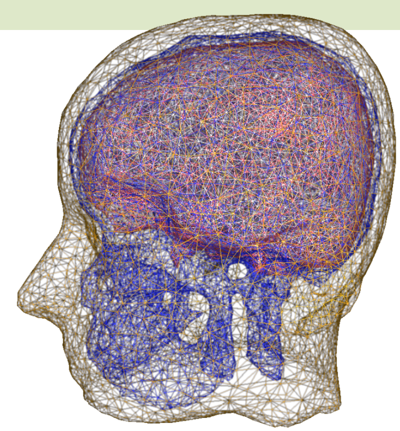


Realistic Head Models

- Boundary Element
- Finite Element
- Finite Difference

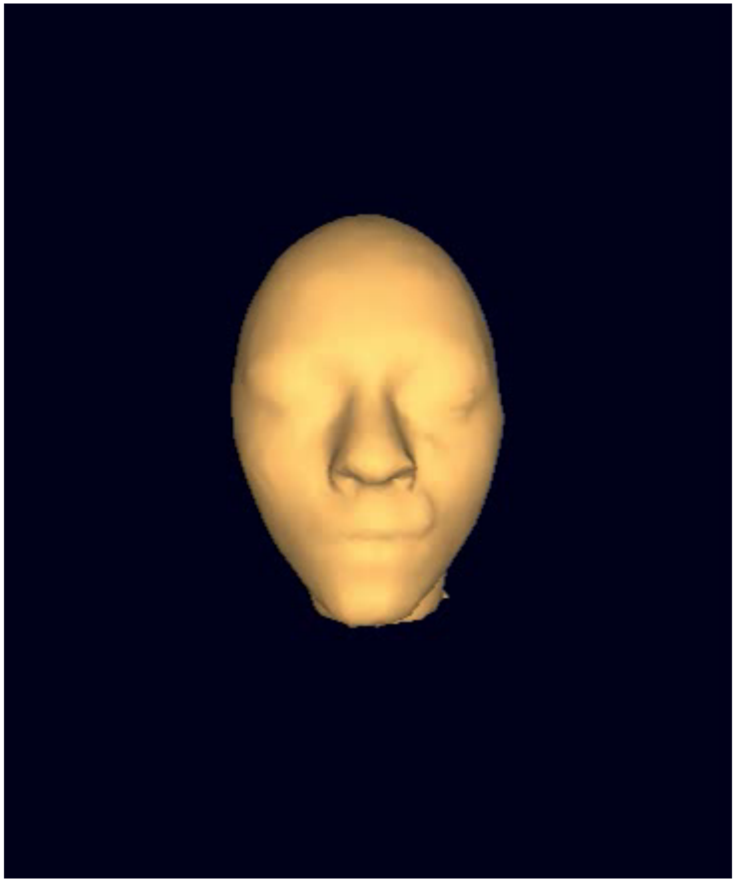
NUMERICAL SOLVER
Represents head shape better, but computationally complex





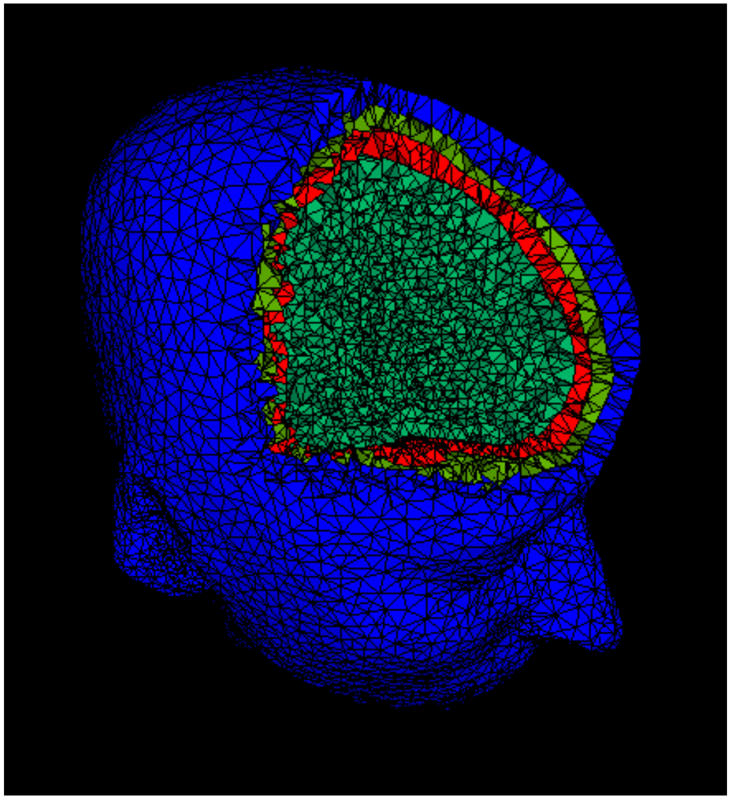
Numerical Head Models

BEM



NFT BEM mesh

FEM

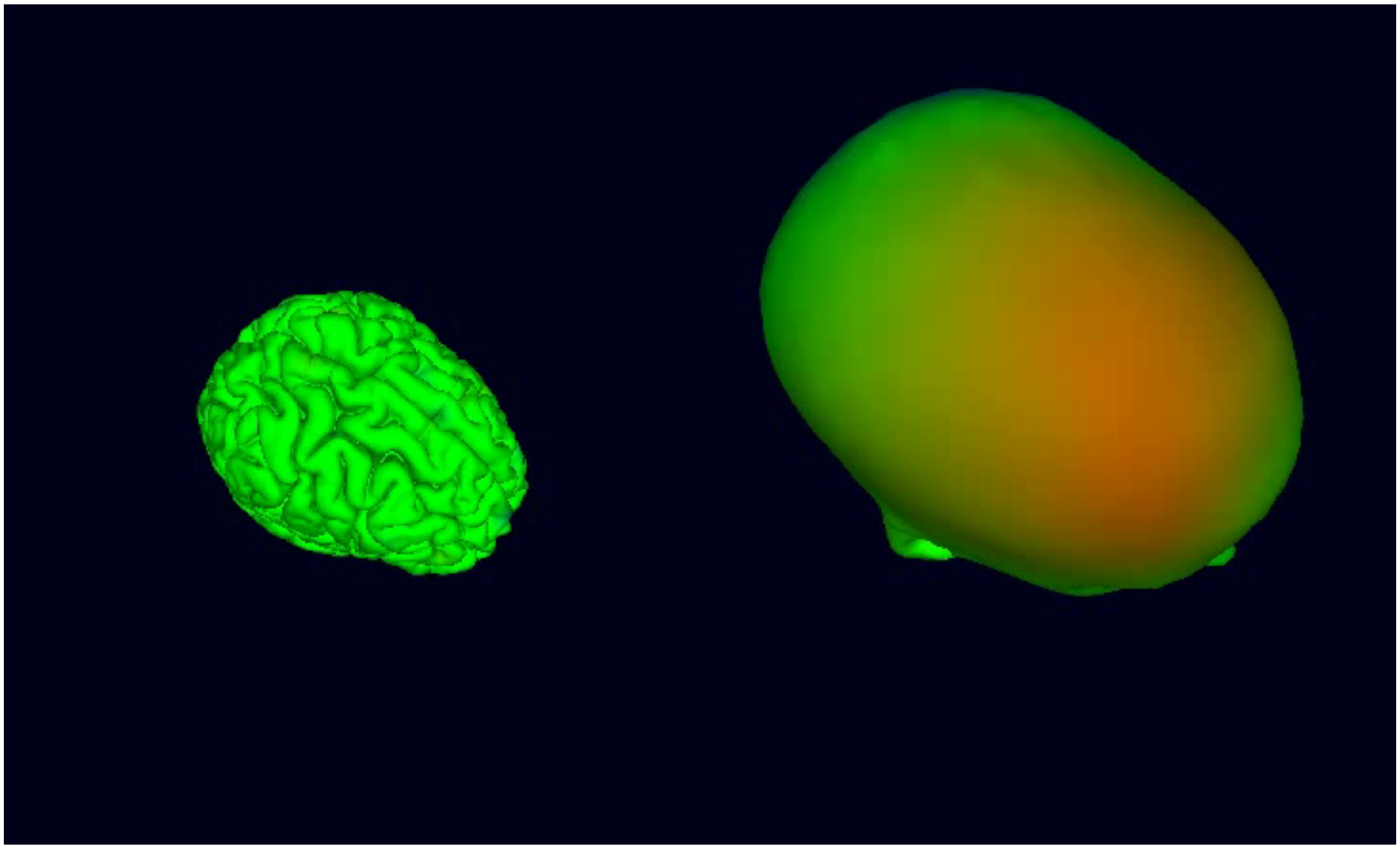


Generated using Tetgen
from NFT BEM mesh

FEM/BEM comparison

	BEM	FEM
Position of computational points	surface	volume
Free choice of computational points	yes	yes
System matrix	full	sparse
Solvers	direct	iterative
Number of compartments	small	large
Requires tesselation	yes	yes
Handles anisotropy	no	yes

Potentials on the scalp



Components of source localization

- Numerical head model
- Choice of numerical method
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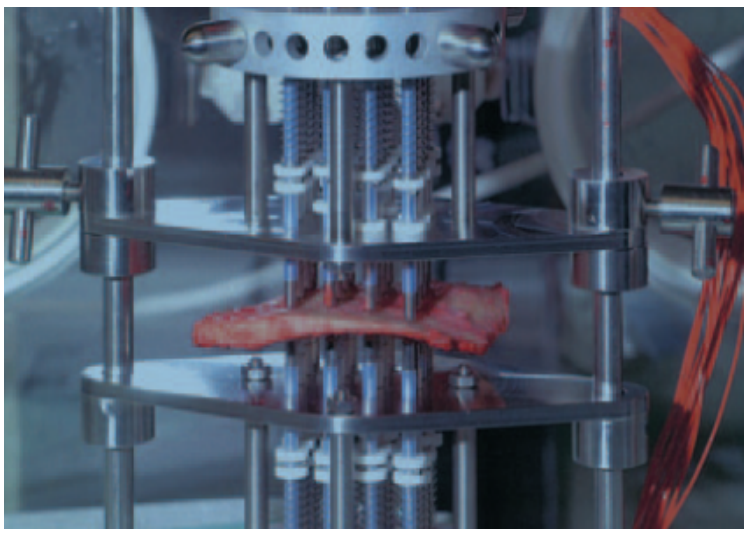
- Processing of EEG signals
- Choice of inverse model

Skull conductivity measurement

Measurement of skull conductivity

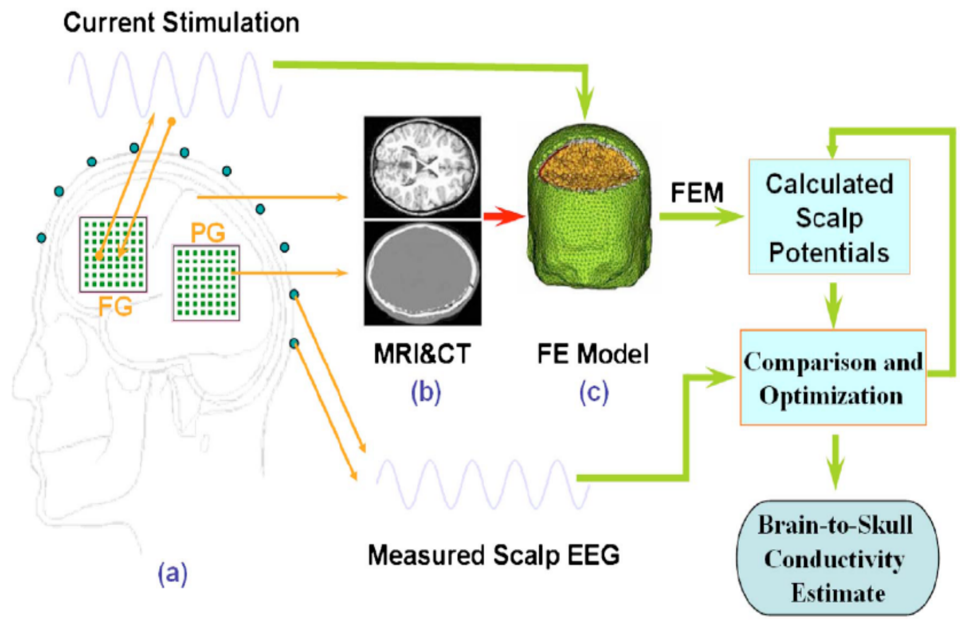
MREIT
Magnetic stimulation
Current injection

In vivo



Hoekama *et al*, 2003

In vitro



He *et al*, 2005

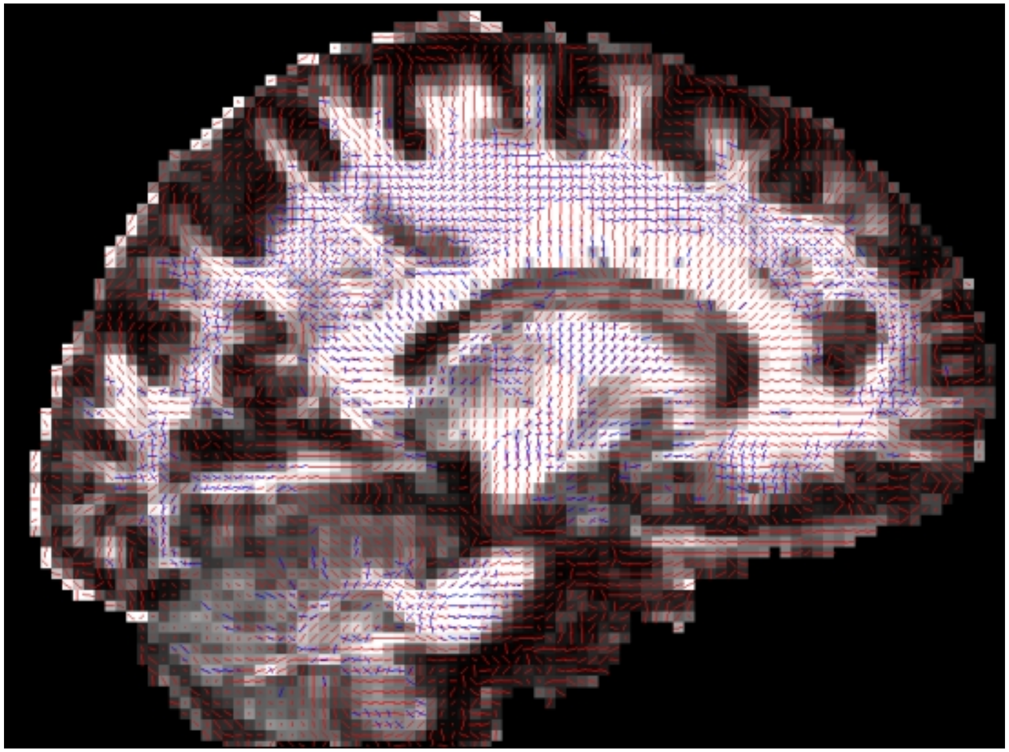
Skull conductivity

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

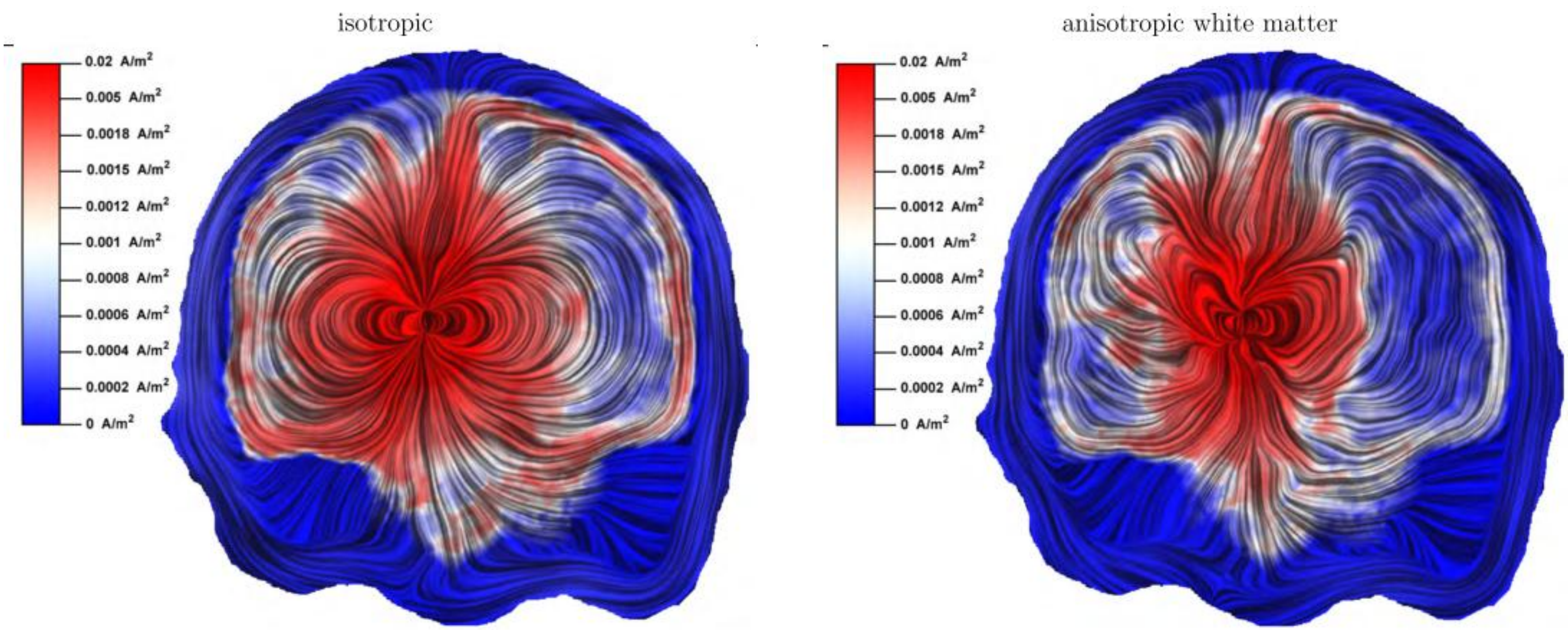
Measurement	Age	σ (mS/m)	ratio
Agar-agar phantom	–	43.6	7.5
Patient 1	11	80.1	4
Patient 2	25	71.2	4.6
Patient 3	36	53.7	6.2
Patient 4	46	34.4	9.7
Patient 5	50	32.0	10.3
Post mortem skull	68	21.4	15.7

Anisotropy

- Directional conductivity for skull and WM.
- WM anisotropy can be obtained from diffusion tensor imaging (DTI).
- WM
  anisotropy
  ratio = 9:1
- Skull
  ratio = 10:1



Anisotropy



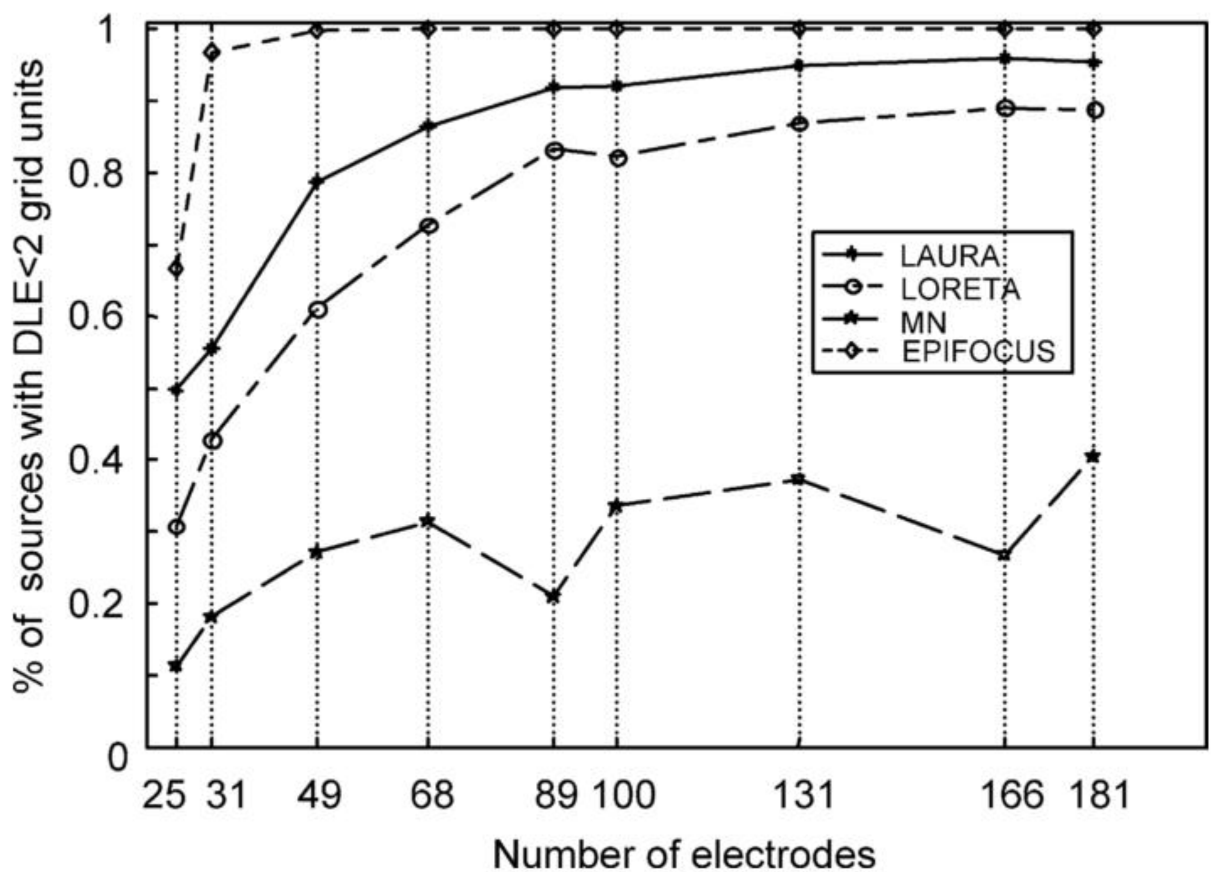
Return currents for a left thalamic source on a coronal cut

Wolters et al, 2006

Components of source localization

- Numerical head model
- Choice of numerical method
- Conductivity distribution in the head
- Co-registration of EEG electrodes with MRI
- Number/position of electrodes on the head surface
- A priori information of source space
- Processing of EEG signals
- Choice of inverse model

Number of electrodes



Michel *et al*, 2004

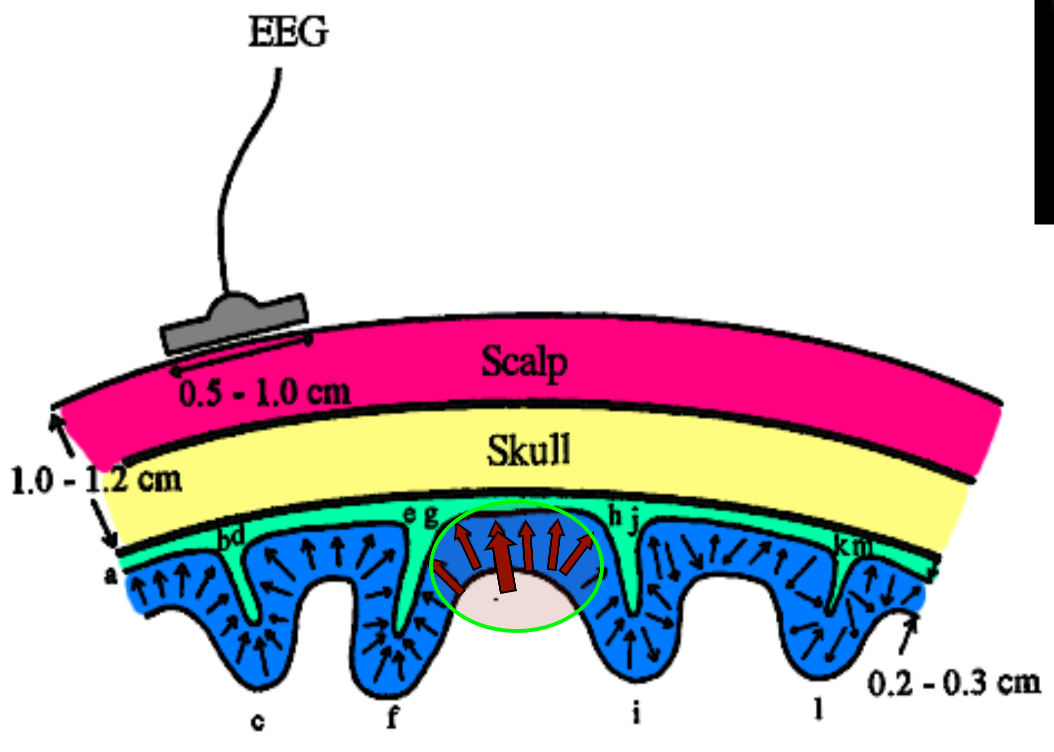
Simulation study, spherical model, 1152 dipoles

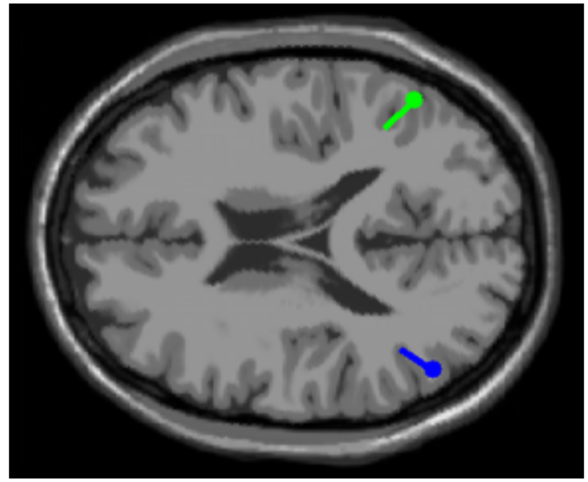
Components of source localization

- Numerical head model
- Choice of numerical method
- Conductivity distribution in the head
- Co-registration of EEG electrodes with MRI
- Number/position of electrodes on the head surface
- A priori information of source space
- Processing of EEG signals
- Choice of inverse model

Source models

Equivalent current dipole



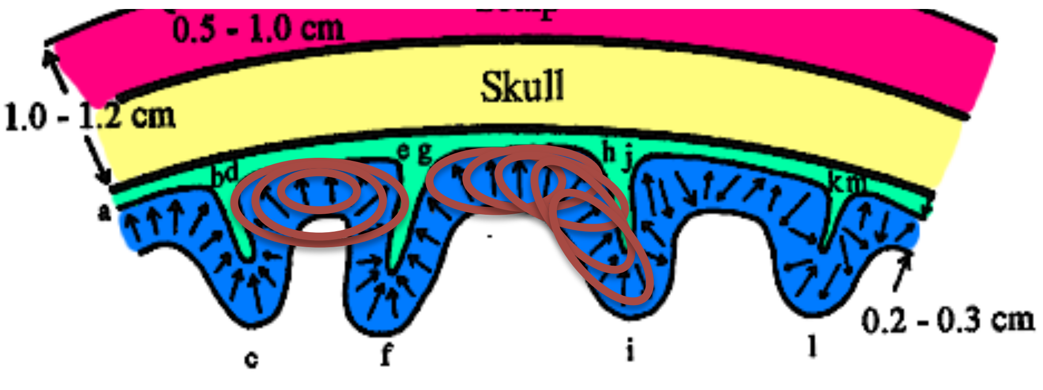


Overdetermined
Nonlinear optimization

Source space:
Brain volume

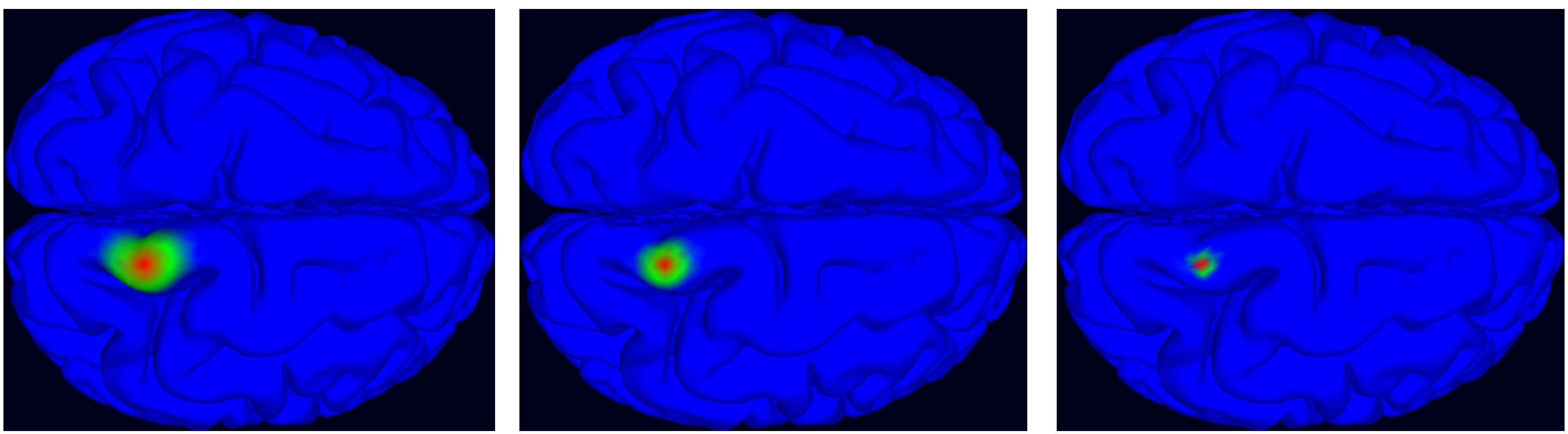
Cortical patch sources

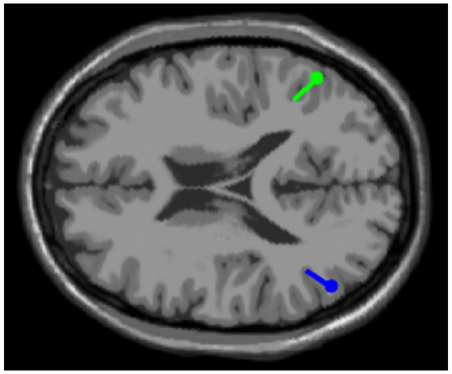
Distributed source models



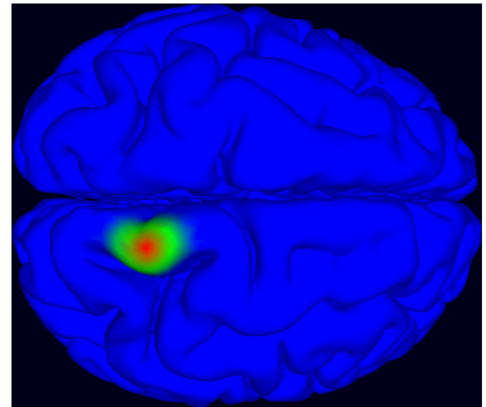
Source space:
Cortical surface

Overlapping patches





Inverse Problem

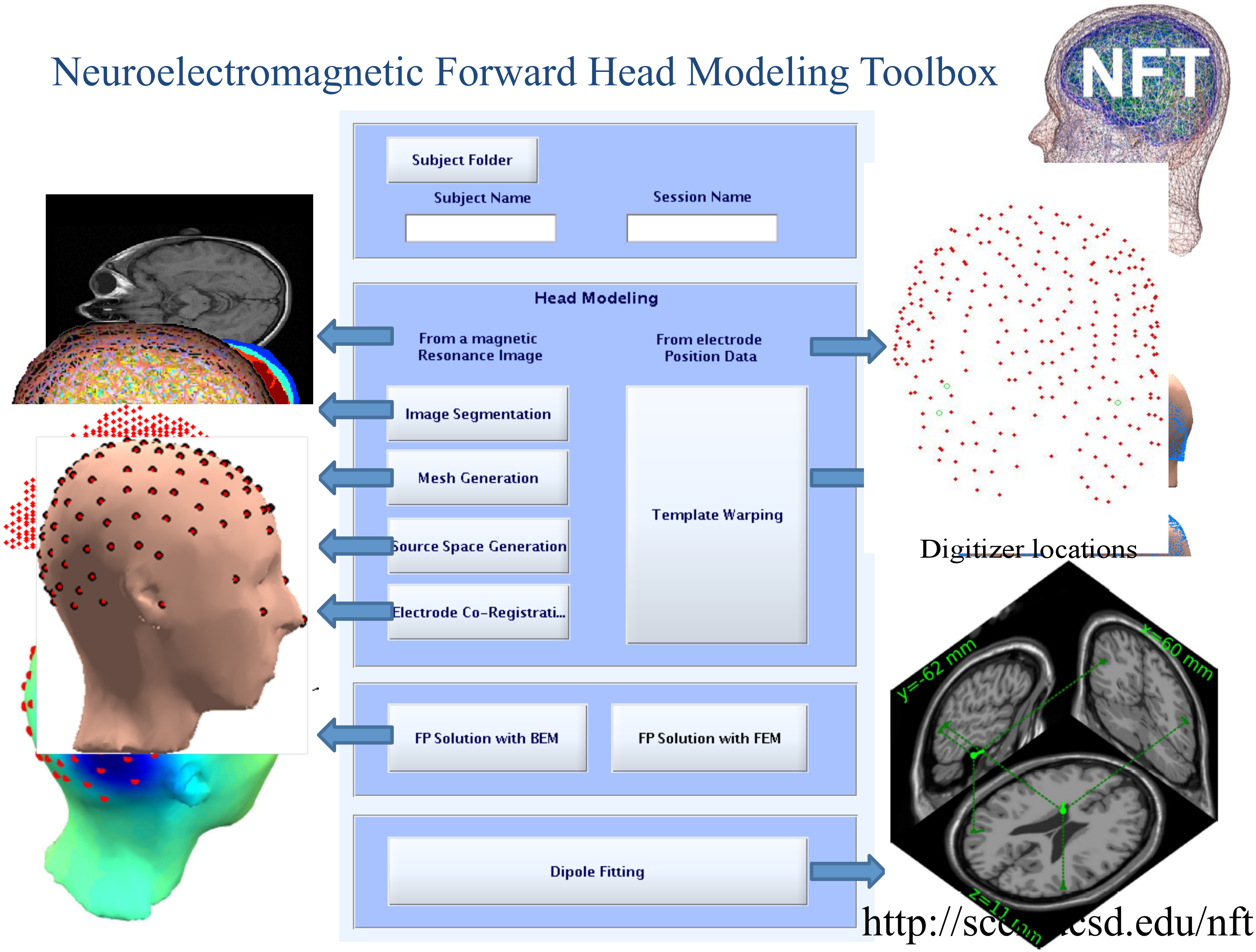


Parametric Methods	**Imaging Methods**
Overdetermined	Underdetermined
Searches for parameters of a number of dipoles	Searches for activation in given locations.
Nonlinear optimization techniques	Linear optimization techniques
May converge to local minima	Needs additional constraints
Non-linear least squares, beamforming, MUSIC, simulated annealing, genetic algorithms, etc.	Bayesian methods, MNE, LORETA, LAURA, etc.

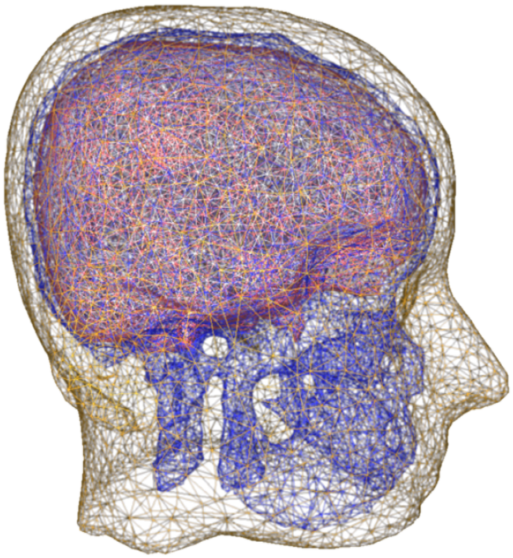
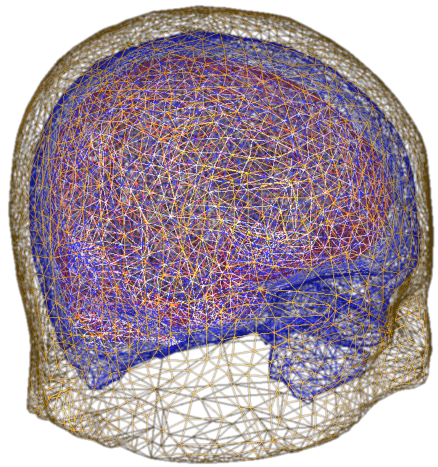
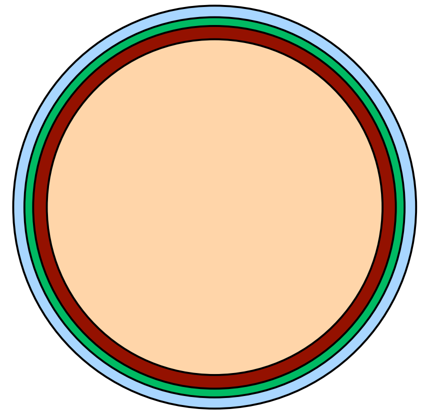
Review articles

- Michel *et al*, EEG source imaging, 2004
- Baillet *et al*, Electromagnetic brain mapping, 2001
- He *et al*, electrophysiological imaging of brain activity and connectivity – challenges and opportunities, 2011.
- Hallez *et al*, Review on solving the forward problem in EEG source analysis, J of Neuroeng and Rehab, 2007.
- Grech *et al*, Review on solving the inverse problem in EEG source analysis, J of Neuroeng and Rehab, 2008.

Neuroelectromagnetic Forward Head Modeling Toolbox



http://sc csd.edu/nft

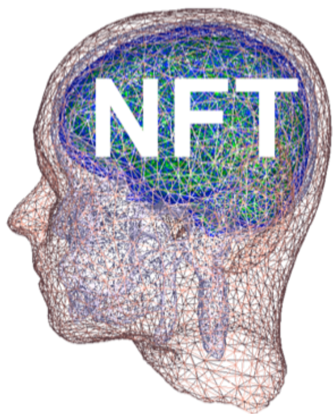
  

Effects of Forward Model Errors on EEG Source Localization

MODELING ERRORS

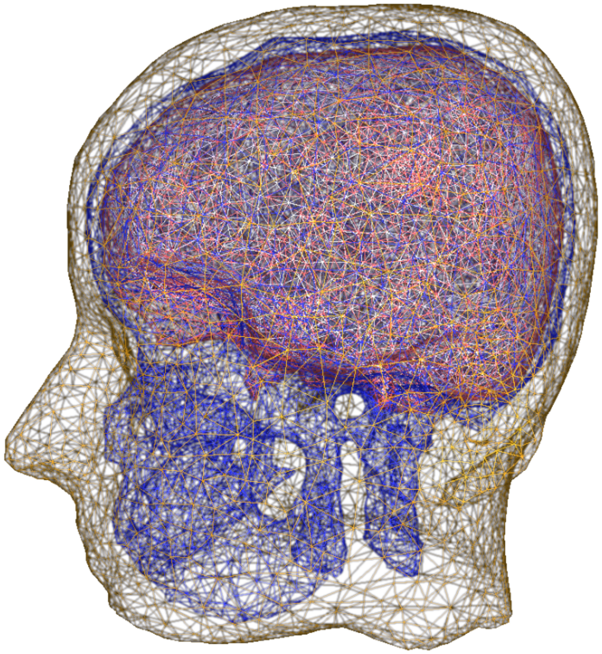
Head Model Generation

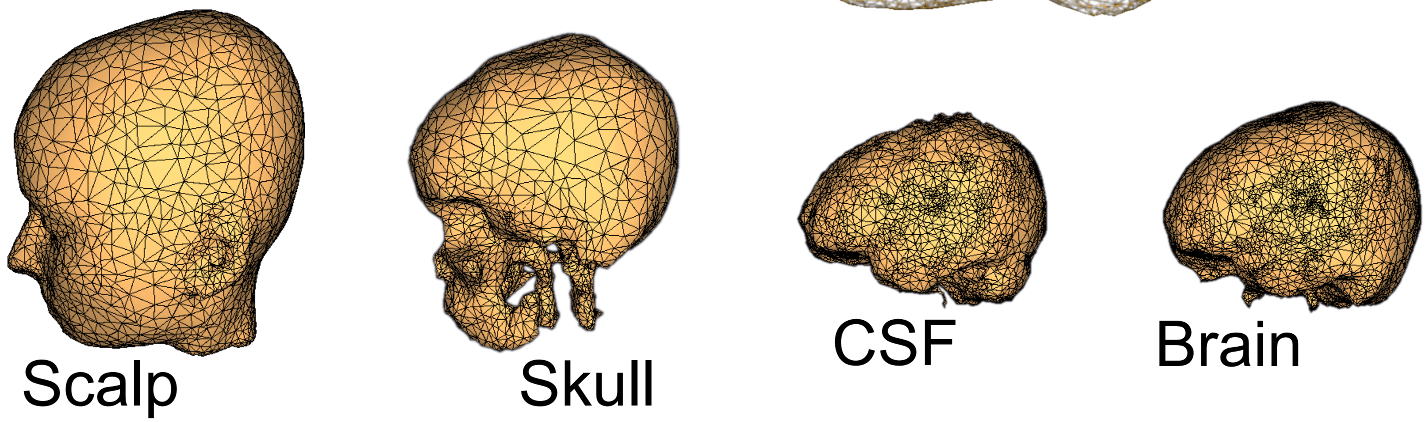
- Reference Head Model
  - From whole head T1 weighted MR of subject
  - 4-layer realistic BEM model
- MNI Head model
  - From the MNI head
  - 3-layer and 4-layer template BEM model
- Warped MNI Head Model
  - Warp MNI template to EEG sensors
- Spherical Head model
  - 4-layer concentric spheres
  - Fitted to EEG sensor locations



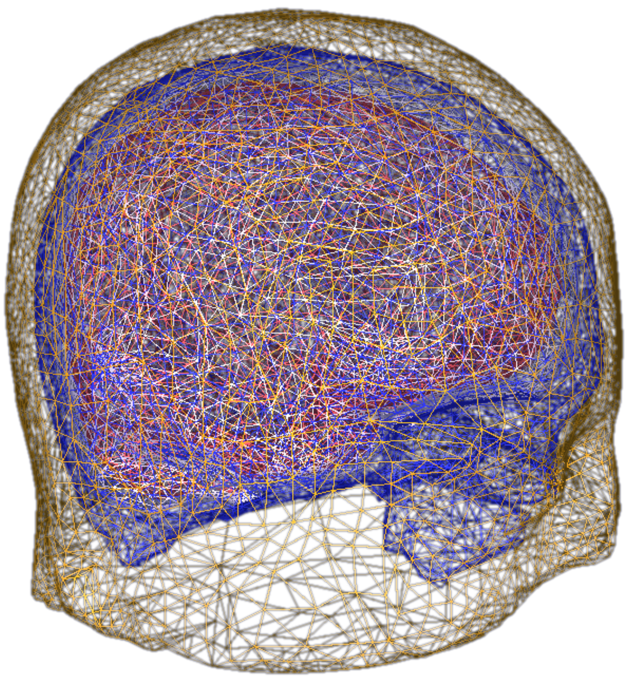
The Reference Head Model

- 18541 nodes
- 37090 elements
  - 6928 Scalp
  - 6914 Skull
  - 11764 CSF
  - 11484 Brain

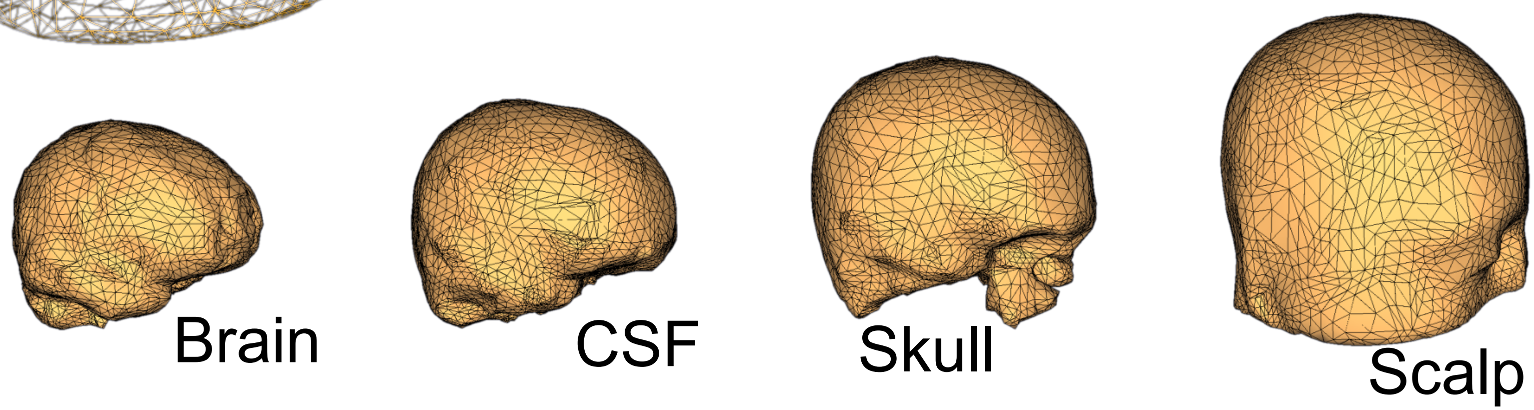




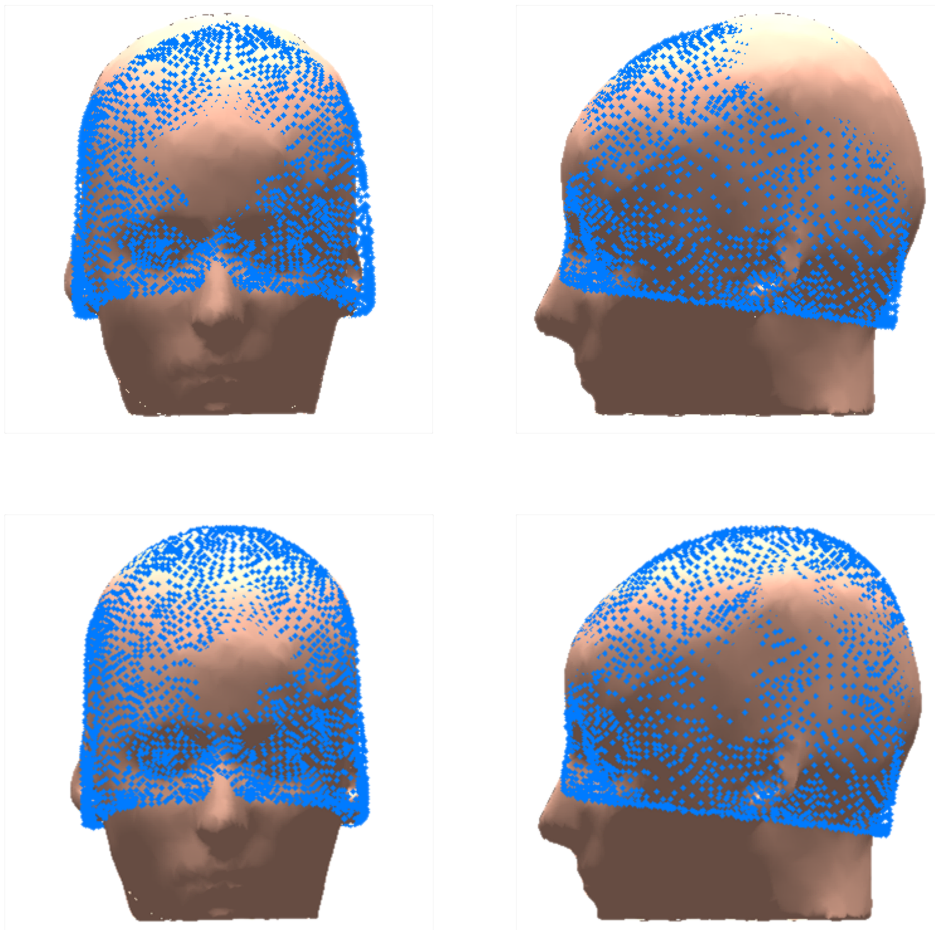
The MNI Head Model



- 4-layer
  - 16856 nodes
  - 33696 elements
- 3-layer
  - 12730 nodes
  - 25448 elements



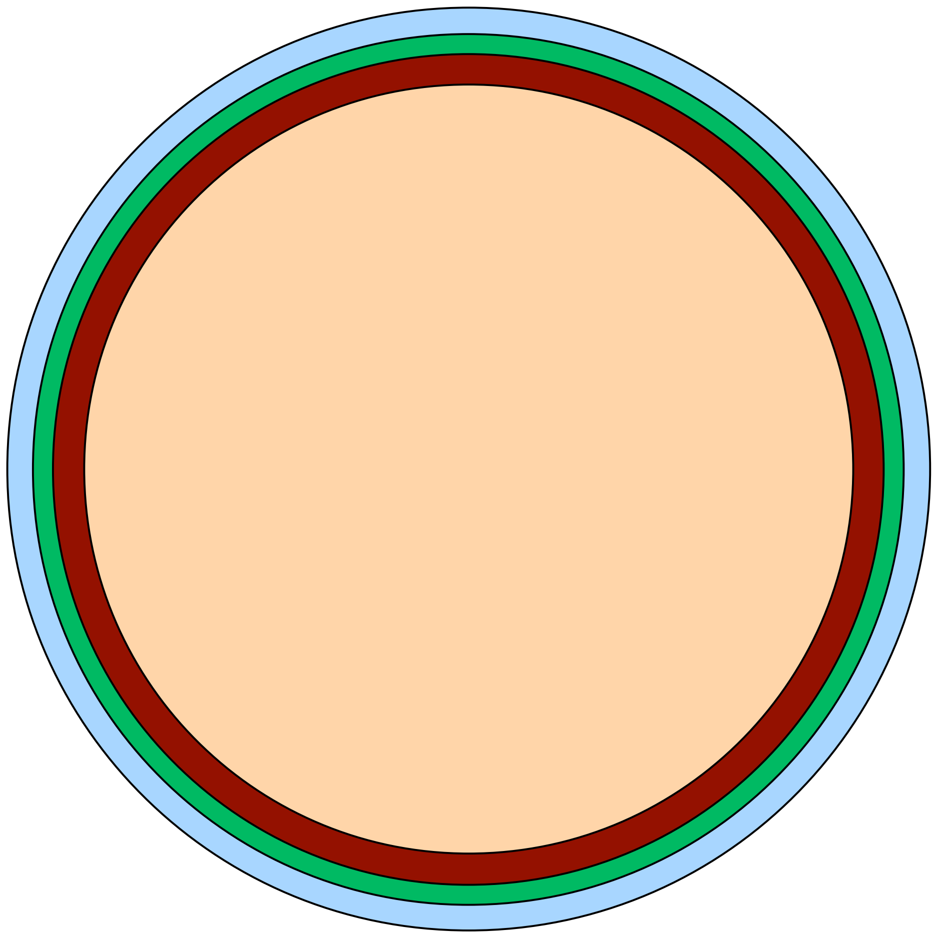
The Warped MNI Head Model



Registered MNI template

Warped MNI mesh

The Spherical Head Model



4-Layer model
Outer layer is fitted to electrode positions

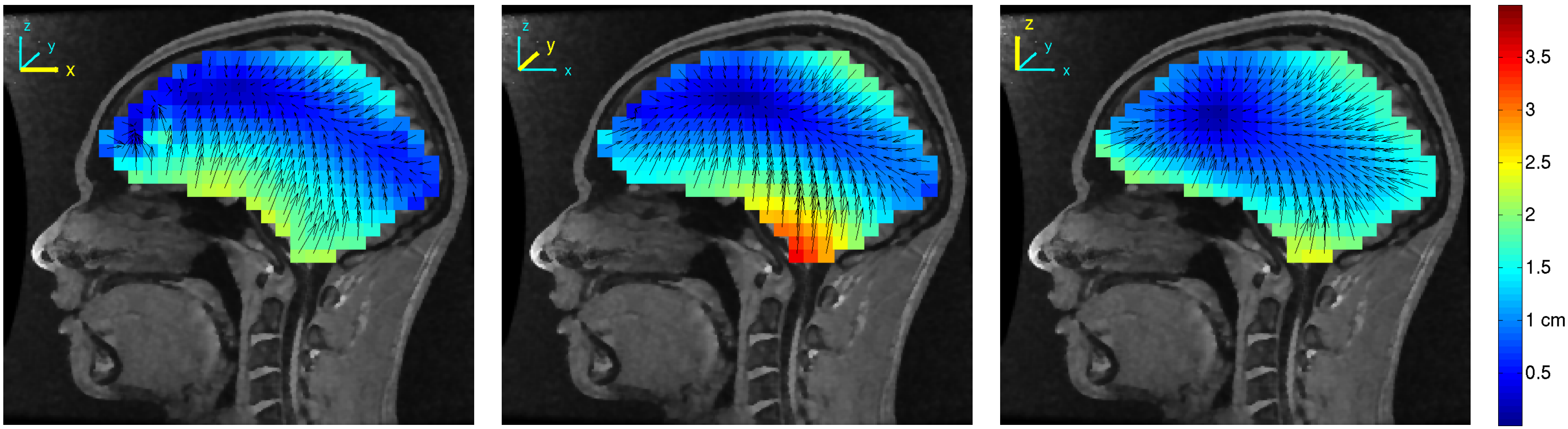
Head Modeling Errors

- Solve FP with reference model
  - 3D grid inside the brain.
  - 3 Orthogonal dipoles at each point
  - ~7000 dipoles total
  - 4 subjects

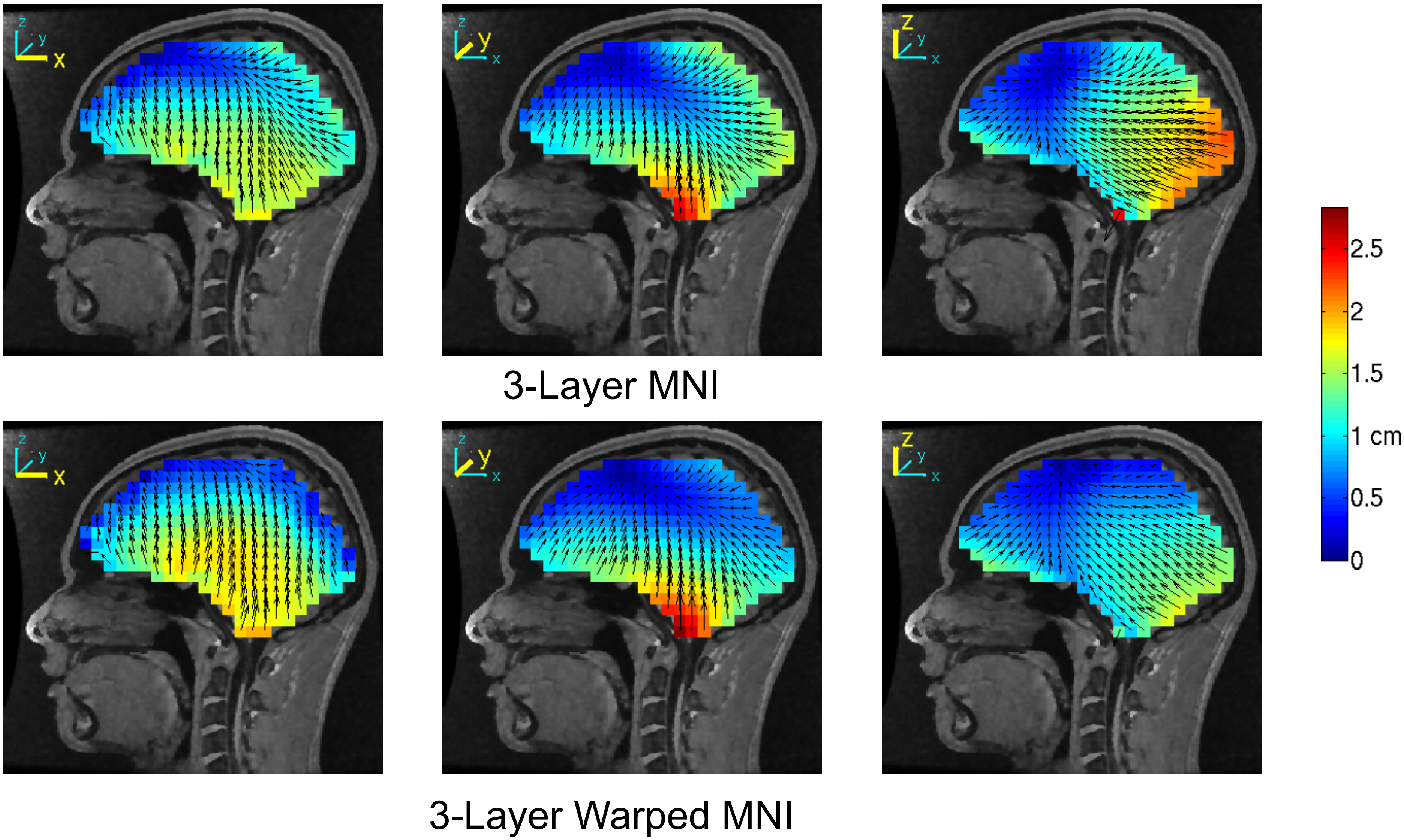
- Localize using other head models
  - Single dipole search.

- Plot location and orientation errors

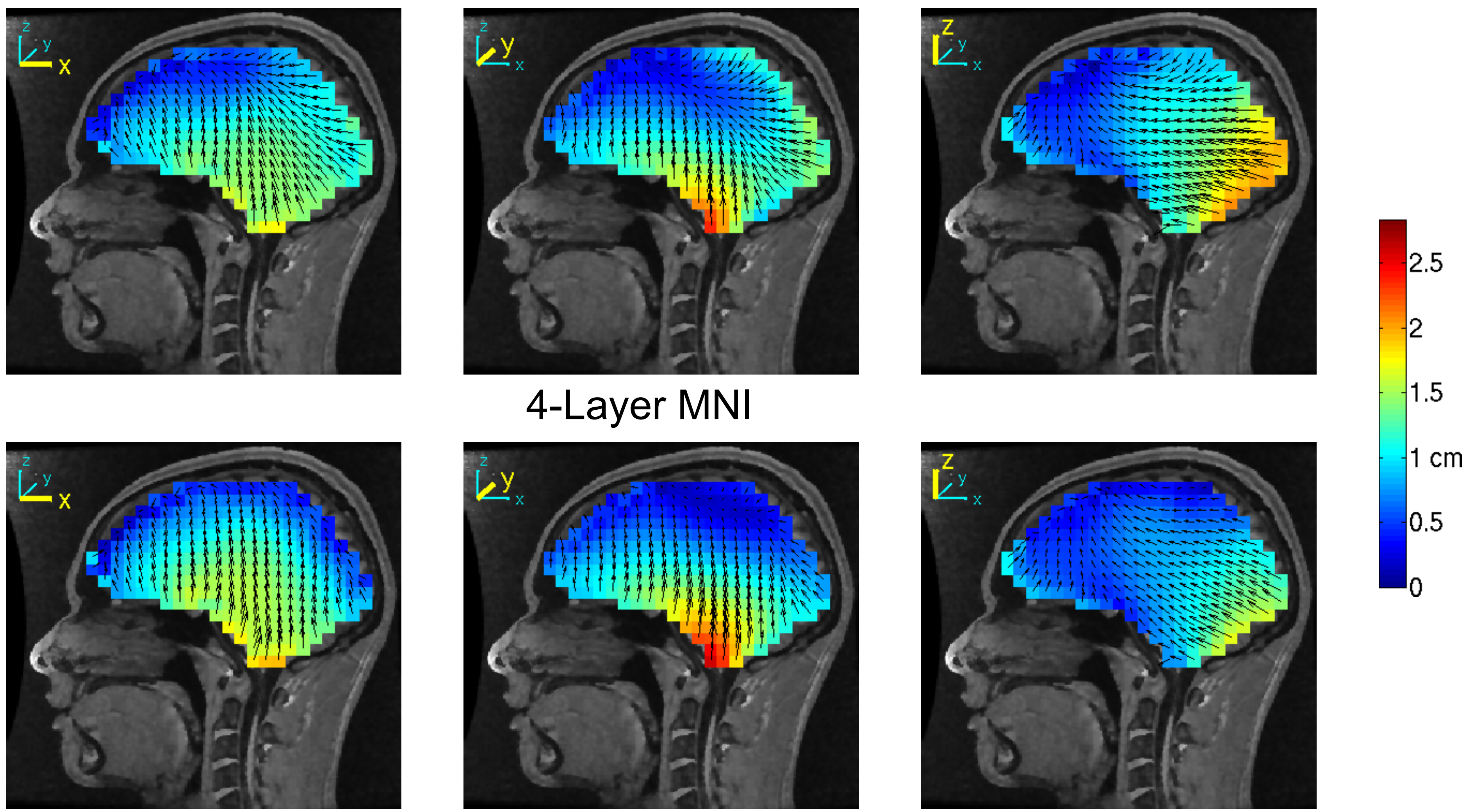
Spherical Model Location Errors



3-Layer MNI Location Errors

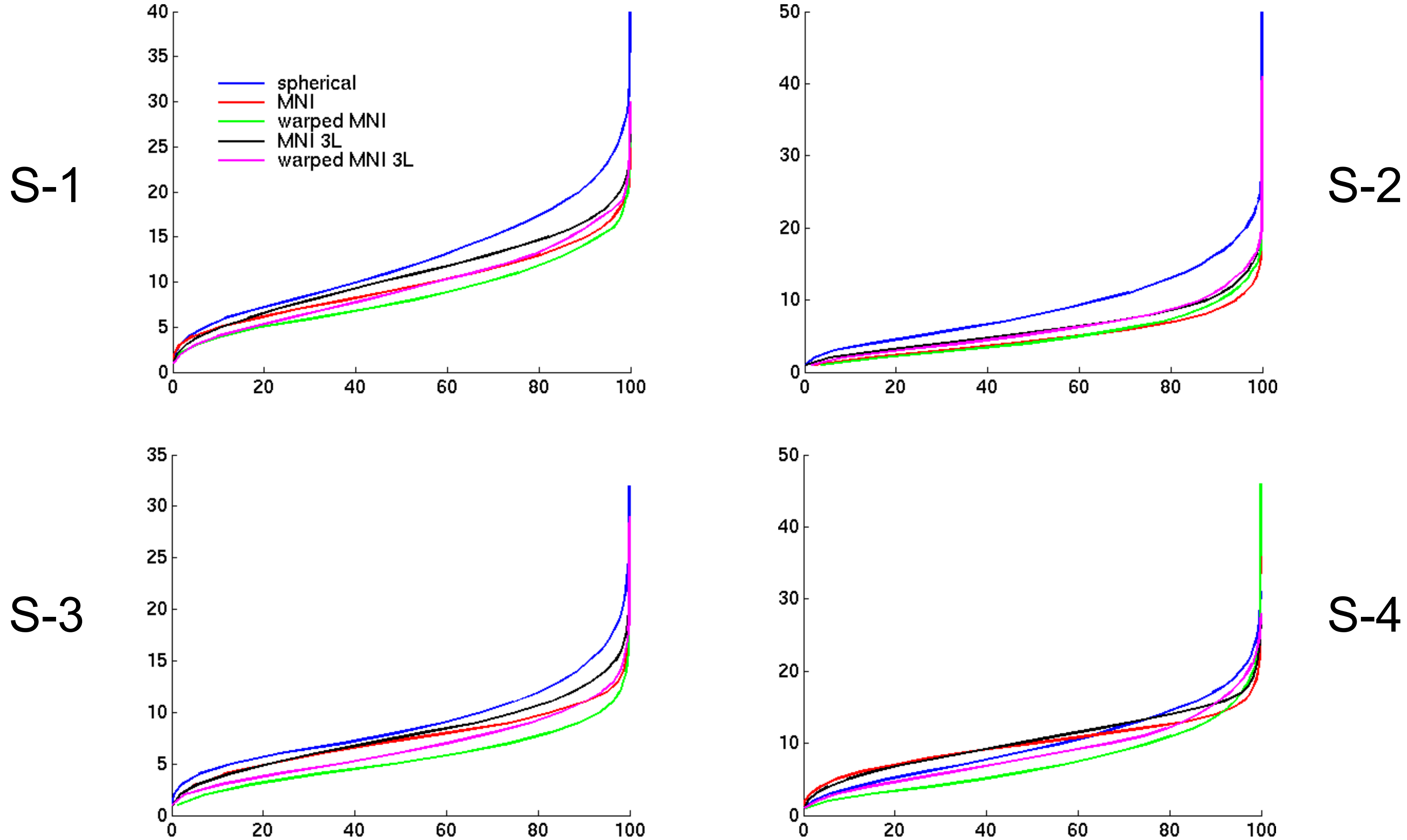


4-Layer MNI Location Errors

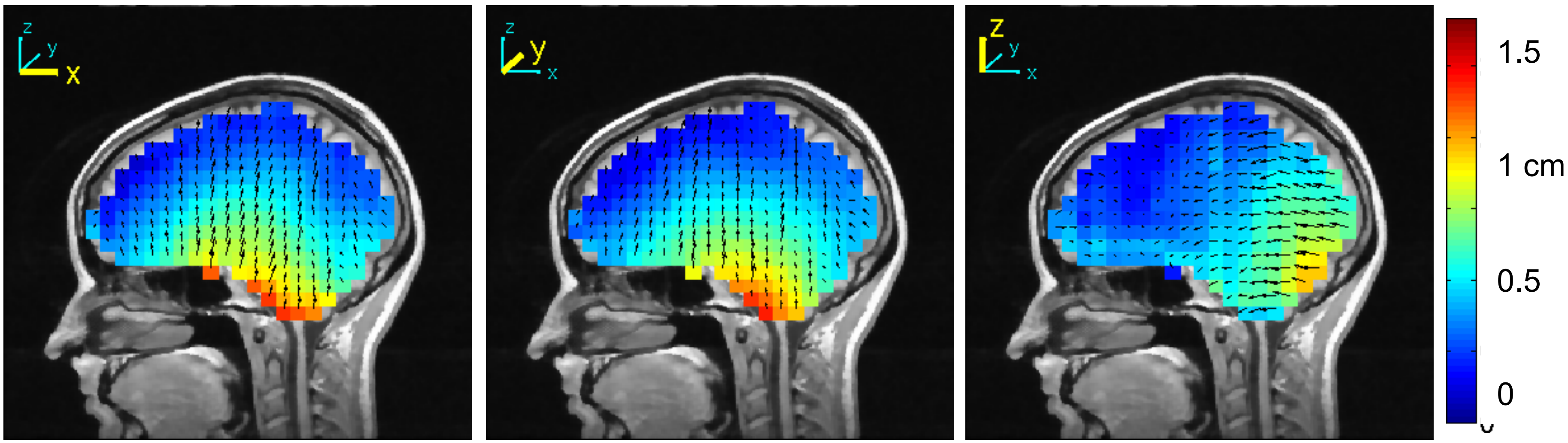


4-Layer Warped MNI

Error Percentiles for Four Subjects



Average Errors for Four Subjects



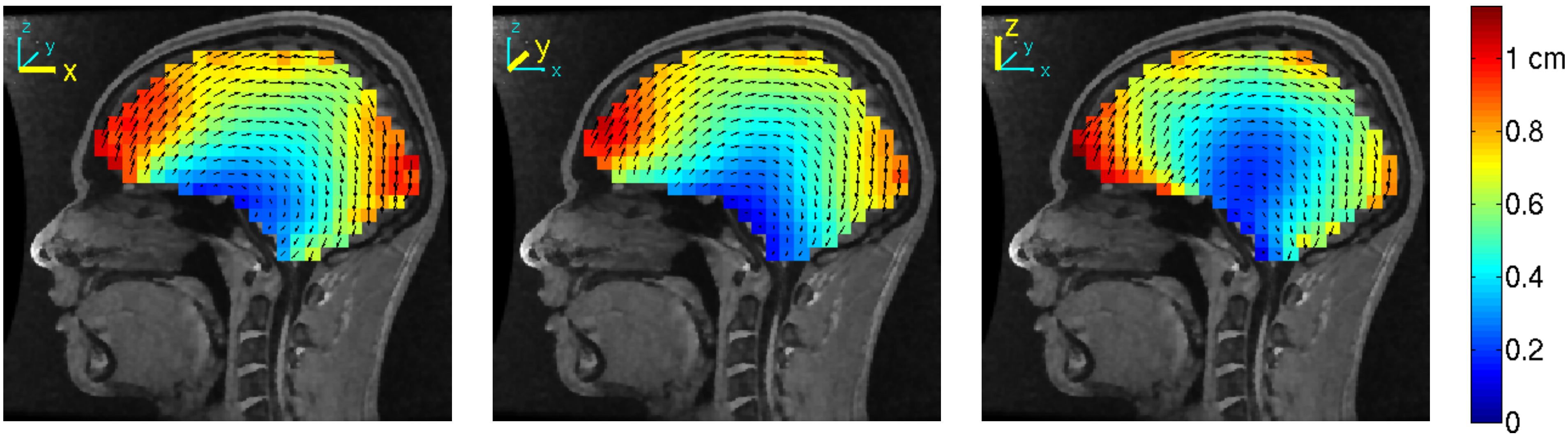
Observations

- Spherical Model
  - Location errors up to 3.5 cm. Cortical areas up to 1.5 cm.
- 3-Layer MNI
  - Large errors where models do not agree.
  - Higher around chin and the neck regions.
- 4-Layer MNI
  - Similar to 3-Layer MNI.
  - Smaller in magnitude.

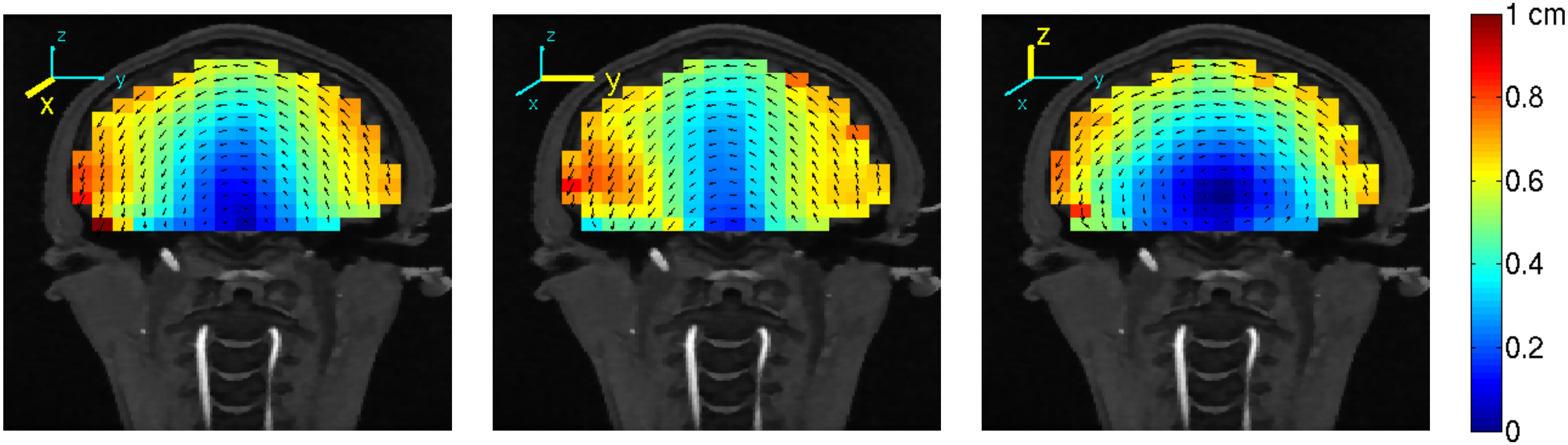
Electrode co-registration errors

- Solve FP with reference model
- Shift all electrodes and re-register
  - 5° backwards
  - 5° left
- Localize using shifted electrodes
- Plot location and orientation errors

5° Backwards Location Errors



5° Left Location Errors



Observations

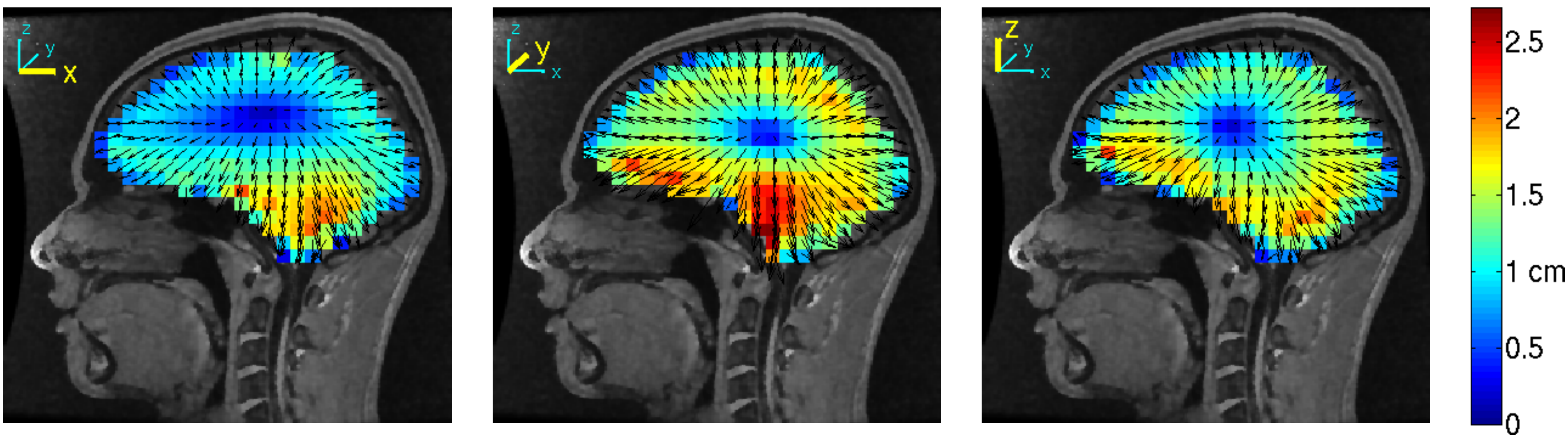
- Errors increase close to the surface near electrode locations.

- Changing or incorrectly registering electrodes may cause 5-10 mm localization error.

Effect of Skull Conductivity

- Solve FP with reference model
  - Brain-to-Skull ratio: 80
- Generate test model
  - Same geometry
  - Brain-to-Skull ratio: 20
- Localize using test model
- Plot location and orientation errors

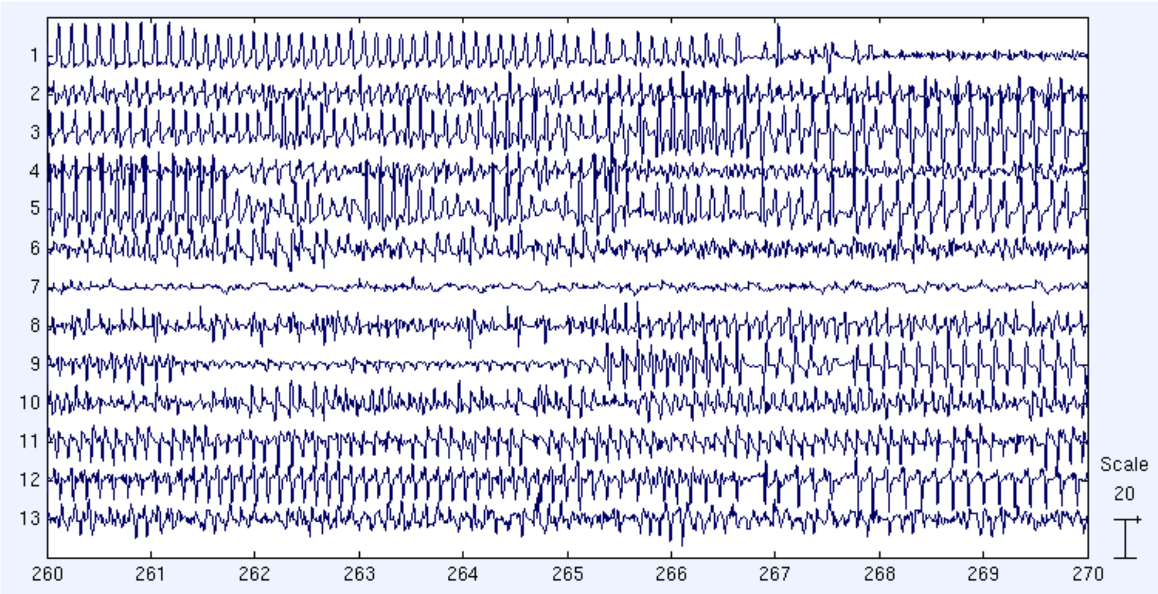
FP ratio: 80 IP ratio: 20

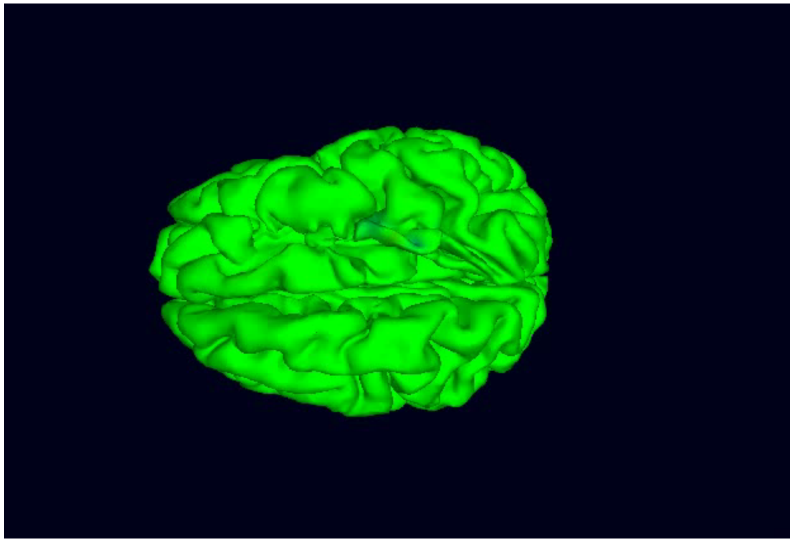


Conclusion

- Head shape
  - Most impact on source localization accuracy.
- Incorrect electrode registration
  - Errors near the electrodes
  - Most studies investigate cortical activity close to the electrodes.
- Electrical properties
  - Number of layers
  - Relative conductivities (Brain-to-Skull ratio)

ICON POSTER: Forward model errors in EEG source localization
Z Akalin Acar, S Makeig (Sunday afternoon)

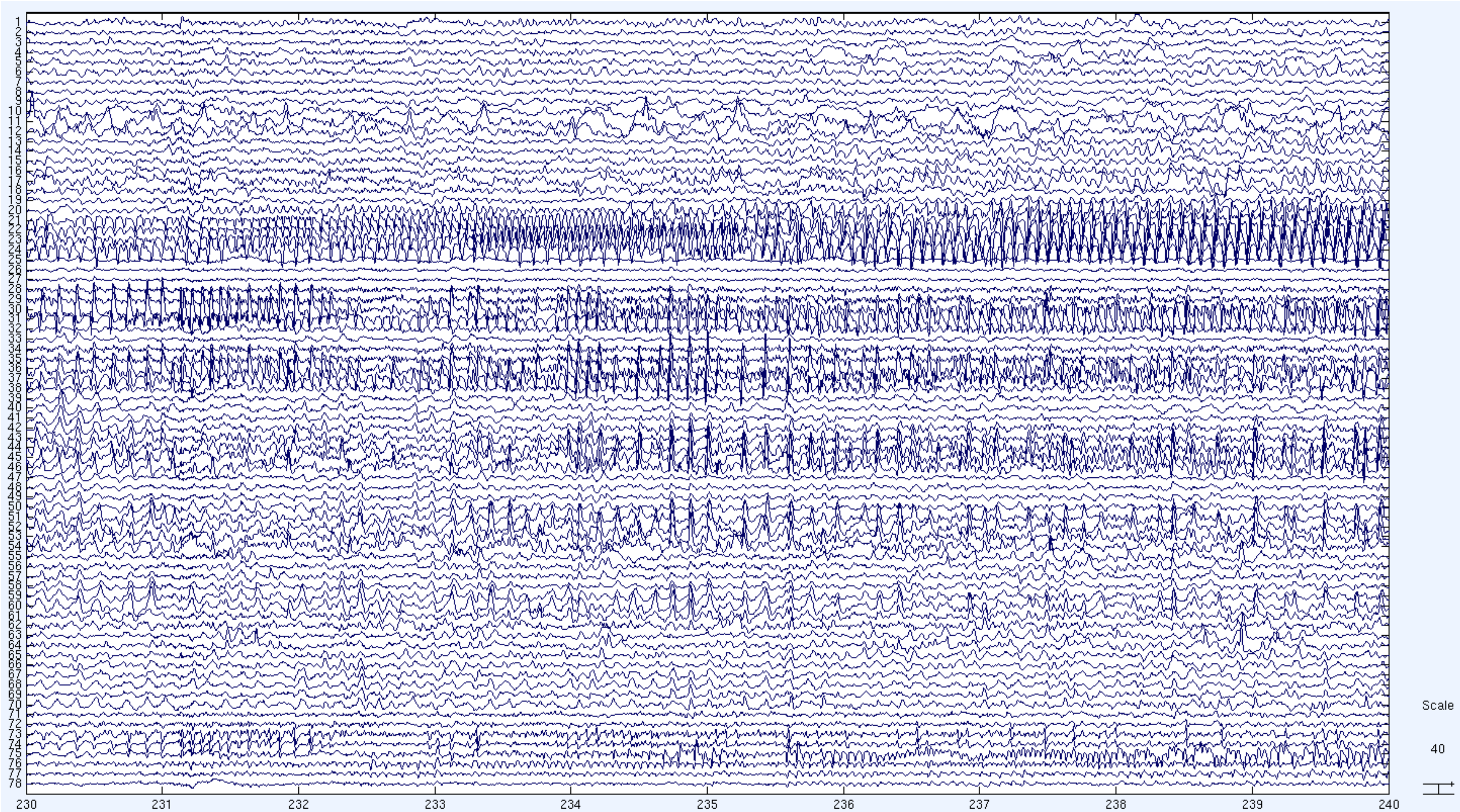




Epilepsy Head Modeling

CASE STUDY

Epilepsy



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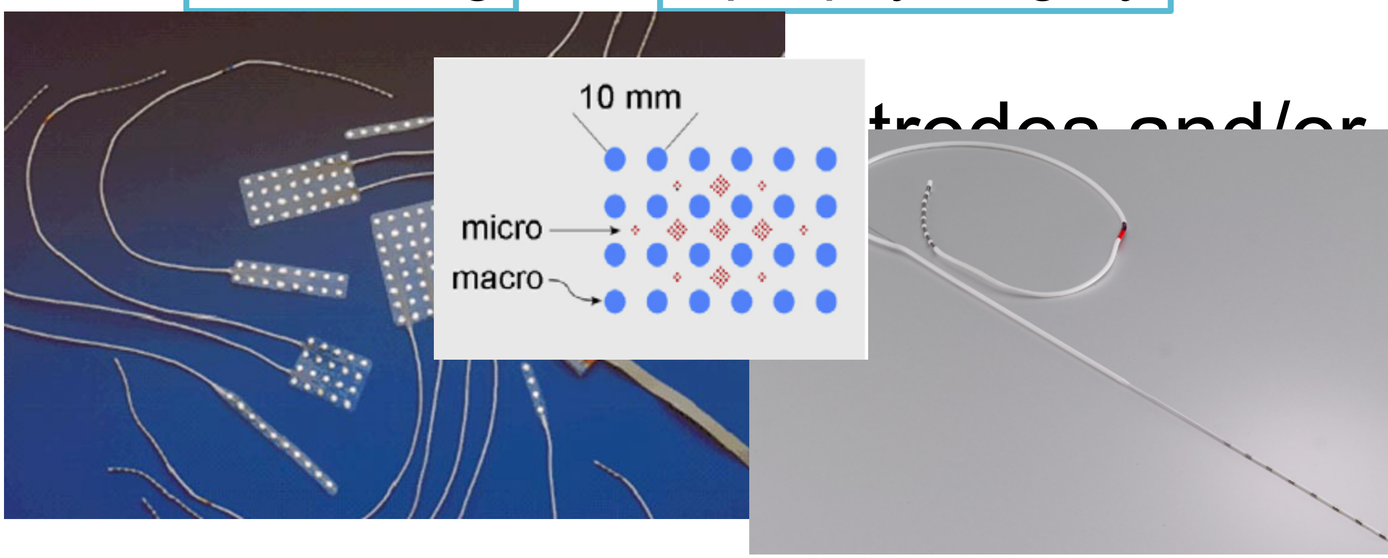
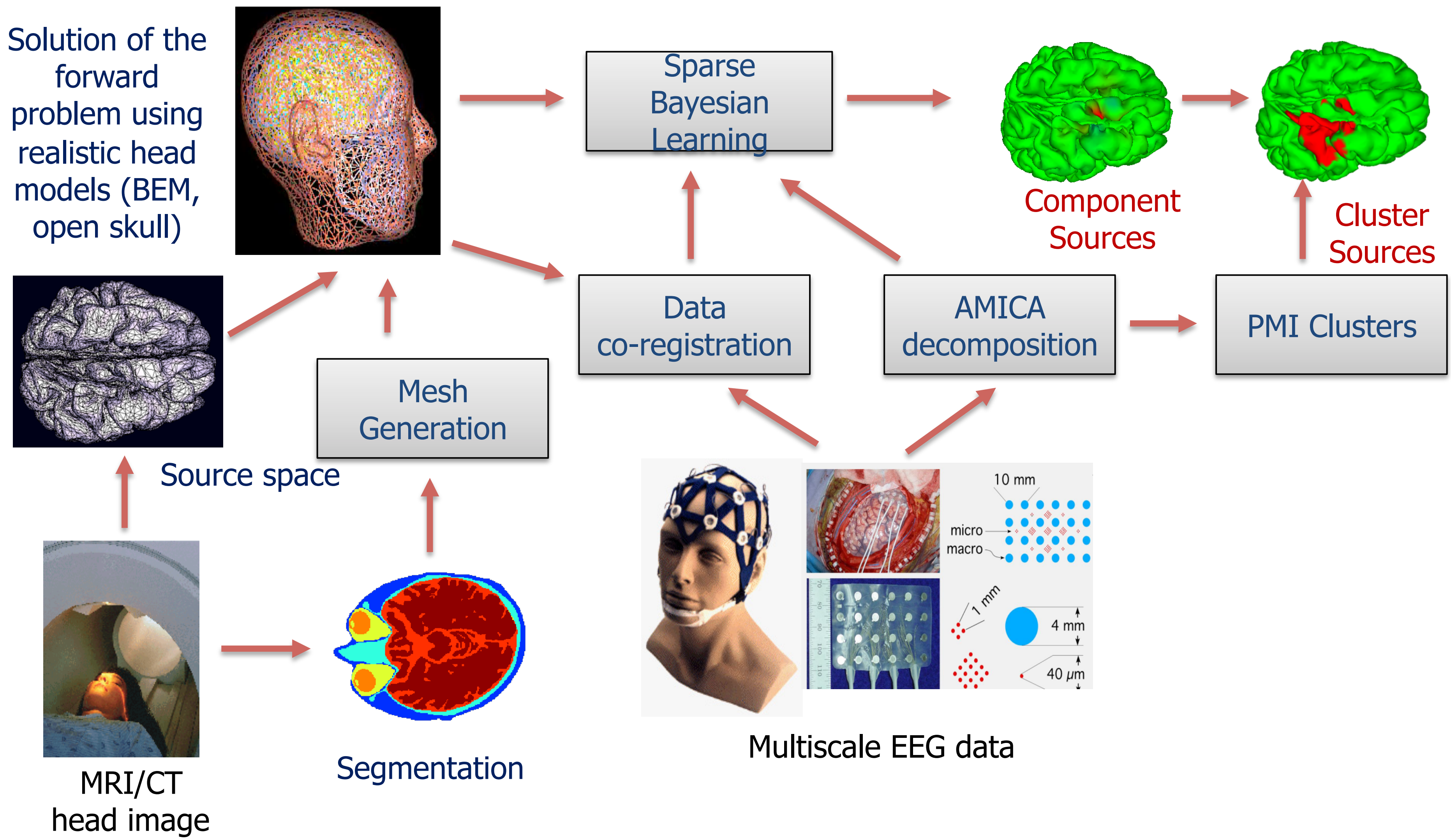
Epilepsy surgery

Scalp EEG
MRI, MEG?, PET? → Surgery for intracranial recording → CT → Recording → Epilepsy surgery

- …trodes and/or strip

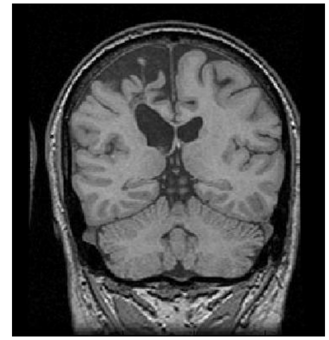


Project Summary

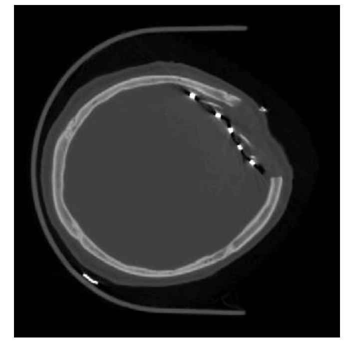


Epilepsy Head Modeling

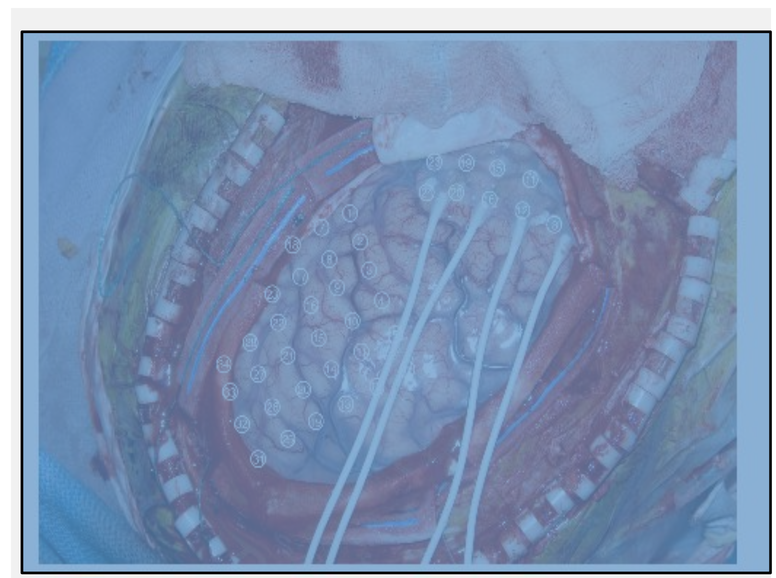
- Large hole in skull
- Plastic sheet
- A pre-surgery MR and post-surgery CT
- Differences in brain shape after surgery
- Co-registration of electrodes
  - Subdural – from CT segmentation
  - Scalp – no digitizer data



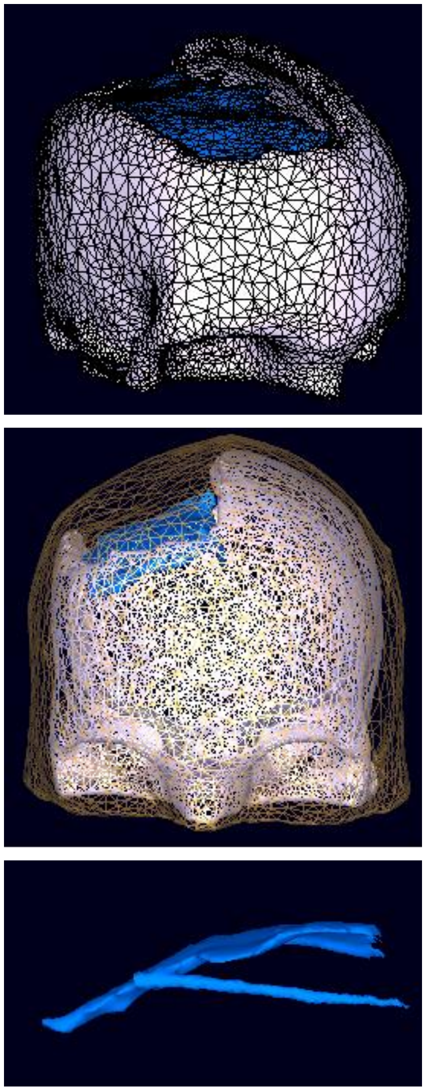
MR



CT



Scalp, skull and sheet models



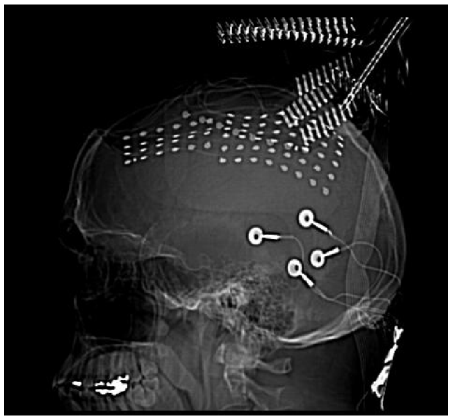
Number of elements

Scalp: 10000

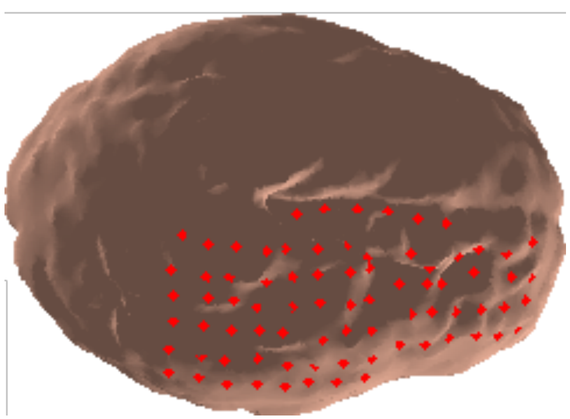
Skull: 30000

Plastic sheet : 7000

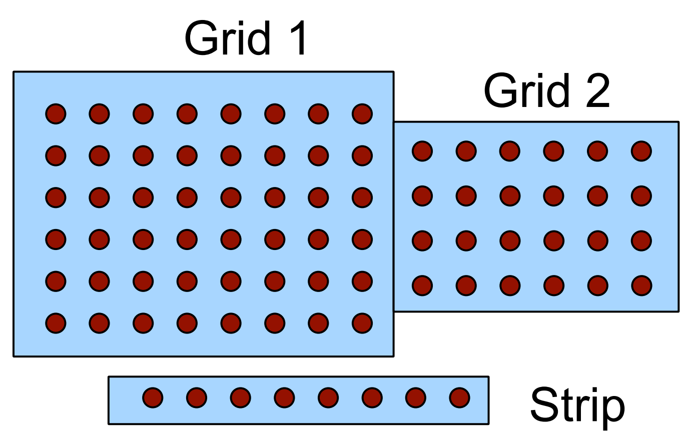
Analyzing Epilepsy Recordings



CT image of the implanted grid electrodes



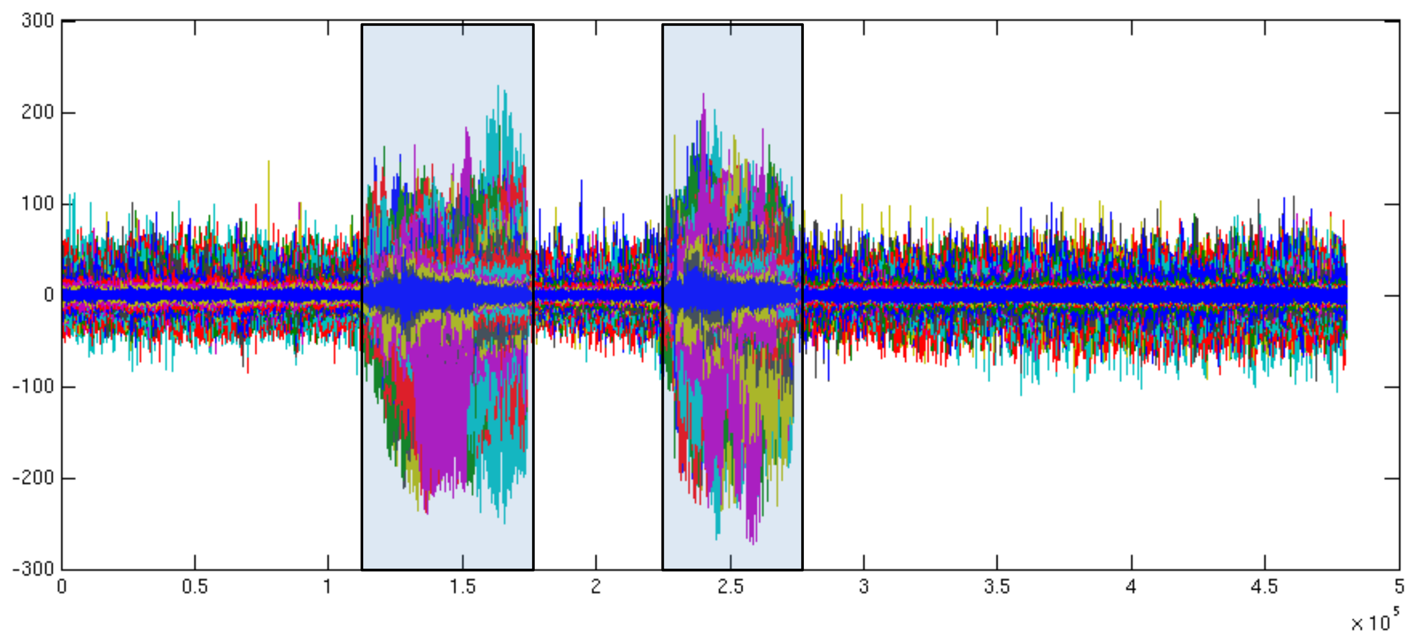
- Pre-Surgical Evaluation
- Rest Data
- Simultaneous recordings
  - 78 iEEG electrodes
  - 29 scalp electrodes
- Provided by Dr. Greg Worrell, Mayo Clinic



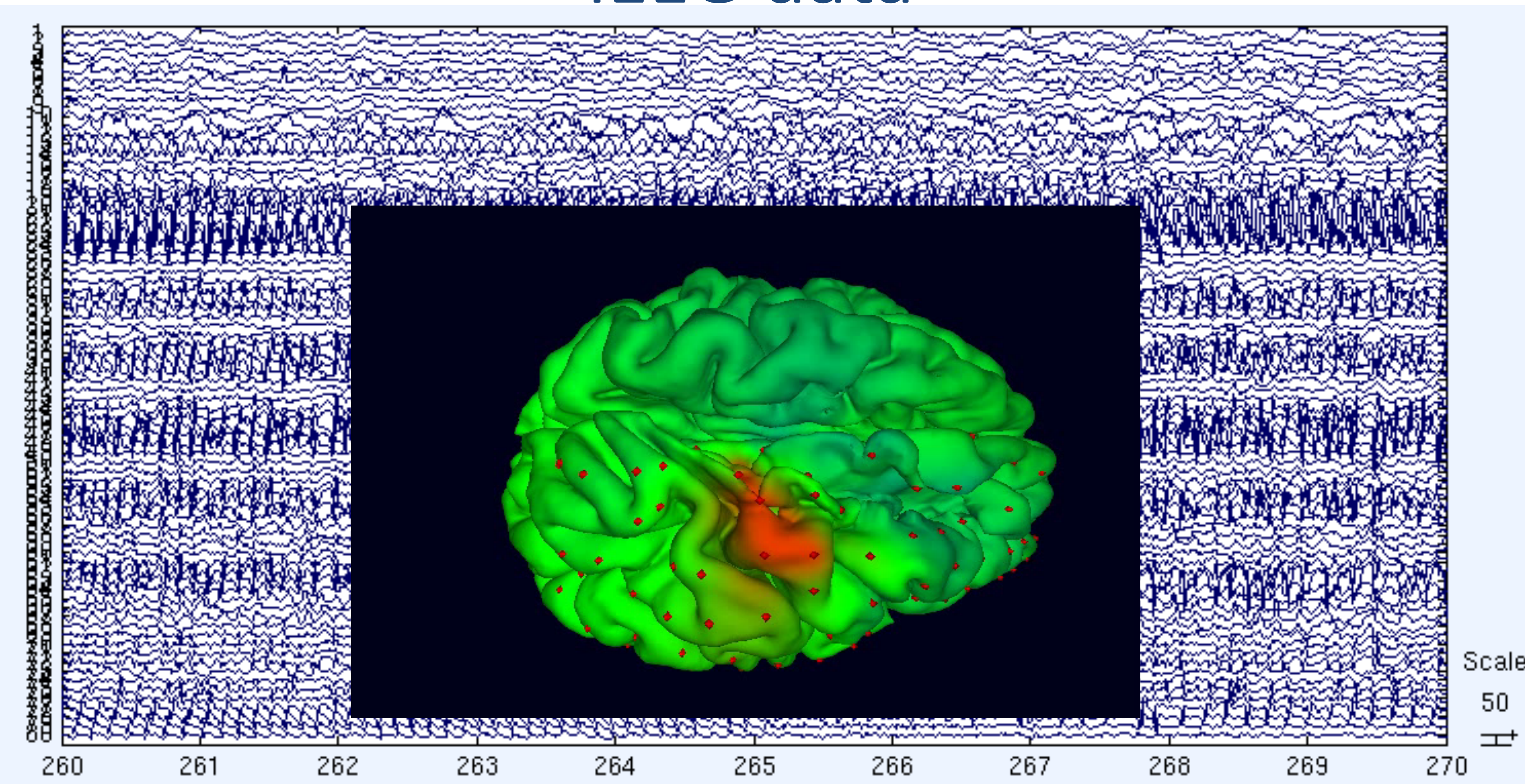
Akalin Acar et al, 2008

Data

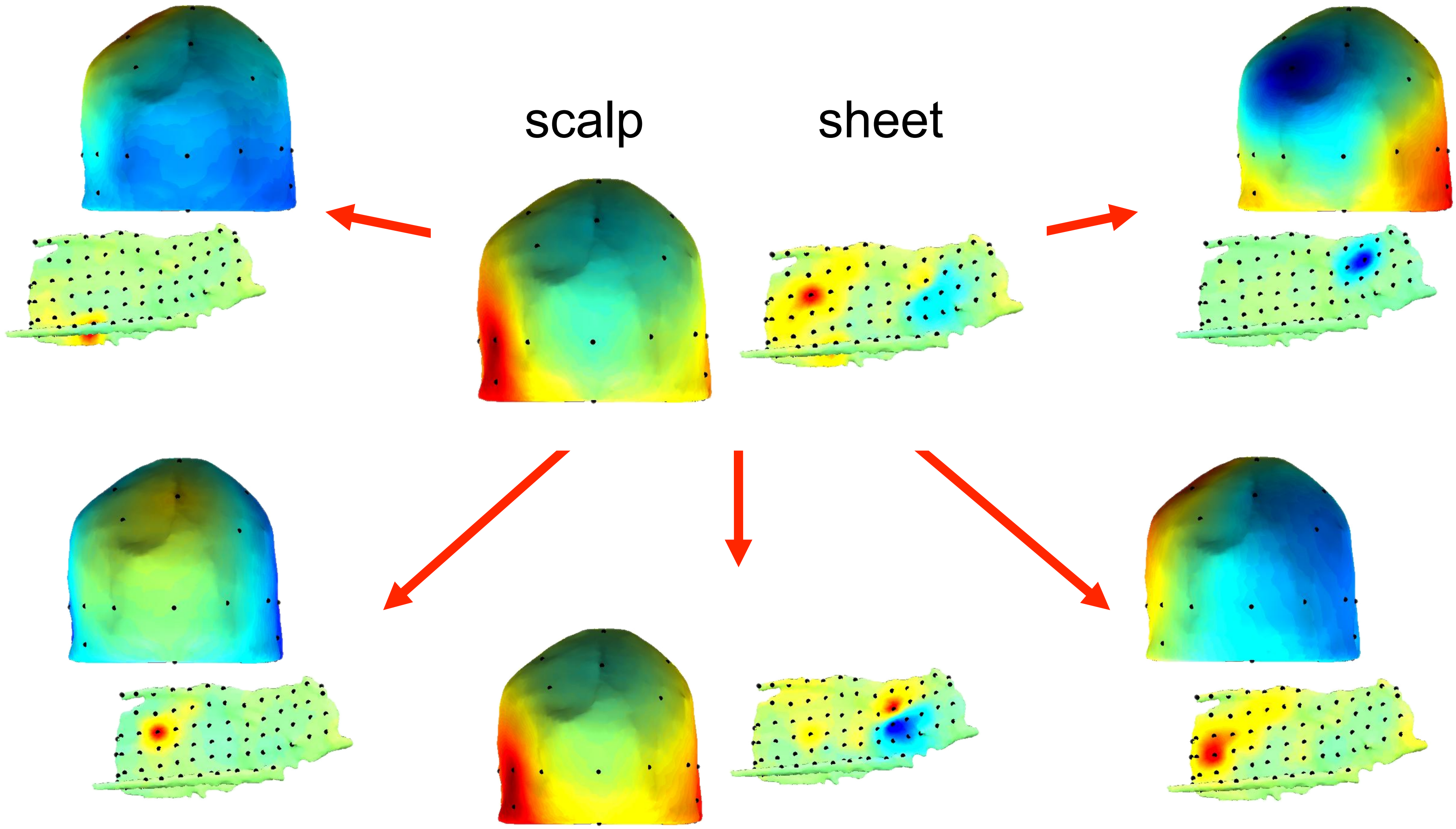
- 16 minutes ECoG + EEG data
- 2 seizures (1.9 min + 1.5 min)
- ECoG = 78 channels, EEG = 29 channels



iEEG data

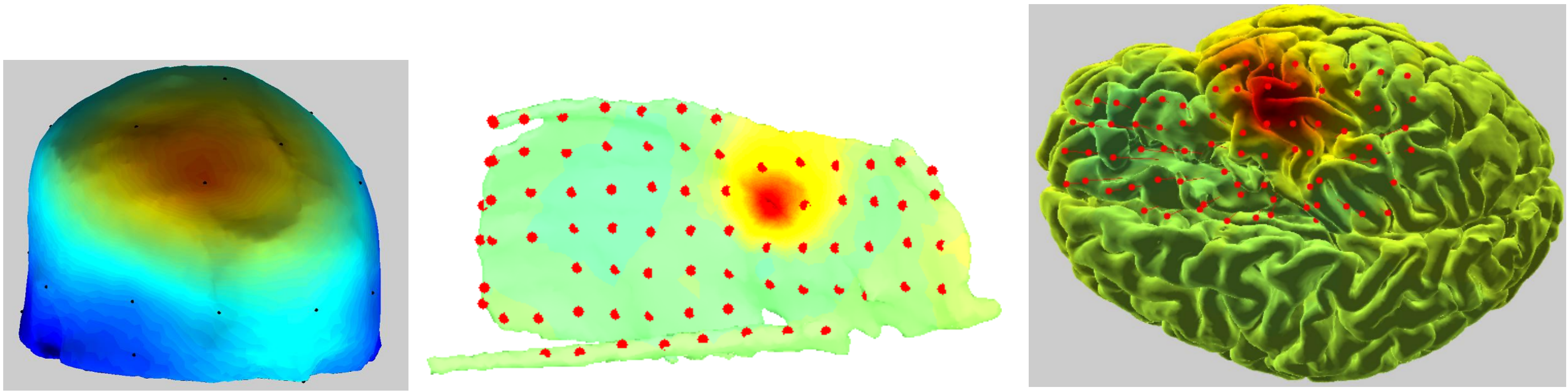


Independent Component Analysis



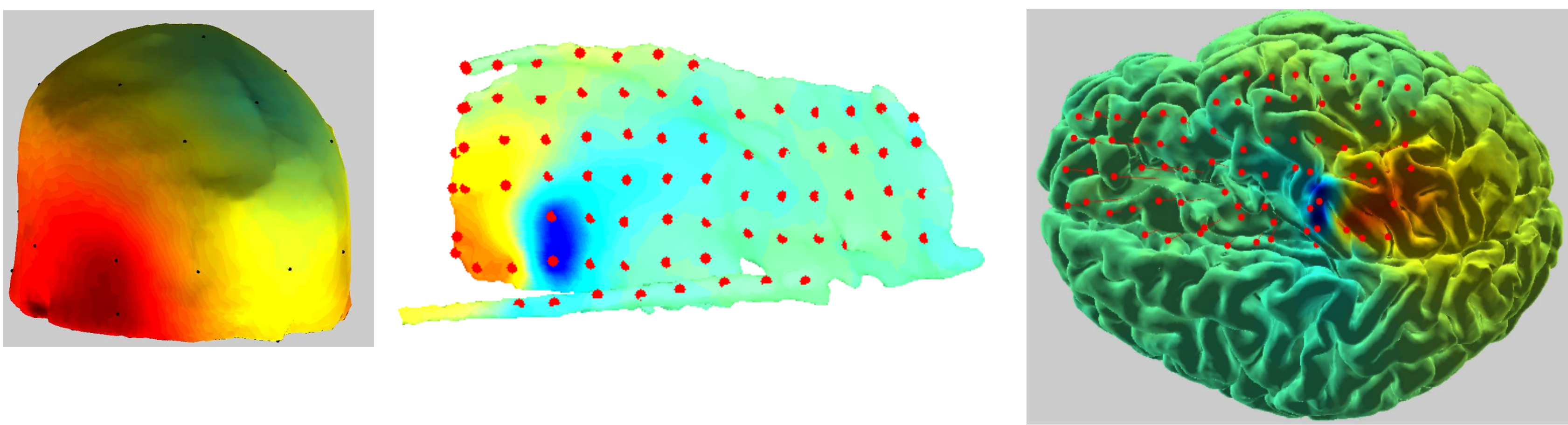
Independent Components

IC 1



Potentials on scalp   Potentials on plastic sheet   On the brain surface

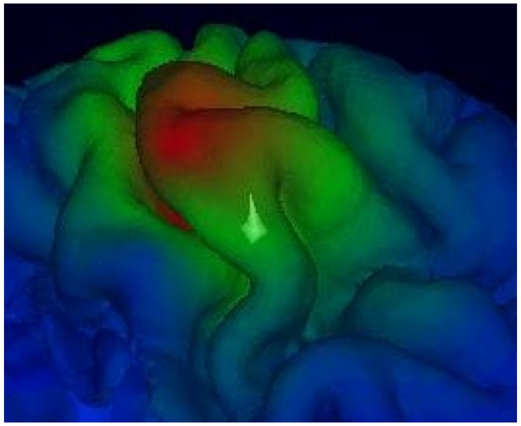
IC 52



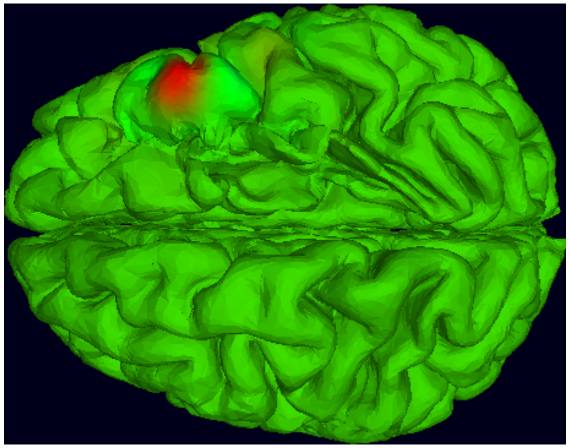
Source Localization Results

Dipole source localization	Distributed source localization - SBL

IC 1

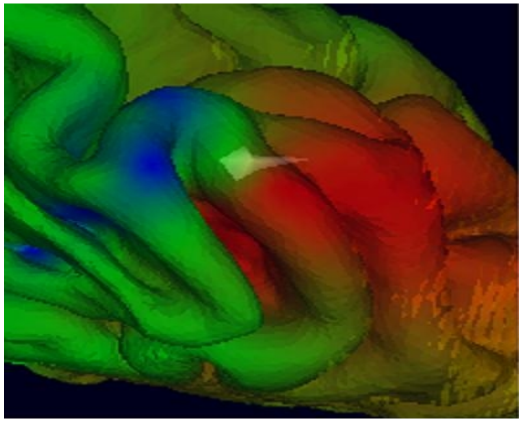


Radial source

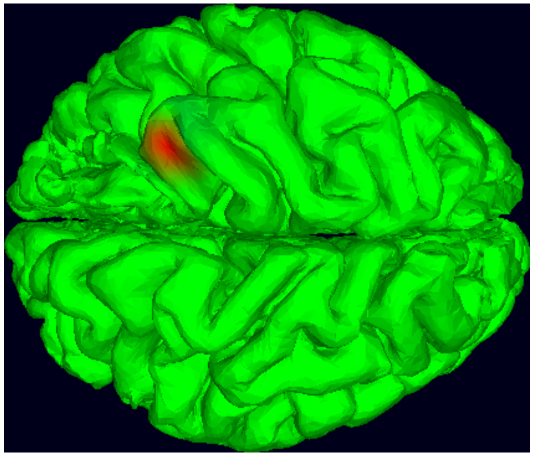


Gyral source

IC 52

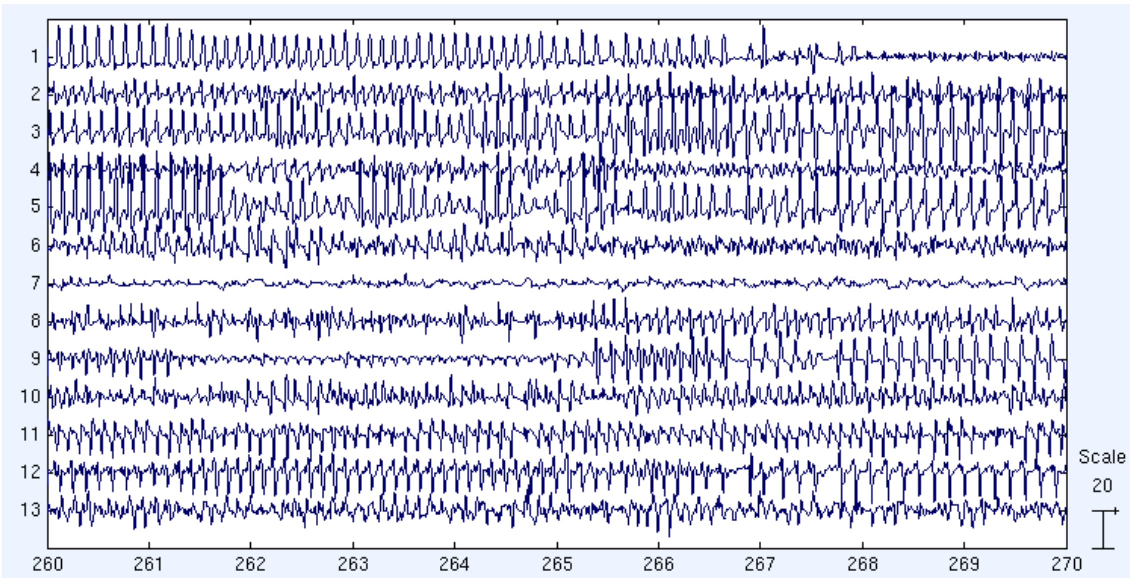


Tangential source

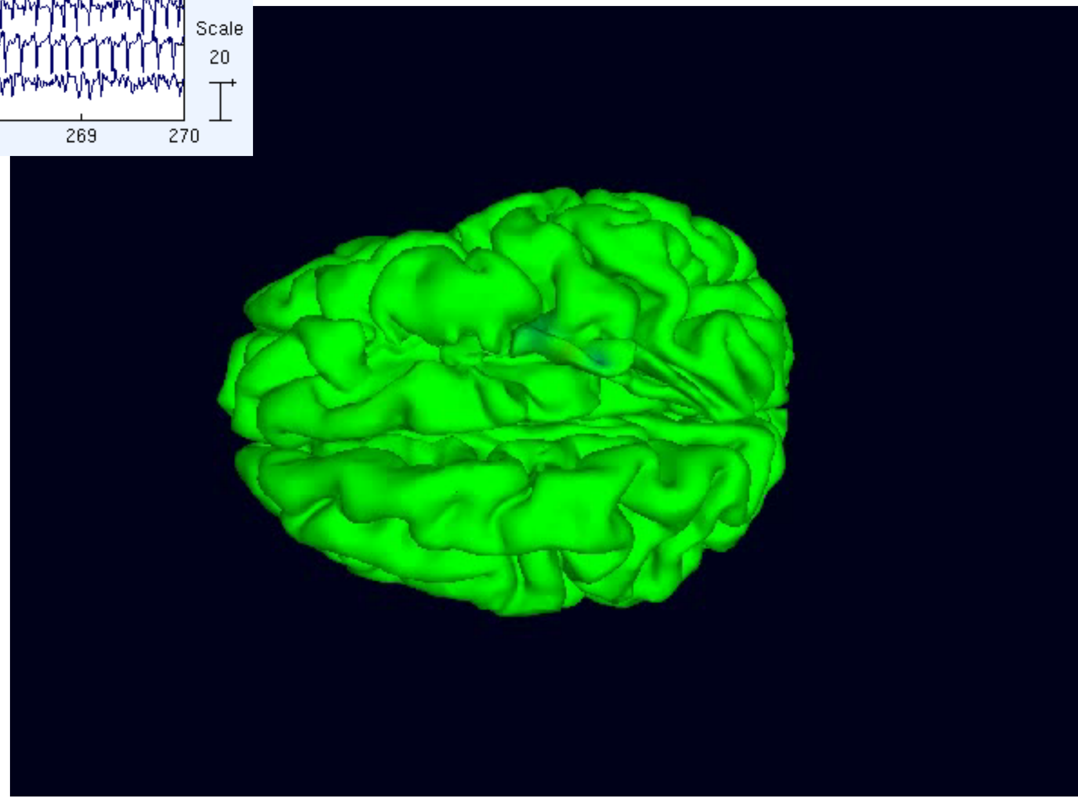


Sulcal source

Cortical activity of seizure components



Activations of 13 seizure components



Cortical activity of Seizure components

$$Movie(t) = \sum_{i=1}^{13} S_i \times Act_i(t)$$

Conclusion

- ICA can detect and identify seizure components in the EEG data.
- Correct source localization requires correct forward problem solution.

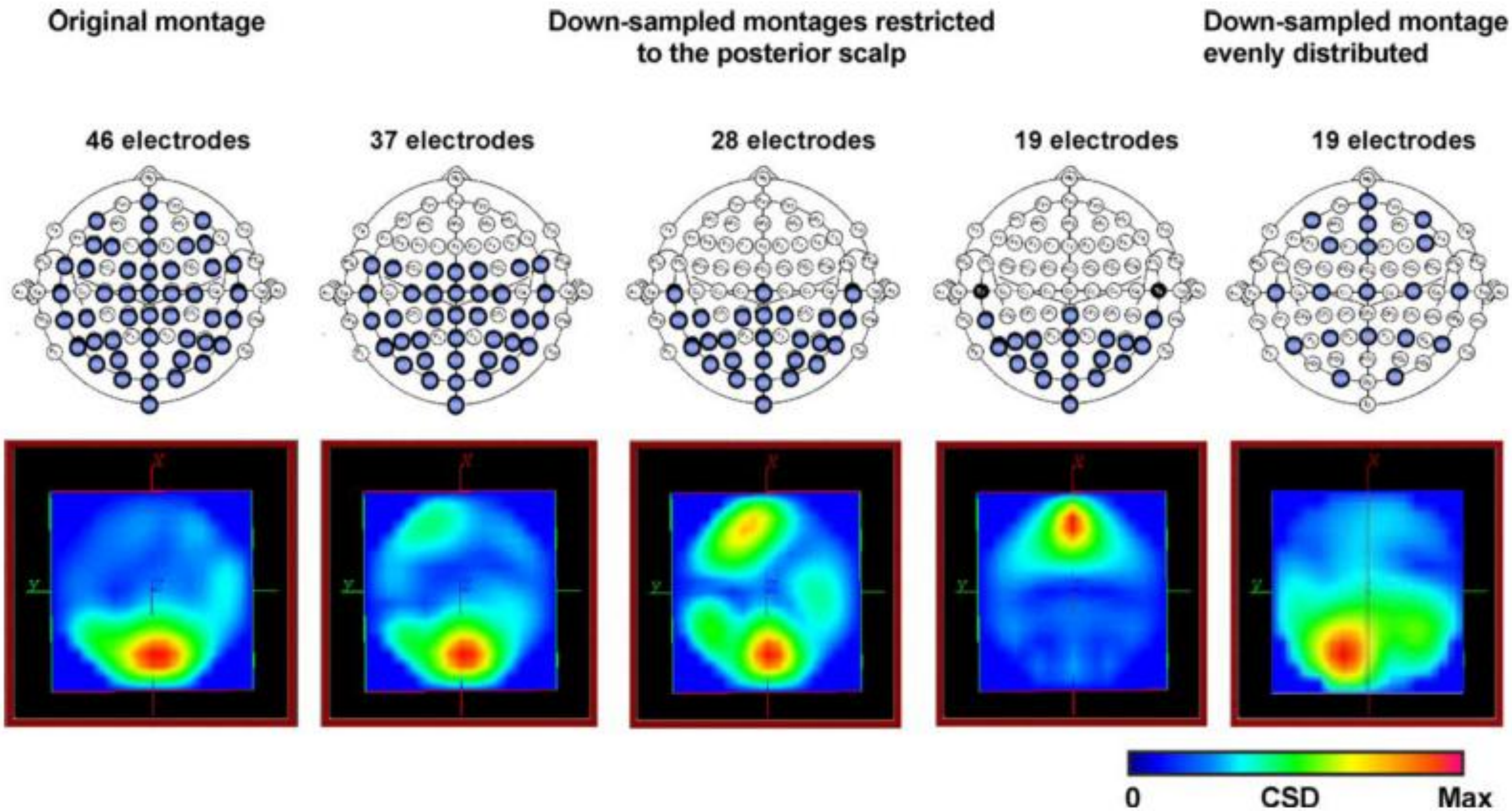
ICON POSTER: Independent Component Analysis and source localization of ECoG data
S Makeig, J Palmer, G Worrell, Z Akalin Acar (Sunday afternoon)

References

1. Z. Akalin Acar, S. Makeig, "Neuroelectromagnetic Forward Head modeling Toolbox", J. of Neuroscience Methods, vol. 190 (2), 258-270, 2010.
2. Z. Akalin Acar, N. Gencer, "An advanced boundary element method (BEM) implementation for the forward problem of electromagnetic source imaging", vol. 49, 5011-5028, 2004.
3. Z. Akalin Acar, G. Worrell, S. Makeig, "Patch-based cortical source localization in epilepsy", Proc. of IEEE EMBC 2009, Minneapolis.
4. Z. Akalin Acar, S. Makeig, "Effect of head models in EEG source localization", Sfn 2010, San Diego.
5. Z. Akalin Acar, S. Makeig, G.Worrell, "Head modeling and cortical source localization in epilepsy", Proc. of IEEE EMBC 2008, Vancouver.
6. Z. Akalin Acar, J. Palmer, G. Worrell, S. Makeig, "Electrocortical source imaging of intracranial EEG data in epilepsy", Proc. of IEEE EMBC 2011, Boston.

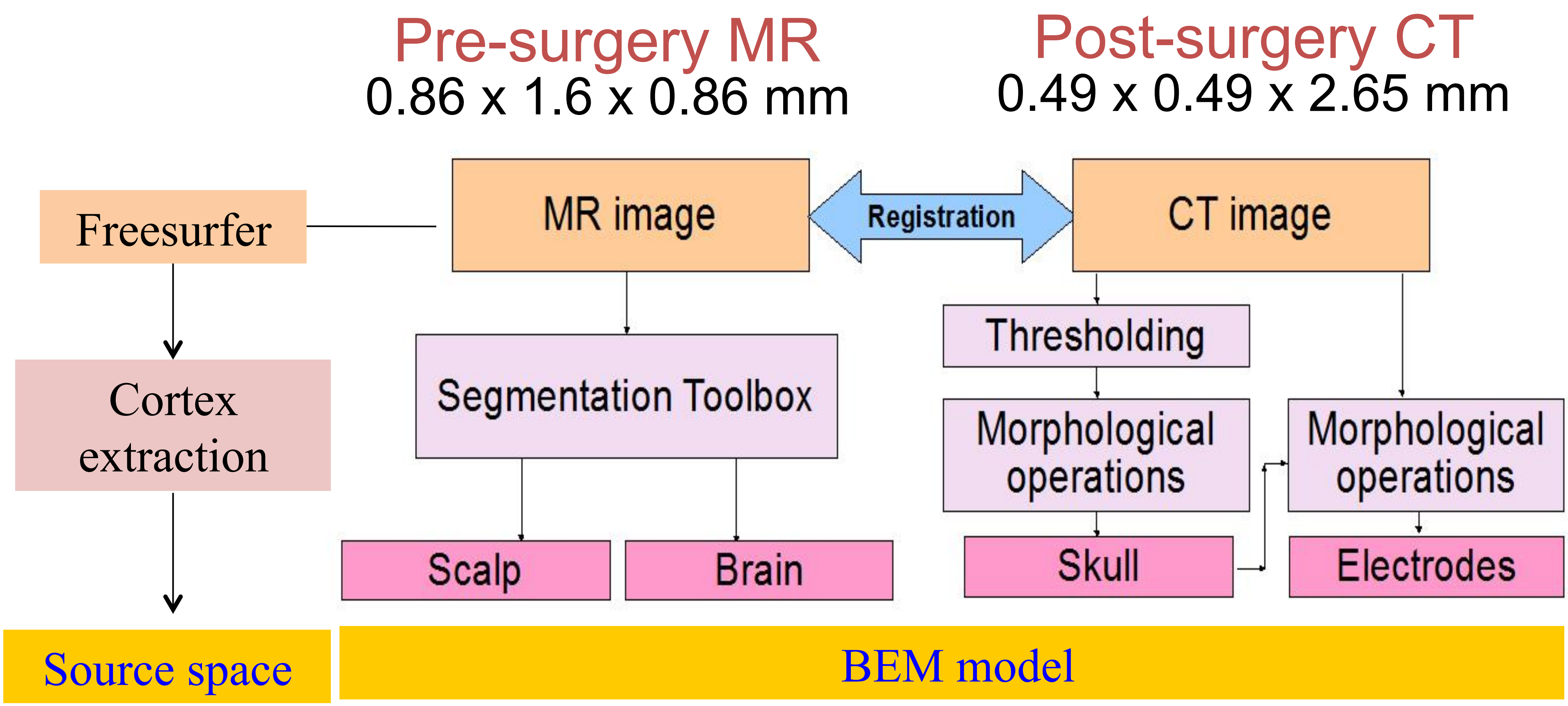
THANK YOU

Distribution of electrodes



Michel *et al*, 2004

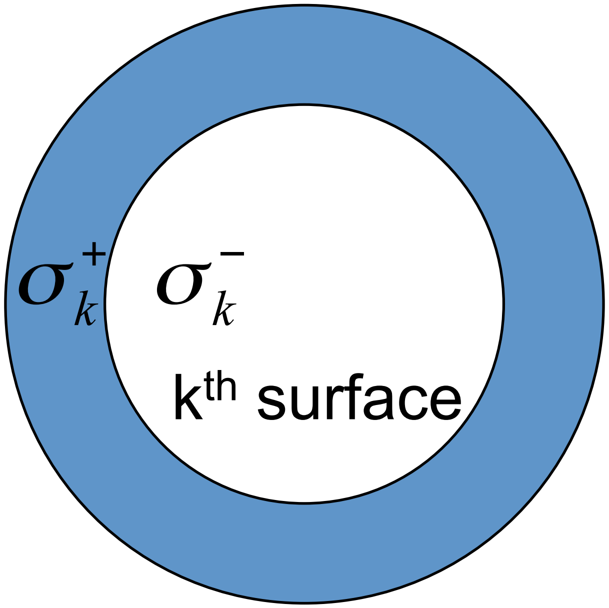
Head modeling in epilepsy



BEM Formulation

Integral equation for Potential Field:

$$\phi(\vec{r}) = 2g(\vec{r}) + \frac{1}{2\pi}\sum_{k=1}^{n}\left(\frac{\sigma_k^- - \sigma_k^+}{\sigma_i^- + \sigma_i^+}\right)\int_{S_k}\phi(\vec{r}^{\,'})\frac{\vec{R}}{R^3}\cdot d\vec{S}_k(\vec{r}^{\,'})$$



BEM Formulation

Integrating the previous integral equation over all elements a set of equations are obtained.

In matrix notation for the potential field we obtain

$$\Phi_{M\times 1} = C_{M\times M}\Phi + g_{M\times 1} \qquad \Phi = [I - C]^{-1} g \qquad \Phi = \mathbf{A}^{-1} g$$

M: number of nodes

The expression for the magnetic field:

$$B_{n\times 1} = B_0 + \mathbf{H}_{n\times M}\Phi$$

n: number of magnetic sensors

Algebraic formulation of the FP

Scalp potentials for N electrodes and p dipoles:

$$V(r) = \sum_{i}^{p} g(r, r_{dip}, d_i) = \sum_{i}^{p} g(r, r_{dip}, e_{d_i}) d_i$$

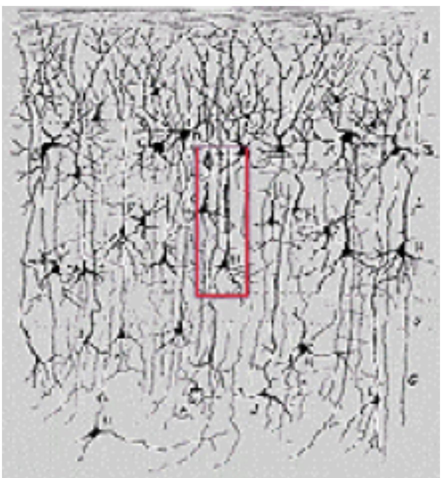
$$V = \begin{bmatrix} V(r_1) \\ \vdots \\ V(r_N) \end{bmatrix} = \begin{bmatrix} g(r_1, r_{dip}, e_{d1}) & \cdots & g(r_1, r_{dip}, e_{dp}) \\ \vdots & \ddots & \vdots \\ g(r_N, r_{dip}, e_{d1}) & \cdots & g(r_N, r_{dip}, e_{dp}) \end{bmatrix} \begin{bmatrix} d_1 \\ \vdots \\ d_p \end{bmatrix} = G(\{r_j, r_{dip_i}, e_{d_i}\}) \begin{bmatrix} d_1 \\ \vdots \\ d_p \end{bmatrix}$$

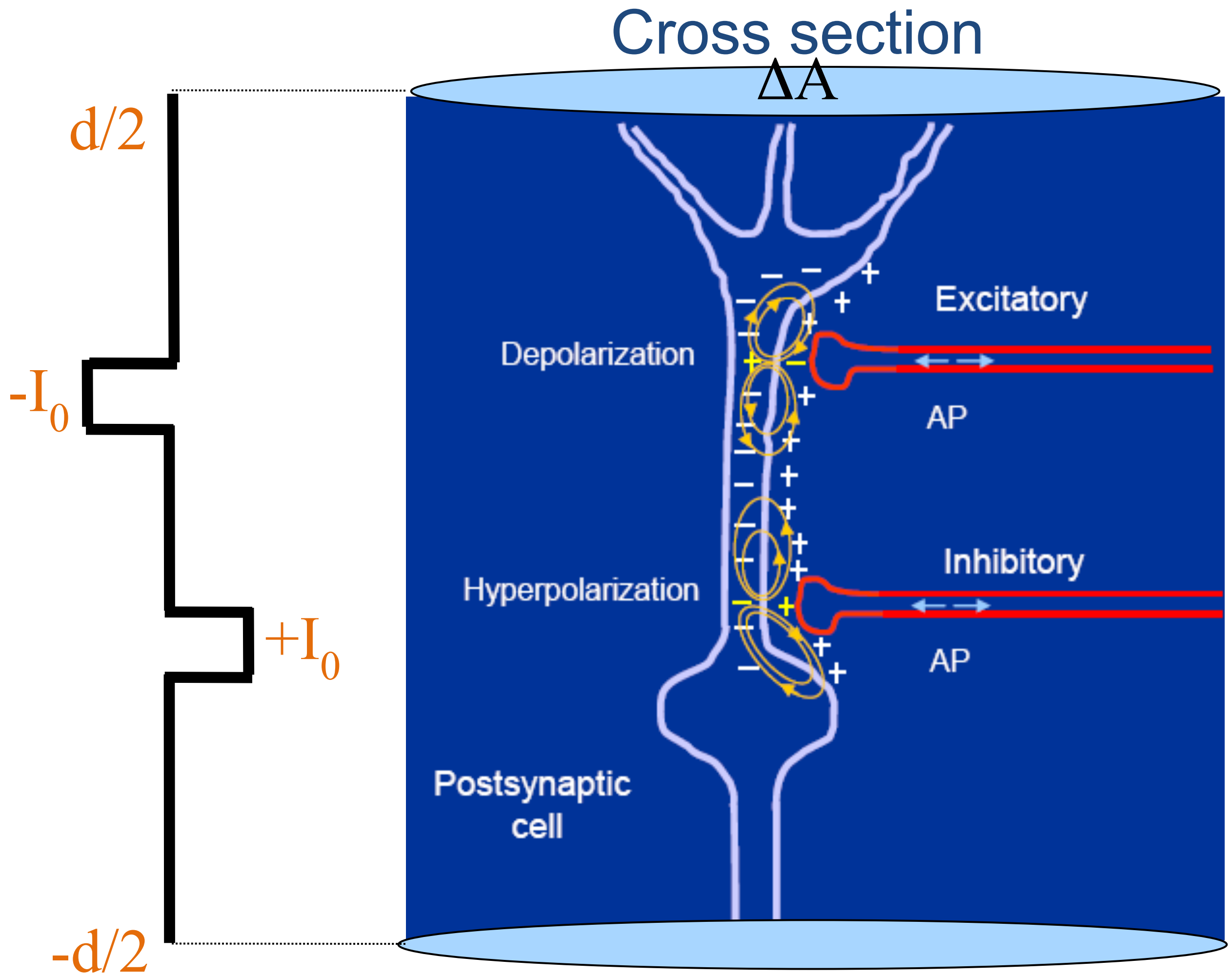
For N electrodes and p dipoles and T discrete time samples:

$$V = \begin{bmatrix} V(r_1,1) & \cdots & V(r_1,T) \\ \vdots & \ddots & \vdots \\ V(r_N,1) & \cdots & V(r_N,T) \end{bmatrix} = G(\{r_j, r_{dip_i}, e_{d_i}\}) \begin{bmatrix} d_{1,1} & \cdots & d_{1,T} \\ \vdots & \ddots & \vdots \\ d_{p,1} & \cdots & d_{p,T} \end{bmatrix}$$

$$V = GD + n$$

Generators of EEG





diameter: 3mm ~10^5-10^6 pyramidal cells
A large pyramidal cell would have ~ 10^4-10^5 synapses