UTHealth®

McGovern Medical School

The University of Texas Health Science Center at Houston

Reconstructing Neural Sources of Activity from SEEG Recordings

(All models are wrong, but some are useful)

Prof. John C. Mosher

Texas Institute for Restorative Neurotechnologies (TIRN)
Department of Neurology

Outline

All models are wrong, but some are useful.

-*George Box*

- Physiological basis of the **Current Column**
- Modeling of the cortical surface
- Invasive Source Modeling

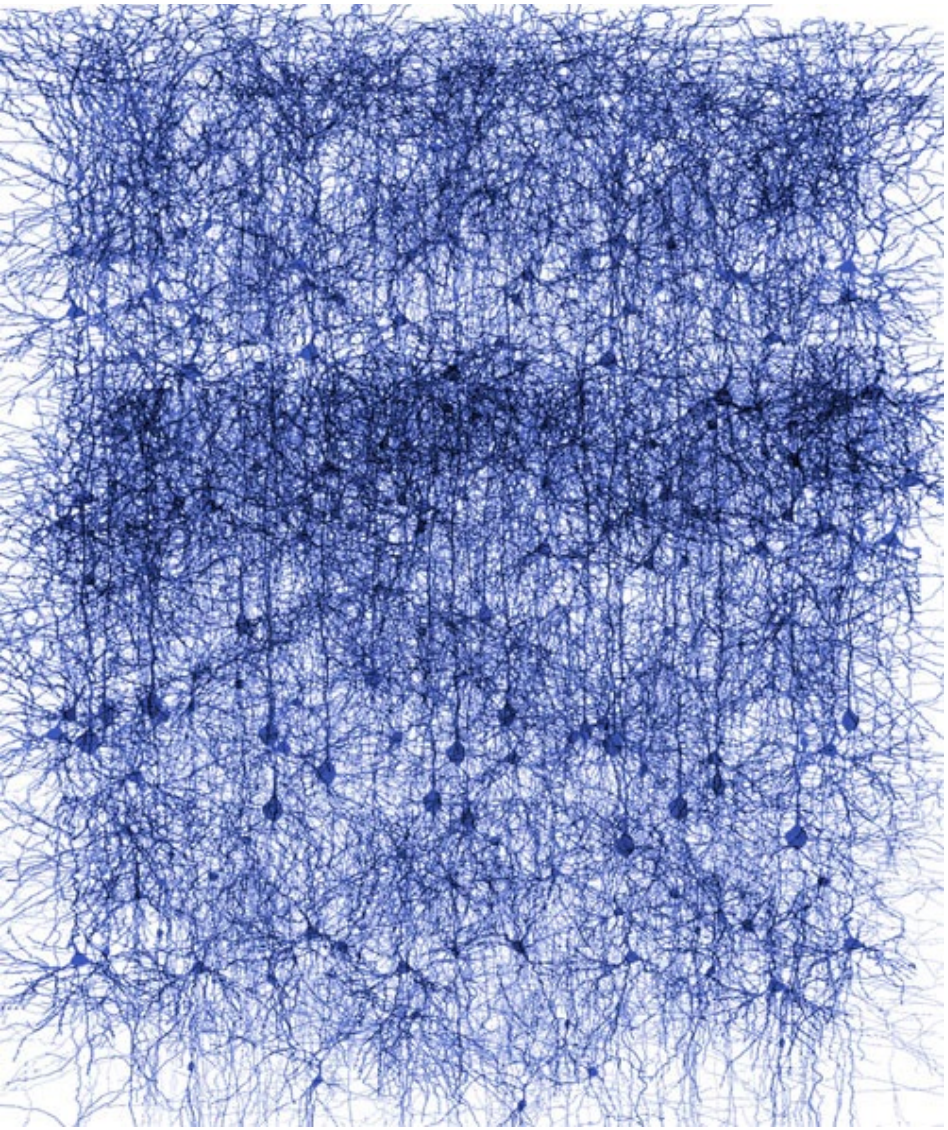
Outline

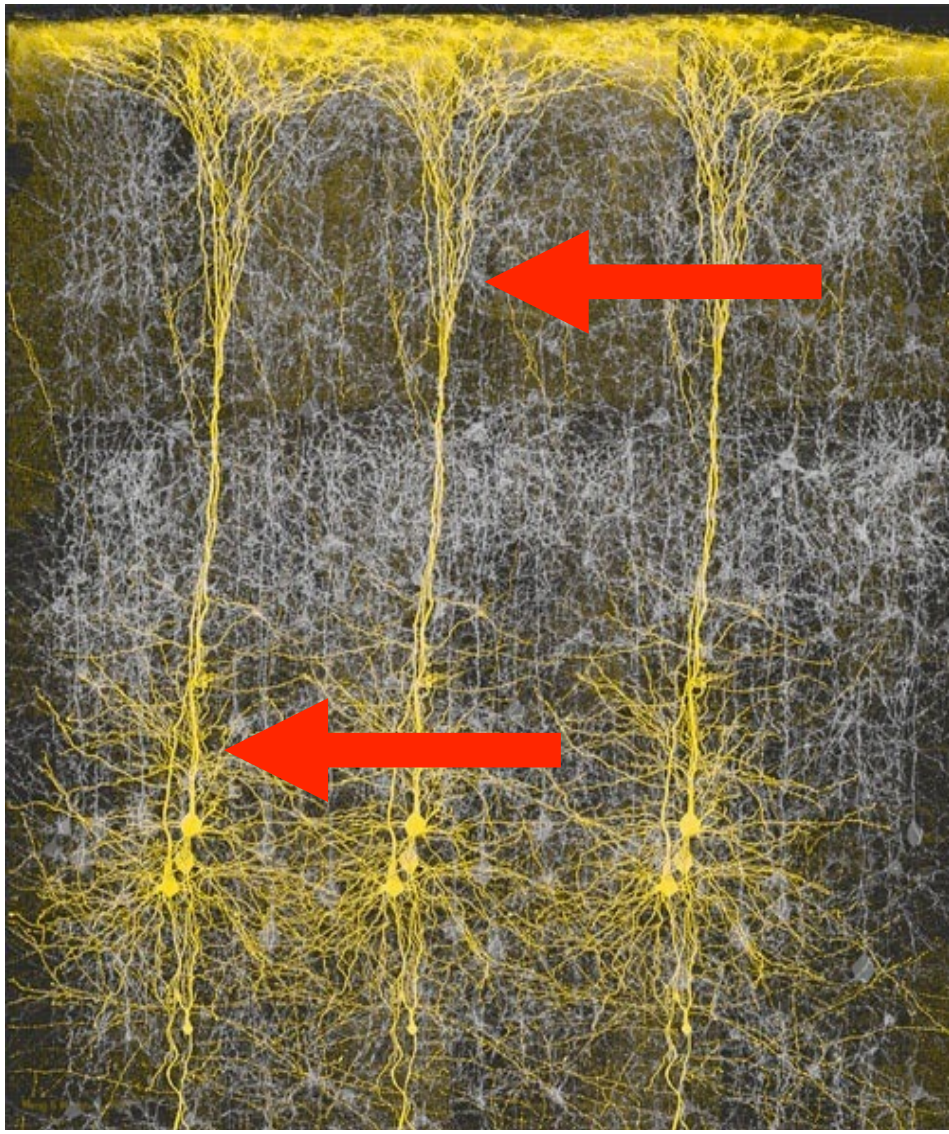
All models are wrong, but some are useful.

-*George Box*

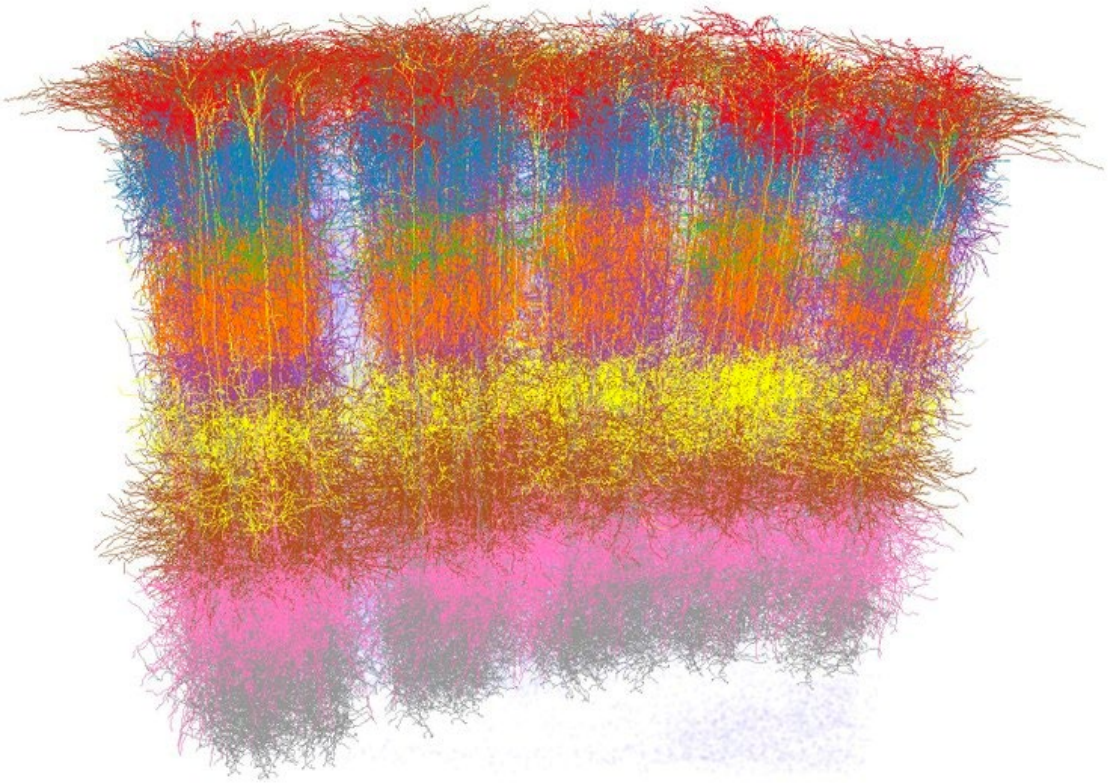
- **Physiological basis of the Current Column**
- Modeling of the cortical surface
- Invasive Source Modeling

A Forest of Neurons in Gray Matter





“Cortical Columns”



- Model the 3D multilayer cortex as columns.
- Emphasize the 2D cortical surface in units of square mm
- This “wrong” model ignores the complexity of the column and the transverse connections.

Cell-type-specific 3D reconstruction of five neighboring barrel columns in rat vibrissal cortex (credit: Marcel Oberlaender et al.)

Excitatory vs Inhibitory PSP

- Ambiguous whether excitatory in upper layers or inhibitory in lower layers.

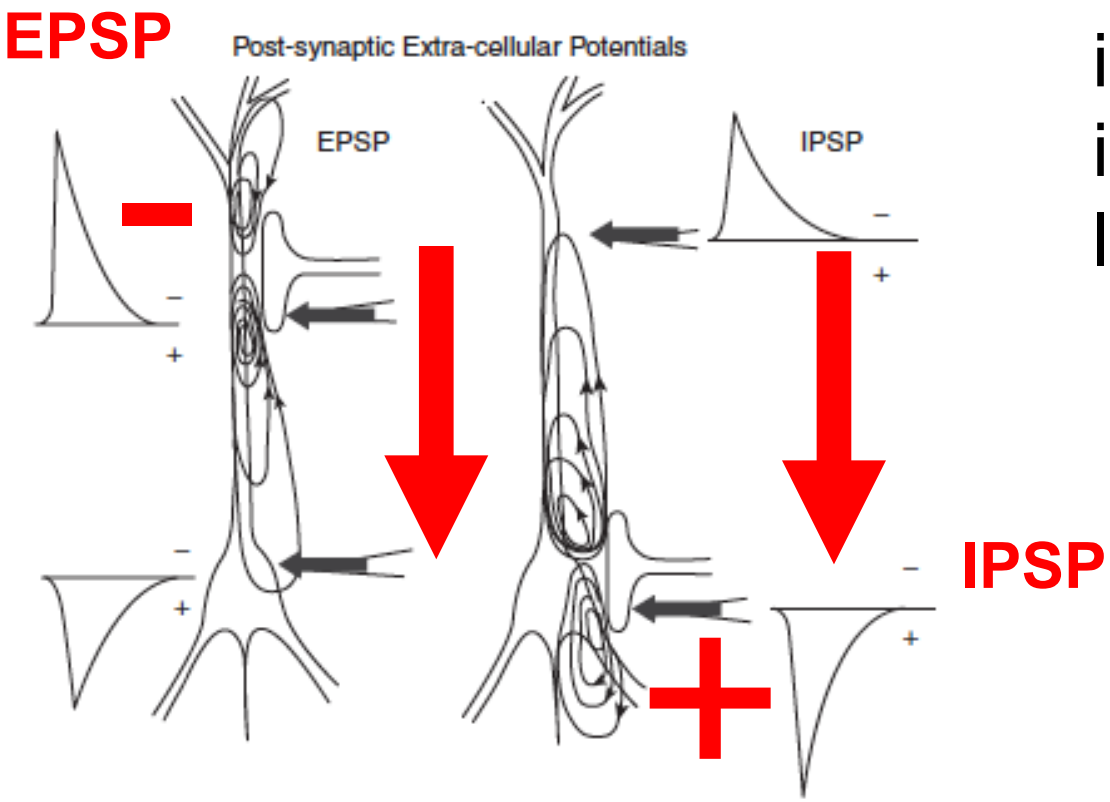
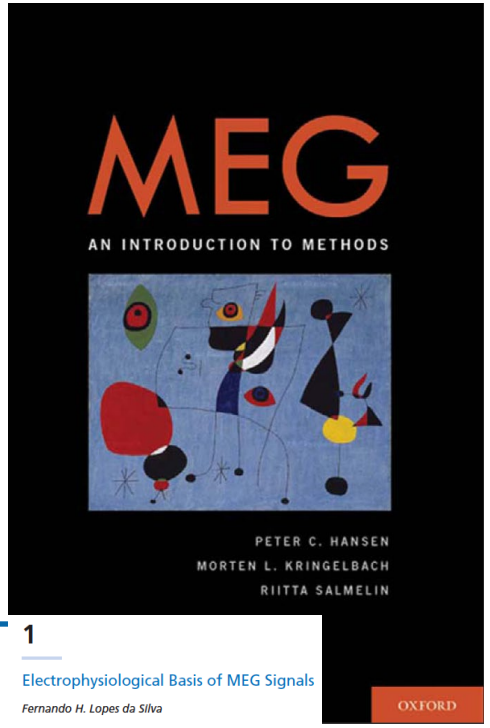
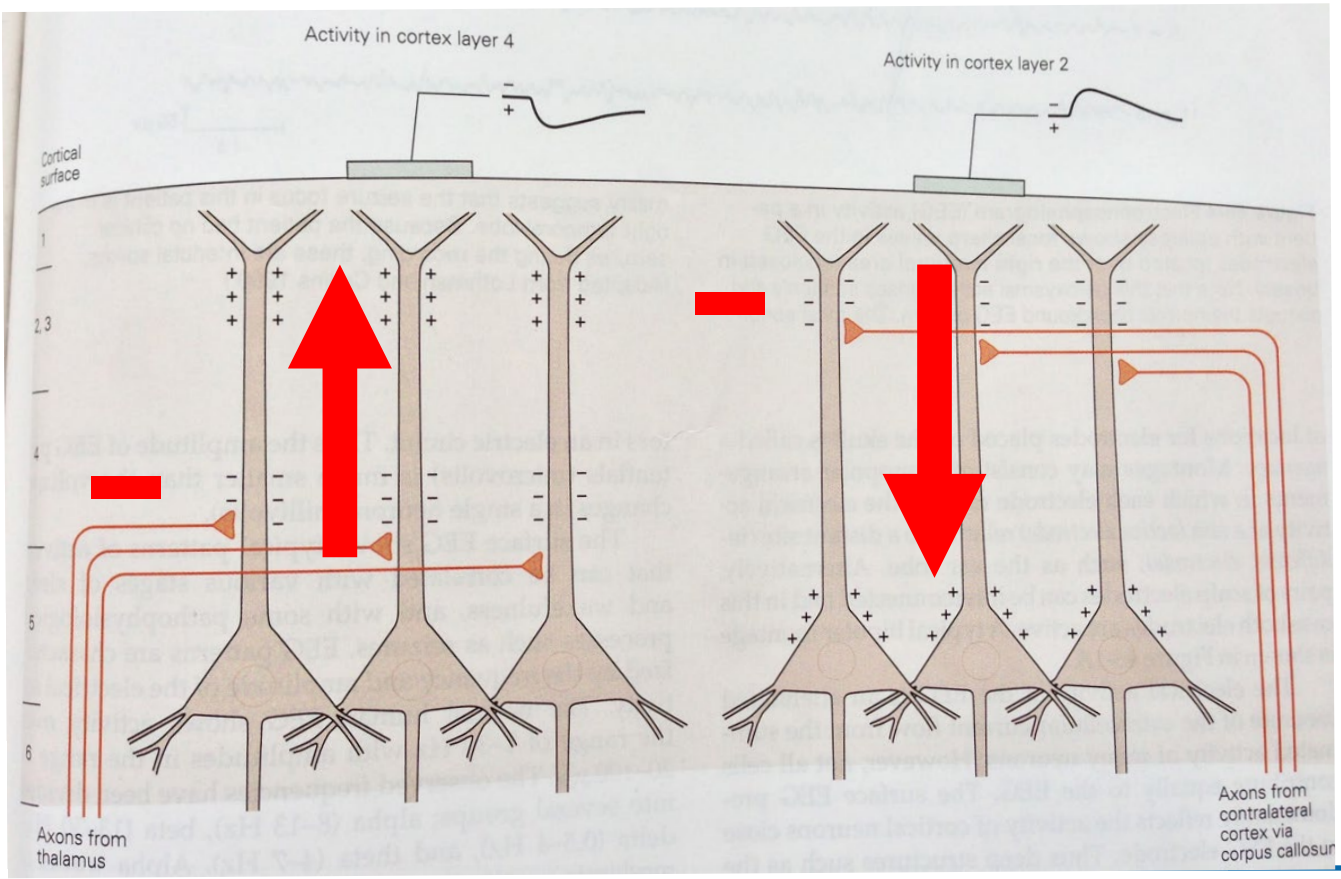


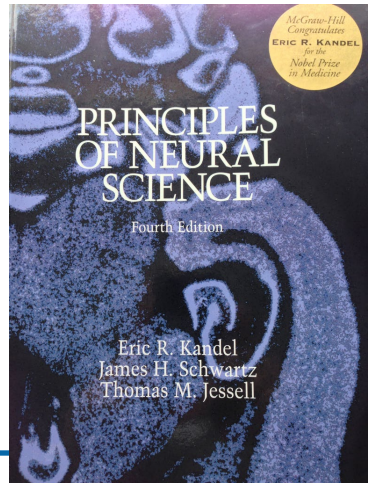
Figure 1–1. Intra- and extracellular current flow in an idealized pyramidal neuron due to different types of synaptic activation. EPSP: excitatory



EPSP Distal vs Proximal

- Thalamo-cortical into Layer 4 -> **Upwards**
- Contralateral-cortical into Layer 2,3 -> **Downwards**





Cortex is NOT Columnar EVERYWHERE

(But good enough for now)

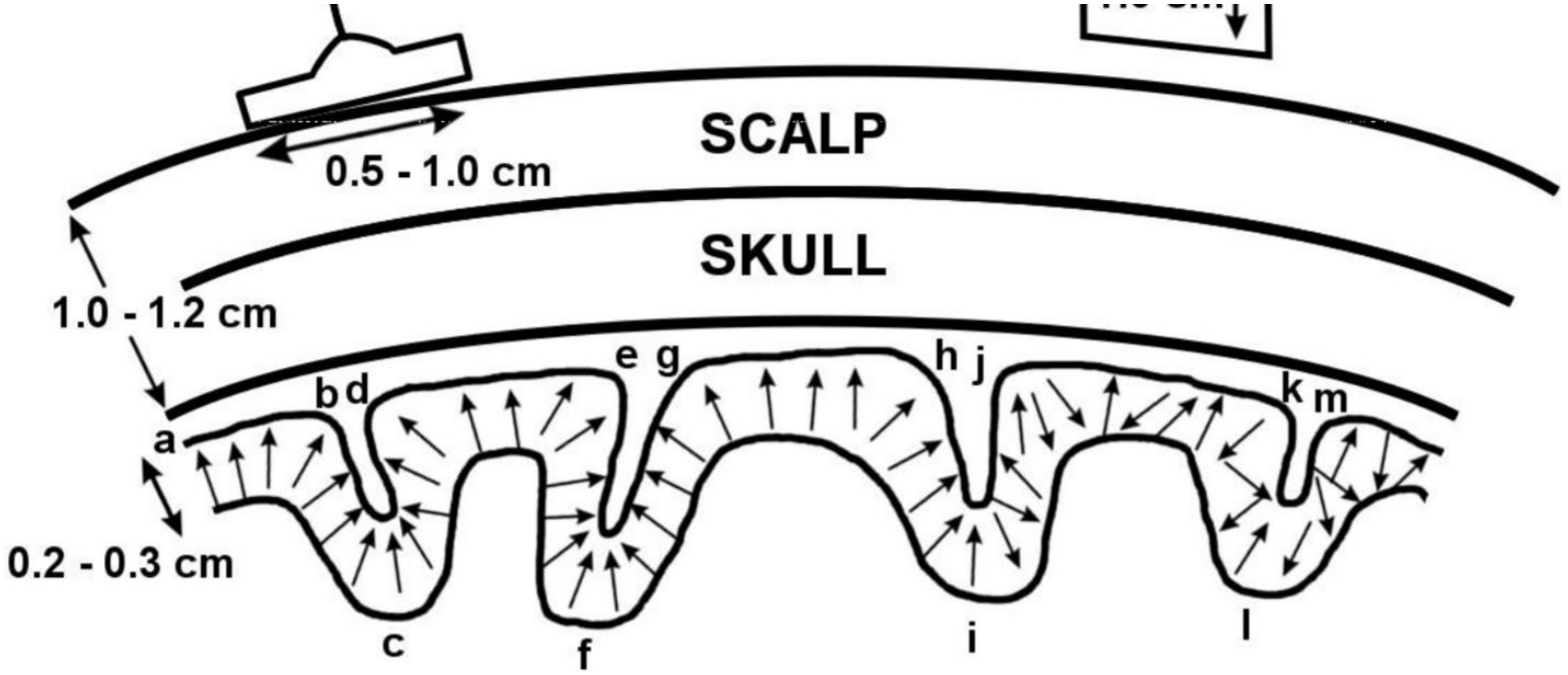


Figure 4. Cortical dipole layers. The arrows represent a snapshot of the macro source function $\mathbf{P}(\mathbf{r}, t)$, which is here assumed to be synchronous and directed perpendicular to the local cortical surface over the extended region a-i. In contrast, $\mathbf{P}(\mathbf{r}, t)$ has random directions in regions i-m.

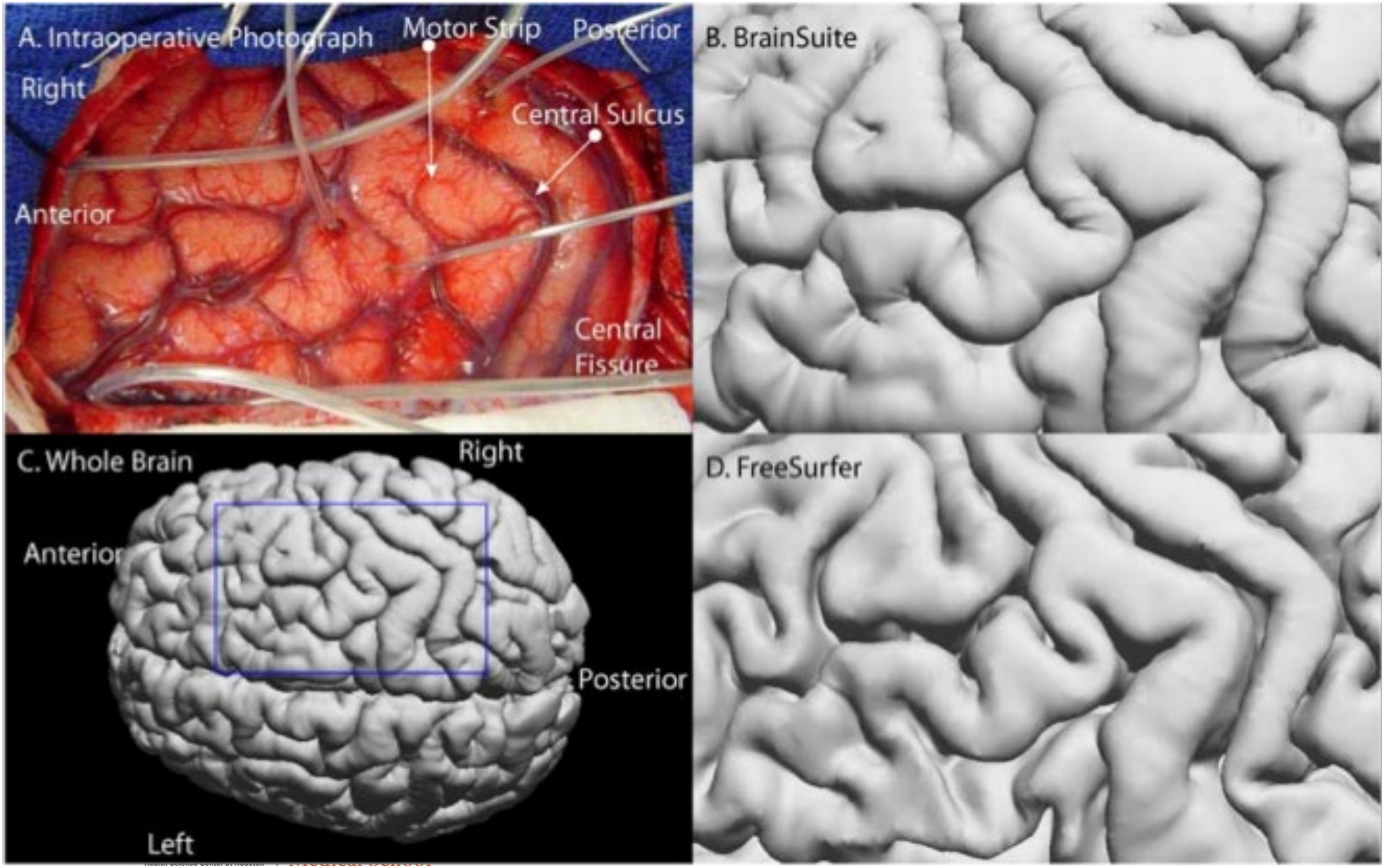
Outline

All models are wrong, but some are useful.

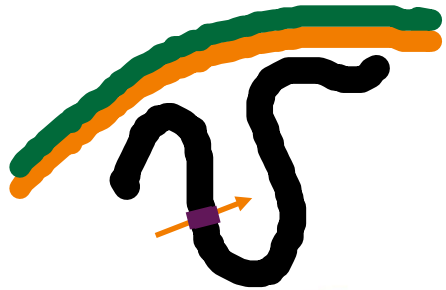
-*George Box*

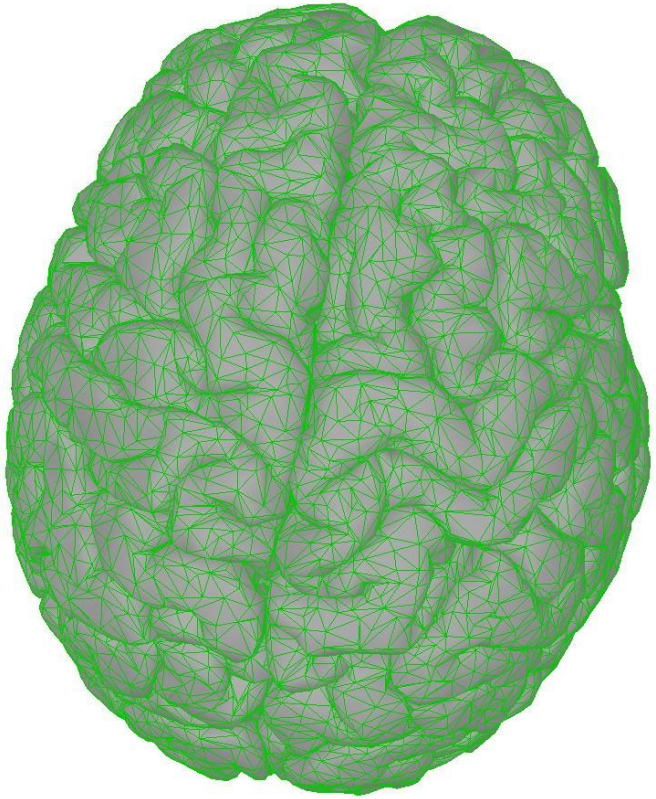
- Physiological basis of the **Current Column**
- **Modeling of the cortical surface**
- Invasive Source Modeling

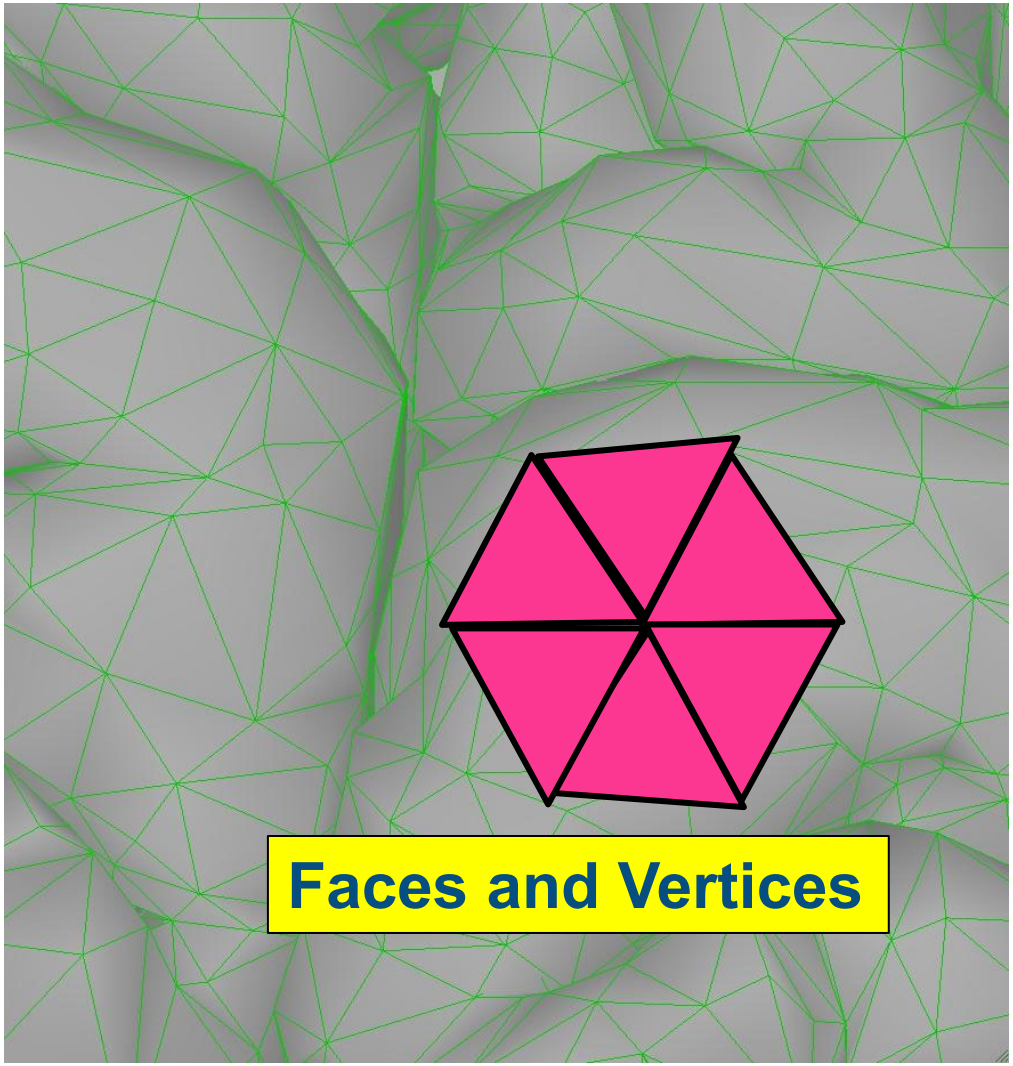
Cortical Surface



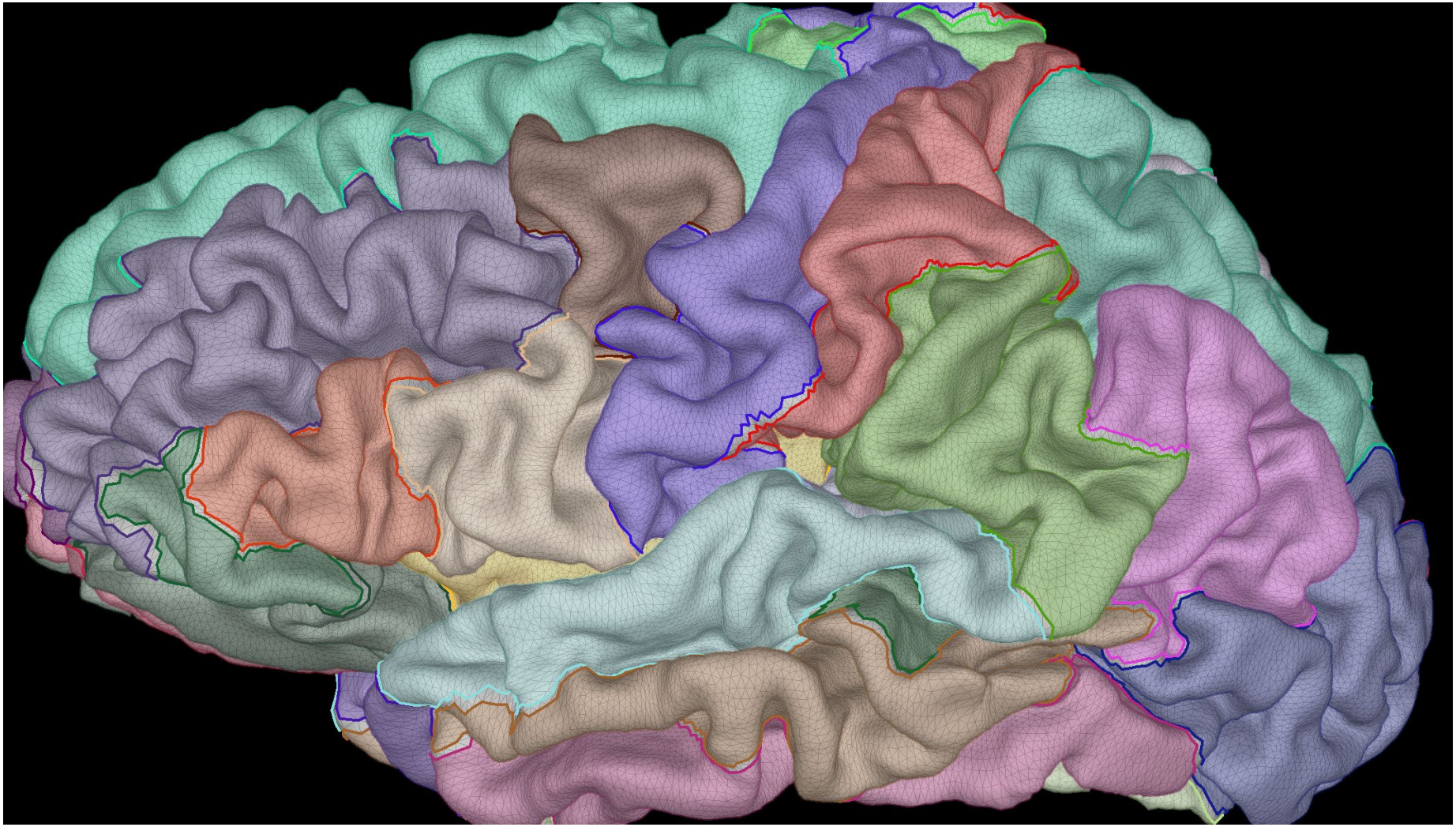
Cortical Modeling of Sources – Many Thousands of Triangles





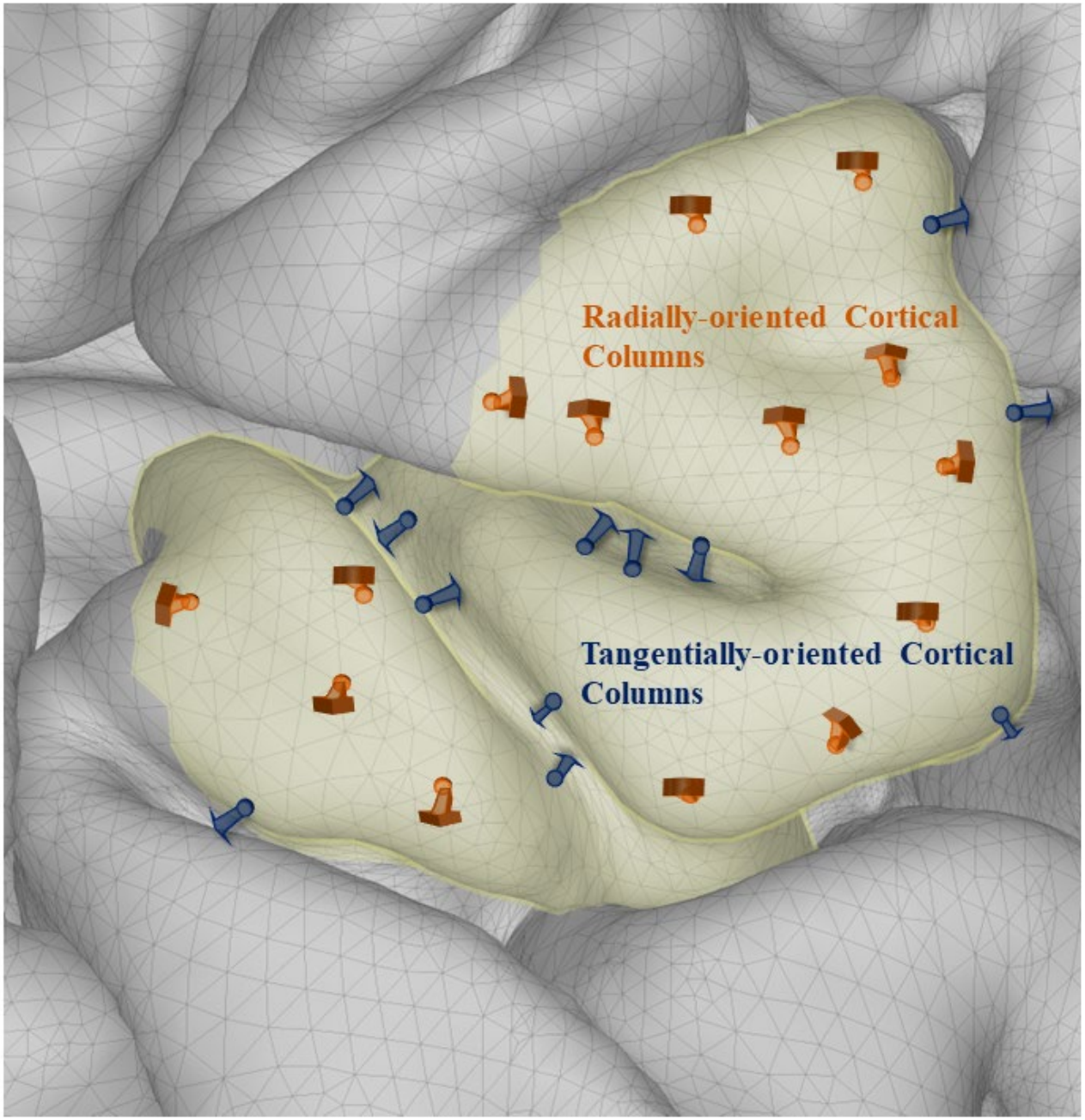


Even Denser, Hundreds of Thousands of Triangles - 252,224 **labeled** vertices, spanning 192,152 square mm



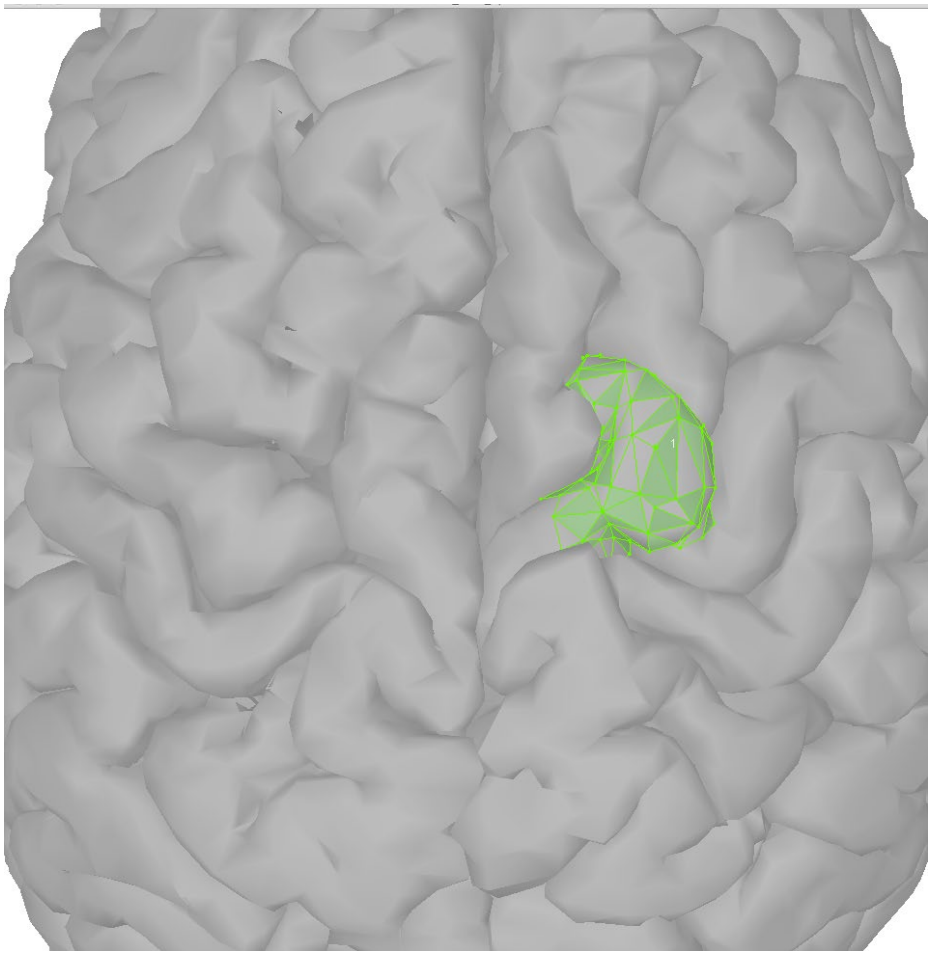
Freesurfer, **269,161** vertices total, **538,314** faces, nearly a perfect surface

Each vertex models an area of about **1 square mm** of a Cortical Column

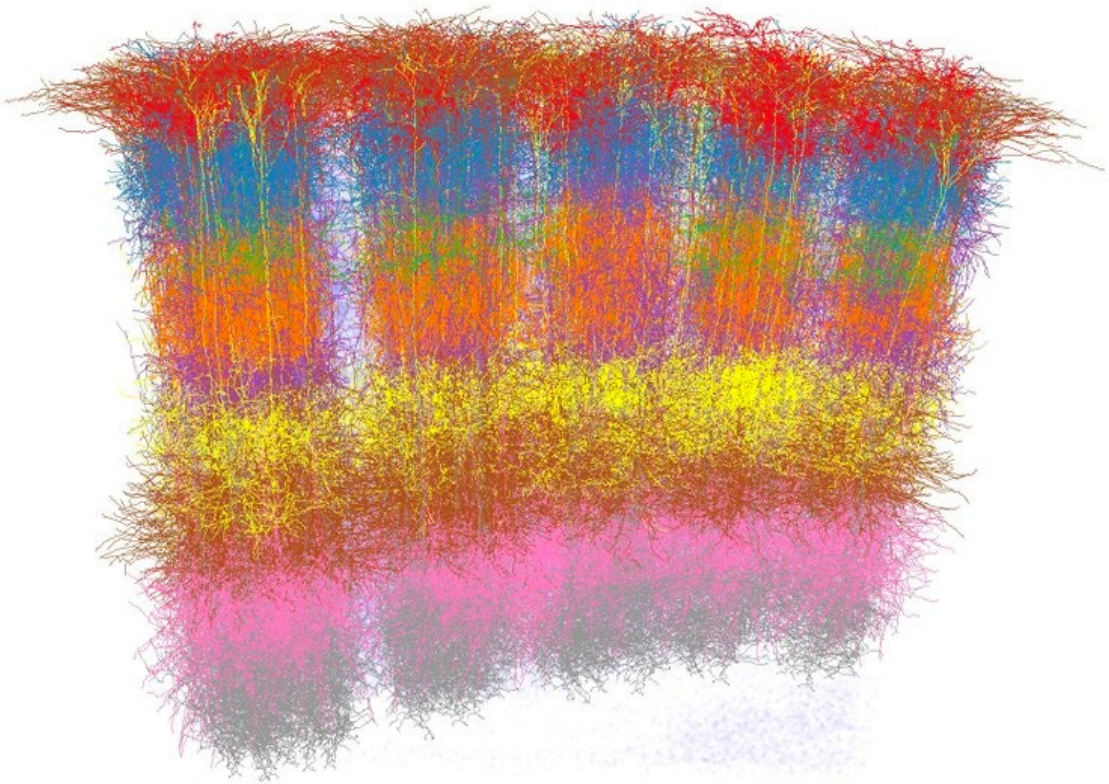


Patches on the Cortex

- Patch models are a collection of vertices, rather than a single dipole per vertex.
- Incorporates the intuitive and physiologic concept of a “distributed” source.



“Cortical Columns”

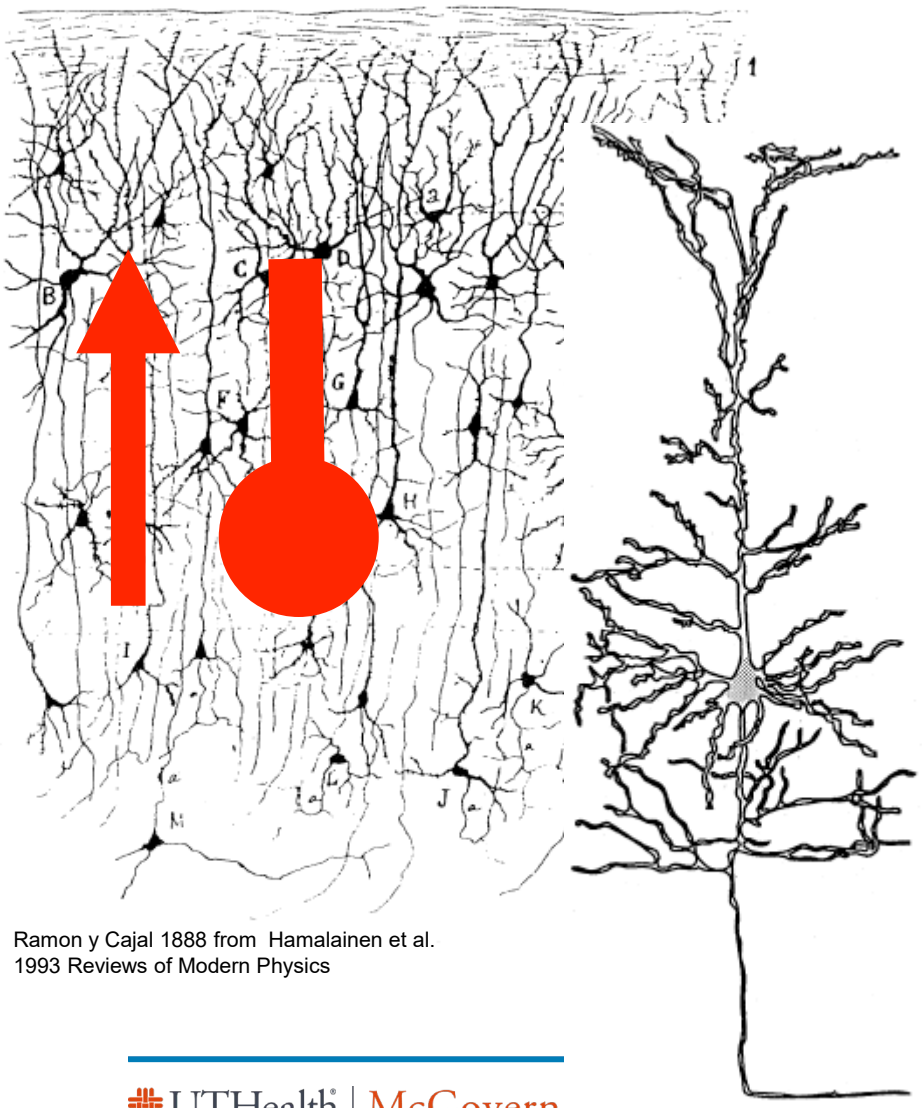


- Back to our “wrong” model: We ask the modeling question:

How much current can one square mm generate?

Cell-type-specific 3D reconstruction of five neighboring barrel columns in rat vibrissal cortex (credit: Marcel Oberlaender et al.)

Current Dipole Moment of Neurons



Ramon y Cajal 1888 from Hamalainen et al.
1993 Reviews of Modern Physics

- Post-synaptic Potentials along the length of the pyramidal cells, effective conductor length of about **2mm** (very arguable)
- Each pyramidal cell generates about

  20 fA-m = 20 pA-mm

  or **10 pA flowing along 2 mm.**
- Therefore, **one million** cells is
  20 nA-m = 20μA-mm,
  about that of an evoked response.
- Epilepsy Spike is about
  200 nA-m = 200μA-mm
- Compare functional stimulation:

  4mA bipolar into 5mm contact separation = 20 mA-mm

  -> 20,000 nA-m!

“Okada Constant” for Current Density

NeuroImage 111 (2015) 49–58

Contents lists available at ScienceDirect

NeuroImage

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

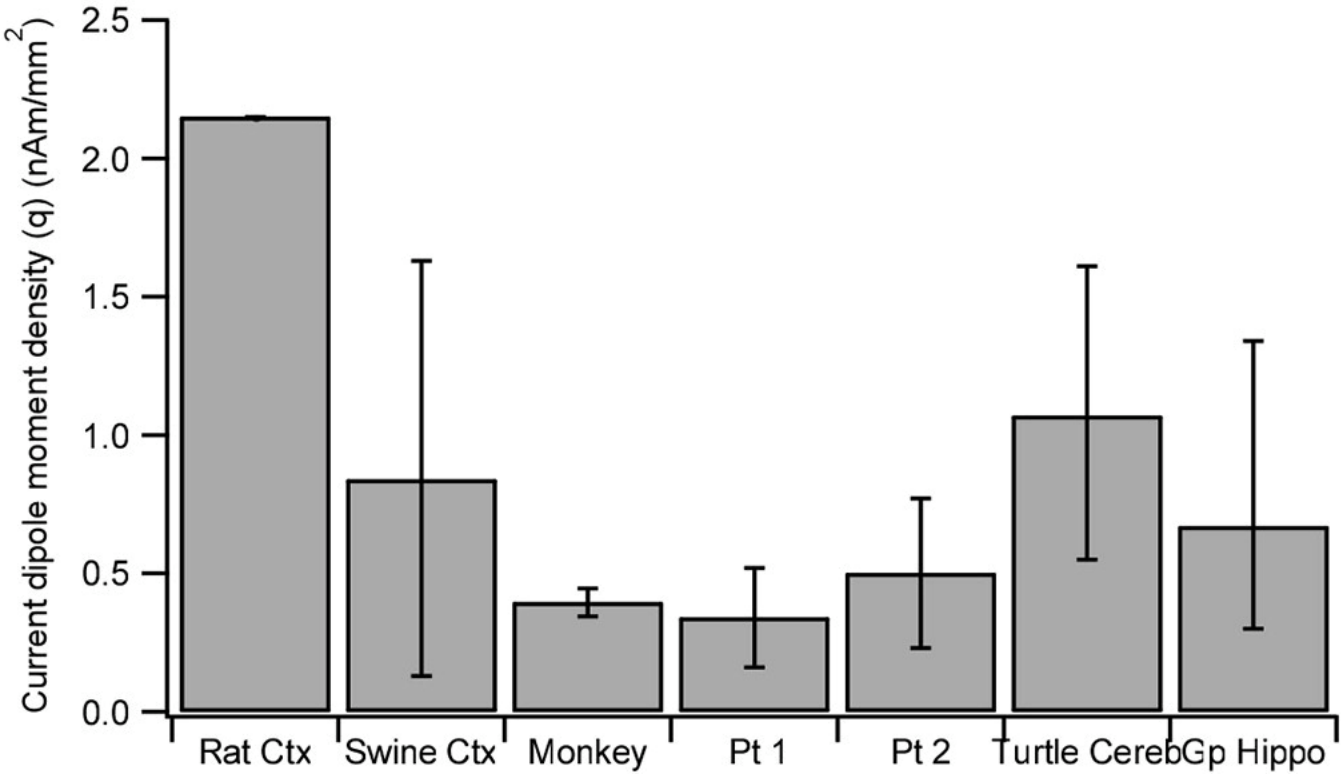
Invariance in current dipole moment density across brain structures and species: Physiological constraint for neuroimaging

Shingo Murakami [a], Yoshio Okada [b,*]

2015 Neuroimage, Vol 111, 49-58

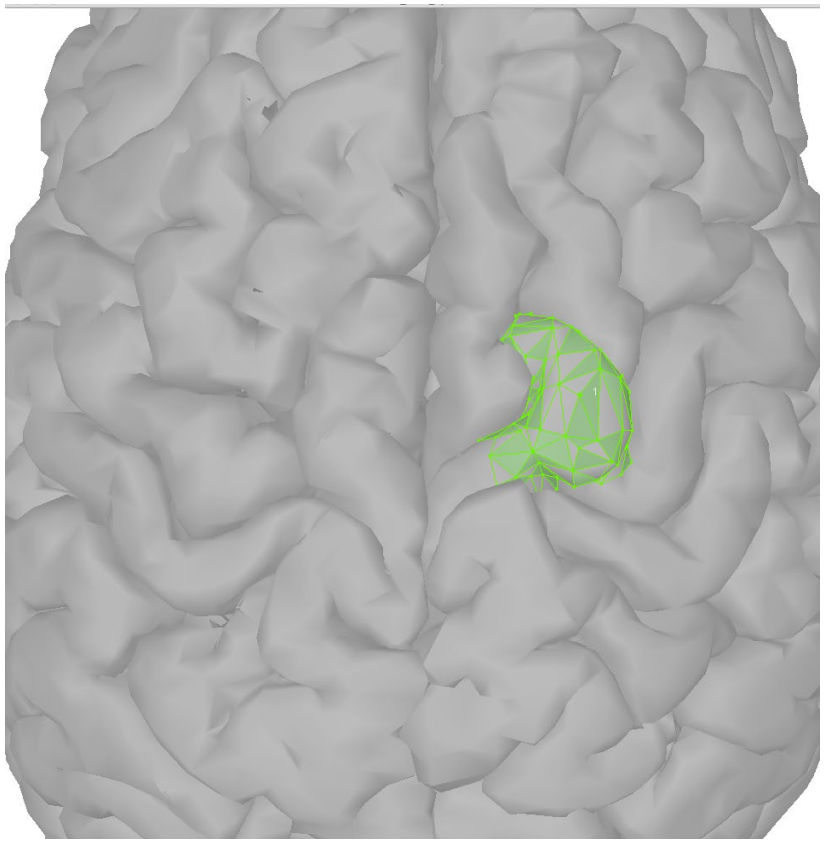
Invariance Across Species – **"About"** 1 nA-m / mm^2

- Units of nA-m per square mm
- Convenient for immediately scaling cortical area



The Equivalent Current Dipole Models a Patch on the Cortex

- Using “Okada Constant”:
  - 20 nA-m is a **minimum** of 20 mm^2 of activated cortex
  - 200 nA-m is **minimum** of 200 mm^2
- Simply varying the current density over the range of 0.1 to 1 nA-m/mm^2 easily changes these extents by a **factor of 10**.



Outline

All models are wrong, but some are useful.

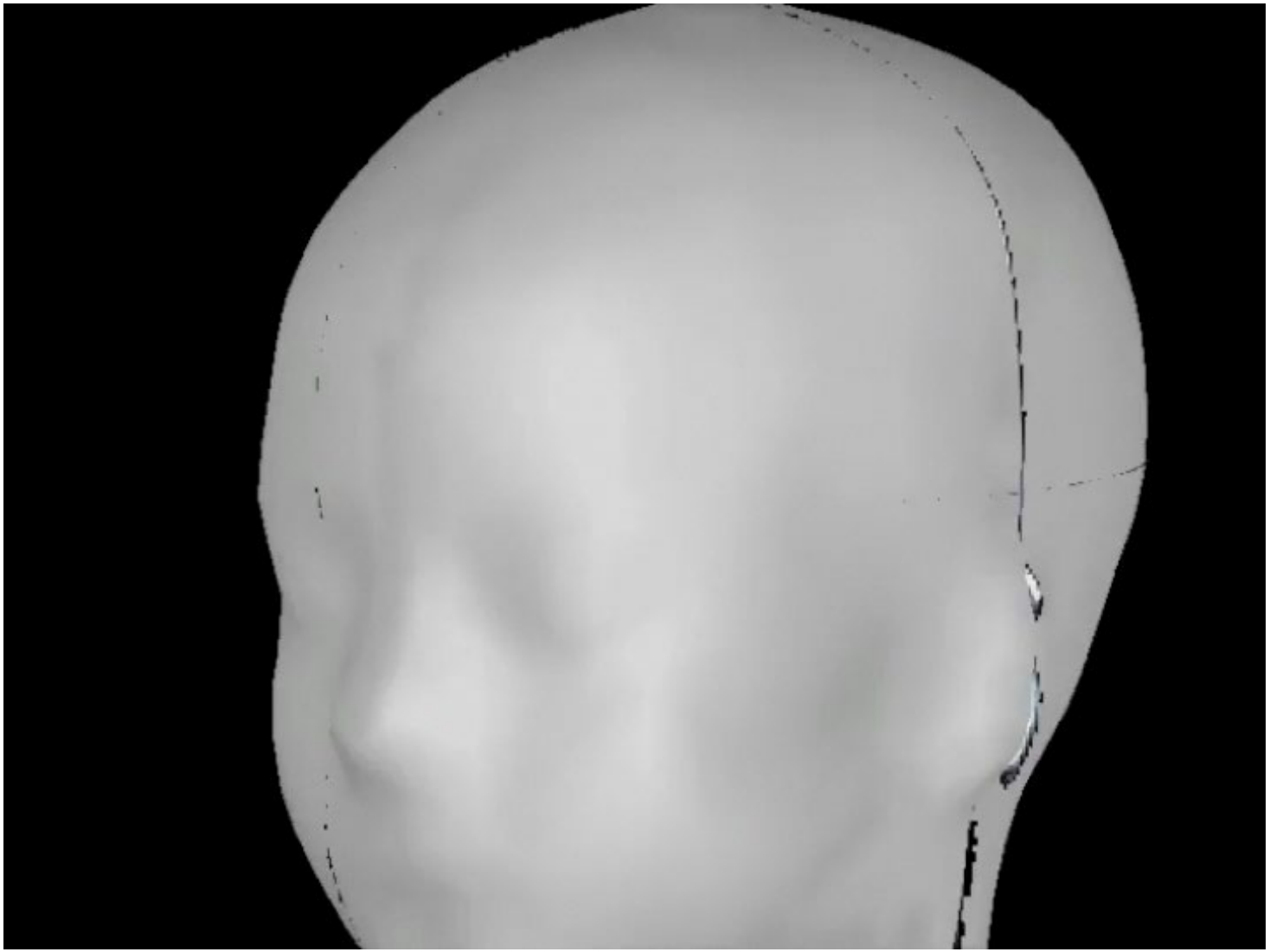
-*George Box*

- Physiological basis of the **Current Column**
- Modeling of the cortical surface
- **Invasive Source Modeling**

Brainstorm SEEG

- SEEG Contacts are registered to the PT anatomy
- Contacts are visualized life-size
- Brainstorm tutorial on how to do in your facility

Brainstorm SEEG Processing



Good Coverage is Important!

Epilepsy Research 128 (2016) 68–72

Contents lists available at www.sciencedirect.com

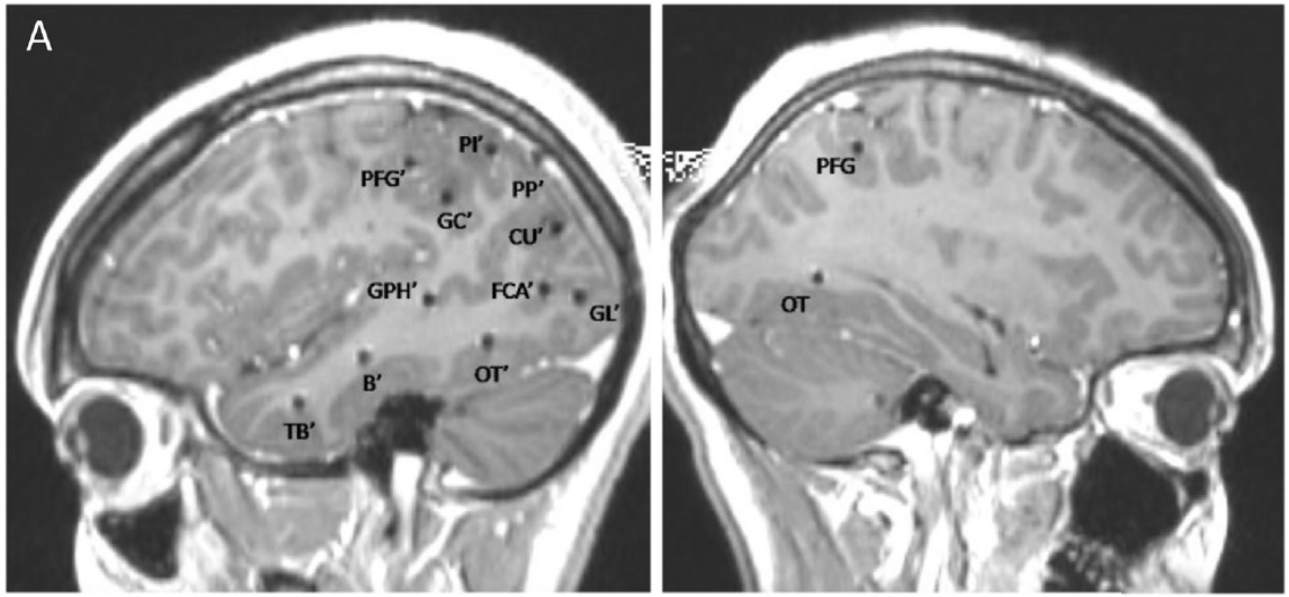
Epilepsy Research

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

Short communication

Simultaneous SEEG-MEG-EEG recordings Overcome the SEEG limited spatial sampling

Martine Gavaret[a,b], Anne-Sophie Dubarry[a,c], Romain Carron[a,d], Fabrice Bartolomei[a,b], Agnès Trébuchon[a,b,1], Christian-George Bénar[a,*,1]



MEG Localized

Epilepsy Research 128 (2016) 68–72

Contents lists available at www.sciencedirect.com

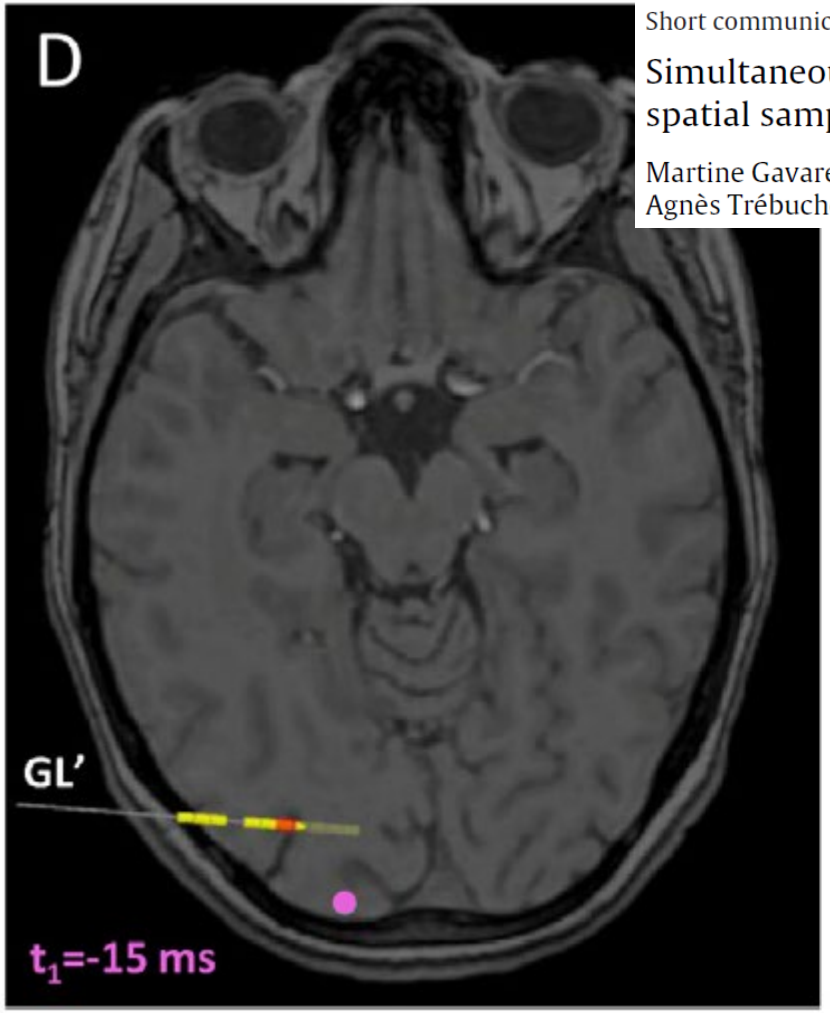
Epilepsy Research

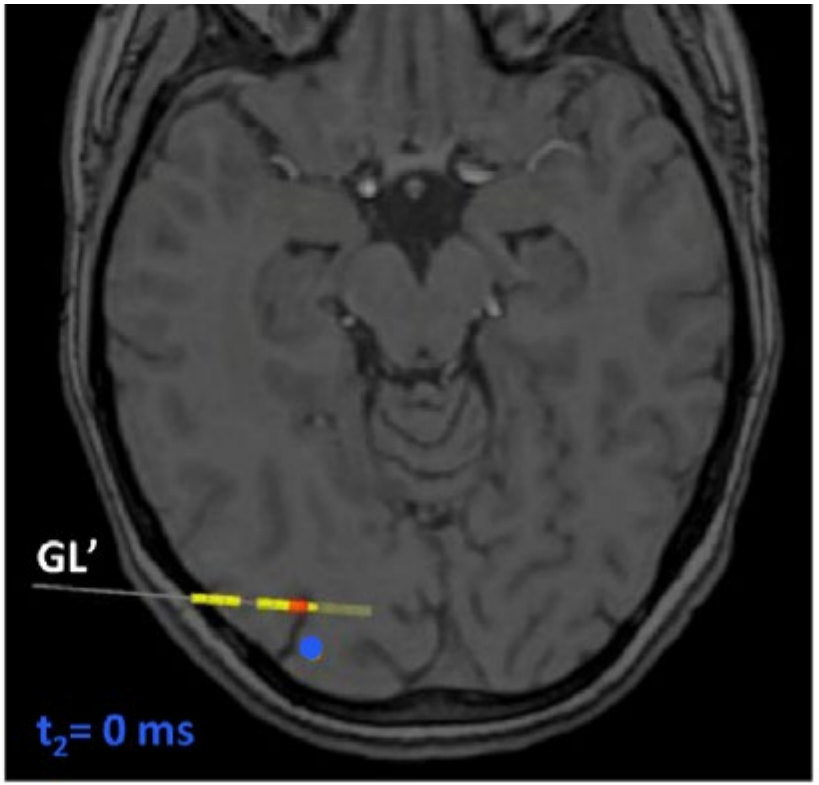
journal homepage: www.elsevier.com/locate/epilepsyres

Short communication

Simultaneous SEEG-MEG-EEG recordings Overcome the SEEG limited spatial sampling

Martine Gavaret[a,b], Anne-Sophie Dubarry[a,c], Romain Carron[a,d], Fabrice Bartolomei[a,b], Agnès Trébuchon[a,b,1], Christian-George Bénar[a,*,1]





UTHealth The University of Texas Health Science Center at Houston | McGovern Medical School

Excellent Reference Paper on Good Practices

NeuroImage 260 (2022) 119438

Contents lists available at ScienceDirect

NeuroImage

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

Advances in human intracranial electroencephalography research, guidelines and good practices

Manuel R. Mercier[a,*], Anne-Sophie Dubarry[b], François Tadel[c], Pietro Avanzini[d], Nikolai Axmacher[e,f], Dillan Cellier[g], Maria Del Vecchio[d], Liberty S. Hamilton[h,i,j], Dora Hermes[k], Michael J. Kahana[l], Robert T. Knight[m], Anais Llorens[n], Pierre Megevand[o], Lucia Melloni[p,q], Kai J. Miller[r], Vitória Piai[s,t], Aina Puce[u], Nick F Ramsey[v], Caspar M. Schwiedrzik[w,x], Sydney E. Smith[y], Arjen Stolk[s,z], Nicole C. Swann[aa], Mariska J Vansteensel[v], Bradley Voytek[g,y,ab,ac], Liang Wang[ad,ae], Jean-Philippe Lachaux[af,1], Robert Oostenveld[s,ag,1]

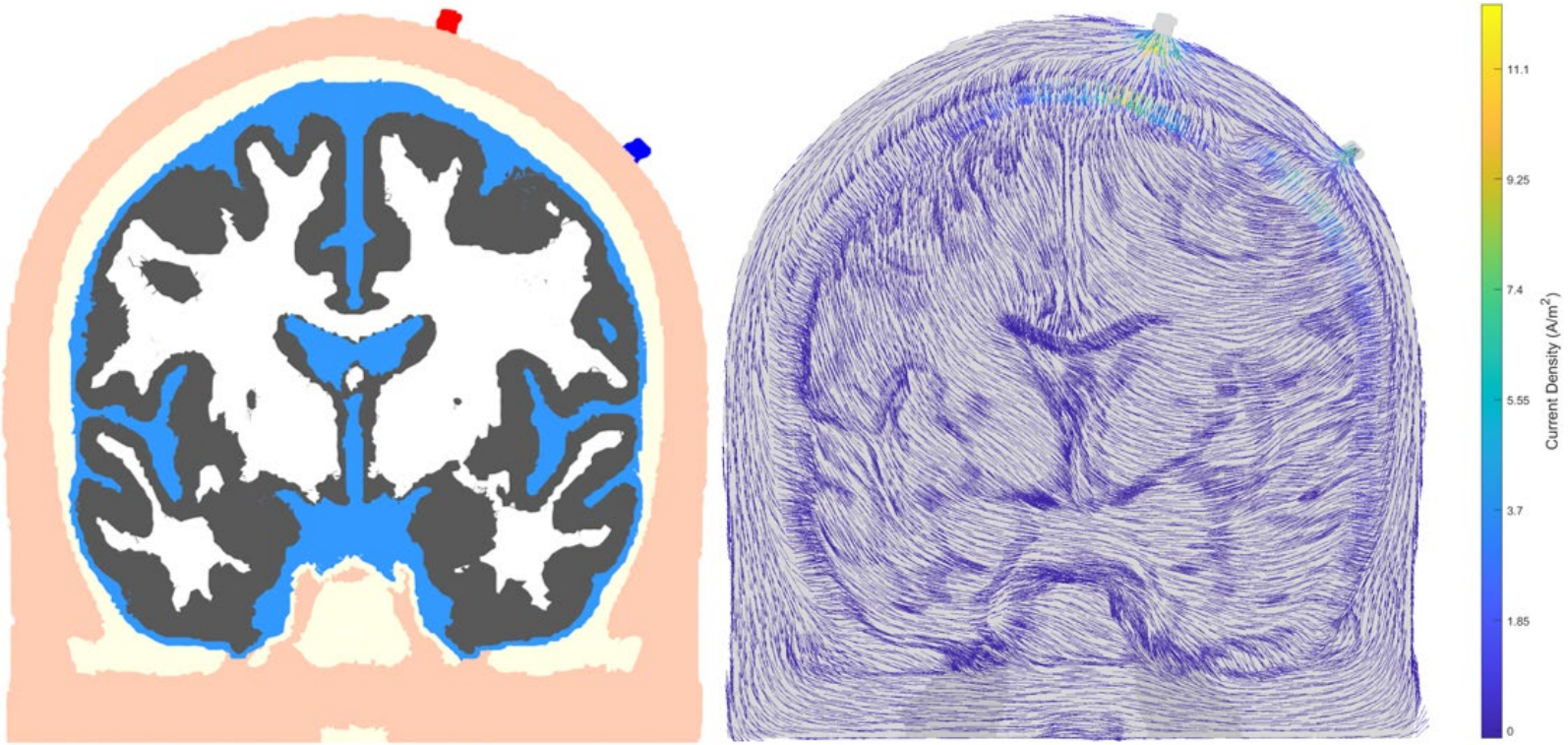
Example Case Study

- PT has PMG (polymicrogyria) in the right peri-rolandic region
  - –suspected seizure onset site
- 17 devices (‘electrodes’) implanted, comprising about 250 electrodes (‘channels,’ ‘contacts’).
- Surface modeling of the “mid” surface between pial and gray/white boundaries.
- (VLC Movie: Viewing the Implantation)

Leadfield Analyses

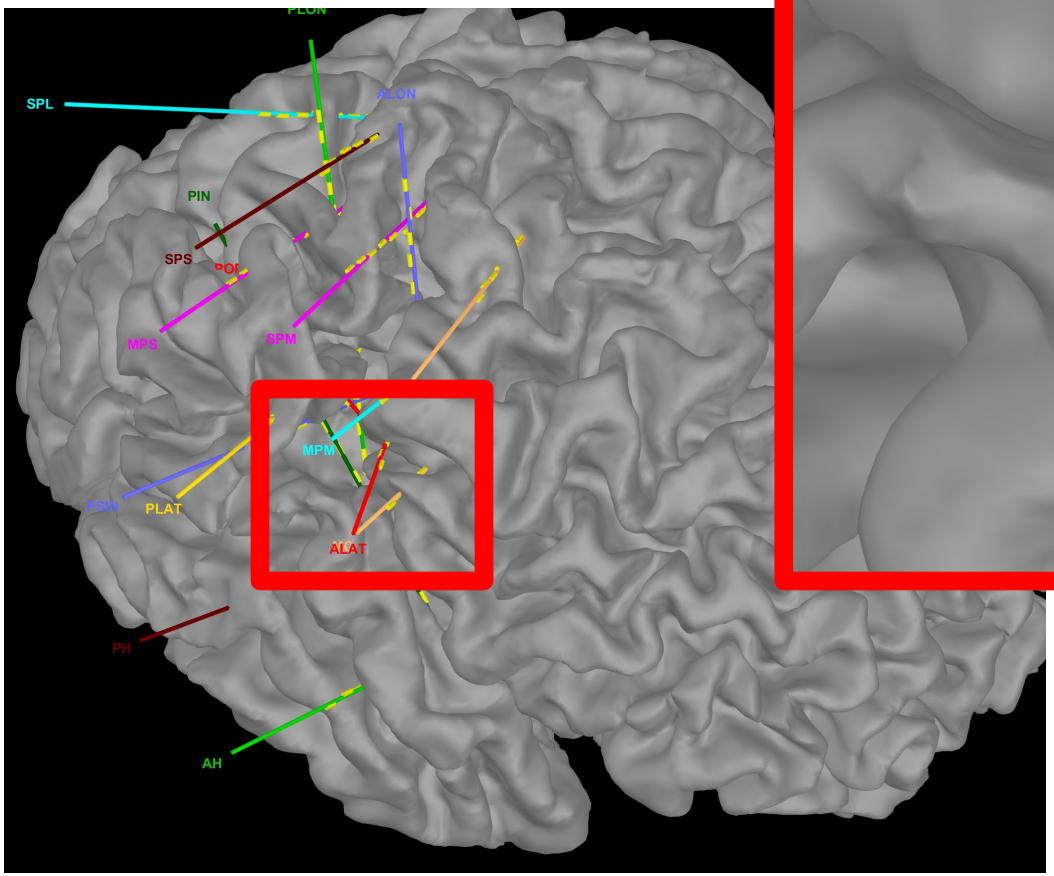
- In this example, the cortical surface comprises ~270,000 vertices, and we have ~250 SEEG contacts.
- For each of the vertices, we calculate the forward model to all contacts.
  - OpenMEEG or DuneNEURO
  - Forward model calculated in x, y, and z directions.
  - Forward matrix is 250 x 3 for each vertex.
- The result is a matrix of size 250 x 810,000.
  - Only a few GB at single precision.
- By reciprocity, each ROW of this matrix represents samples of the leadfields for that contact.

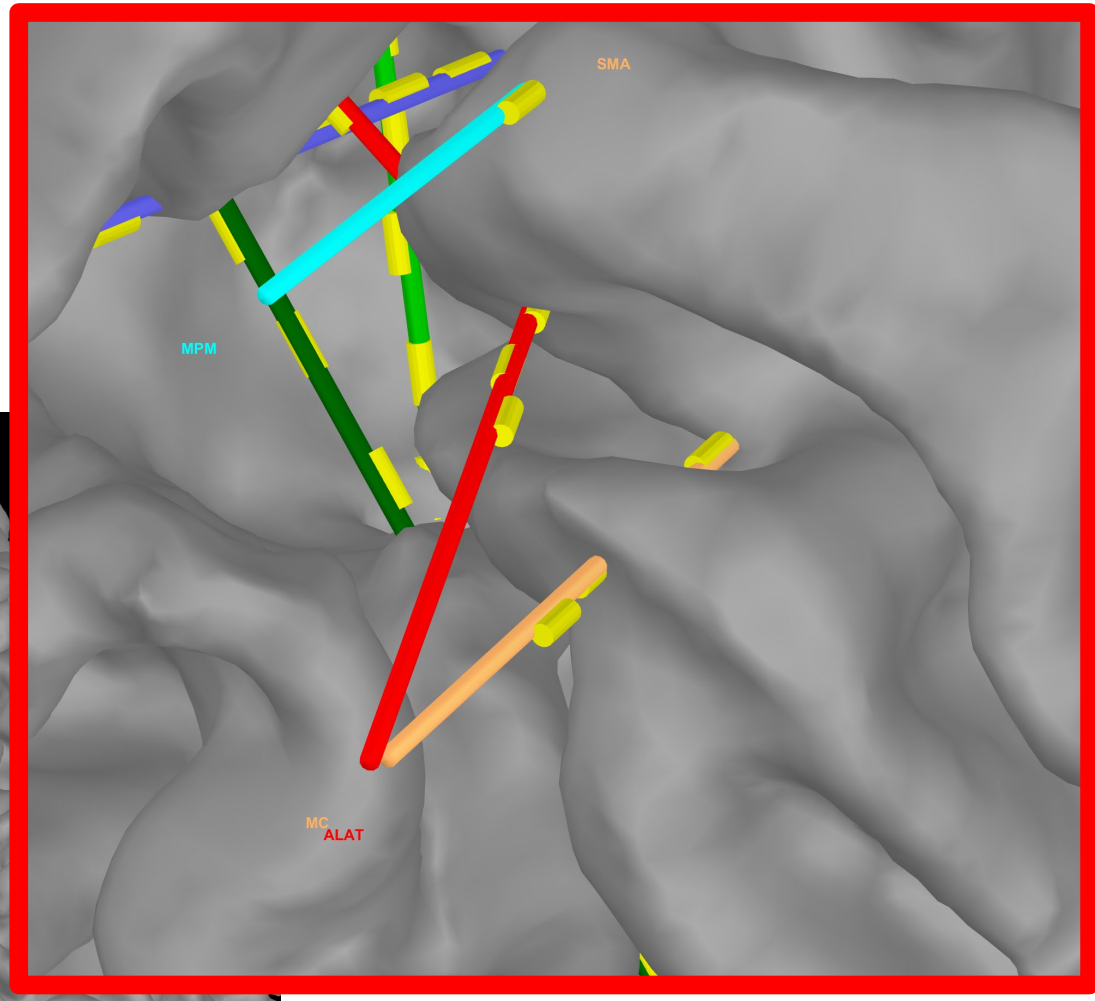
FEM Lead-Fields in a Five Compartment Model



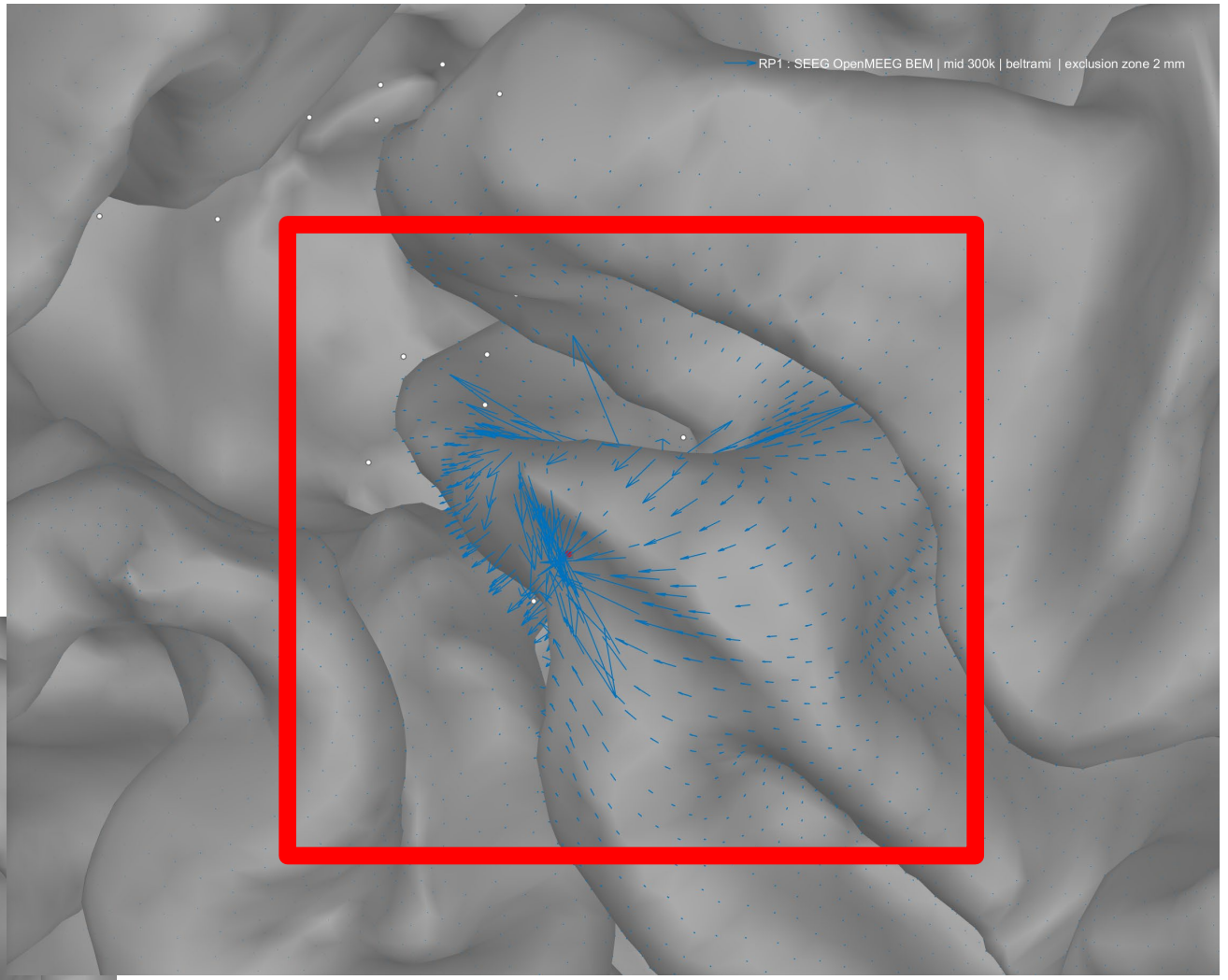
- DUNEuro – Brainstorm implementation.
  - Duneuro is based on the DUNE library (distributed and unified numerics environment)
  - Brainstorm provides a Matlab interface to duneuro
  - Example here is the lead fields through a five isotropic compartment
  - REF: Duneuro.org and neuroimage.usc.edu/brainstorm

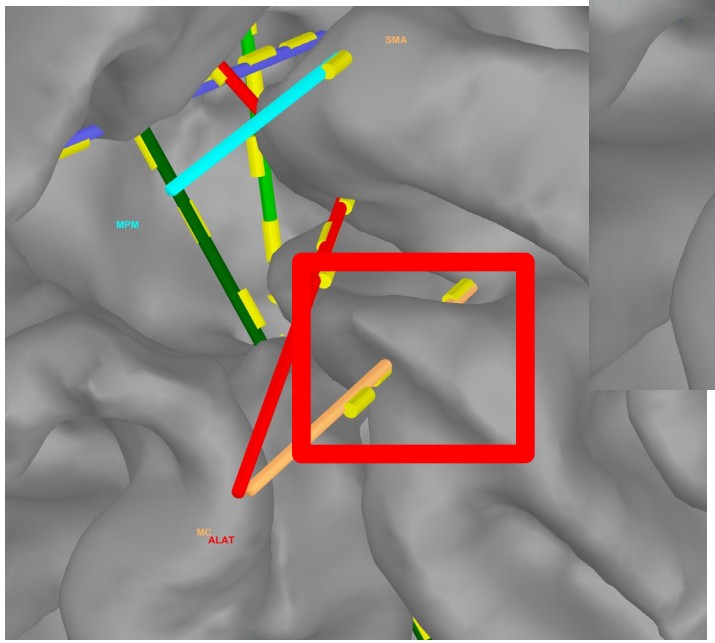
Leadfields


PLON
SPL
ALON
PIN
SPS
POL
MPC
SPM
MPM
PSN
PLAT
ALAT
PH
AH

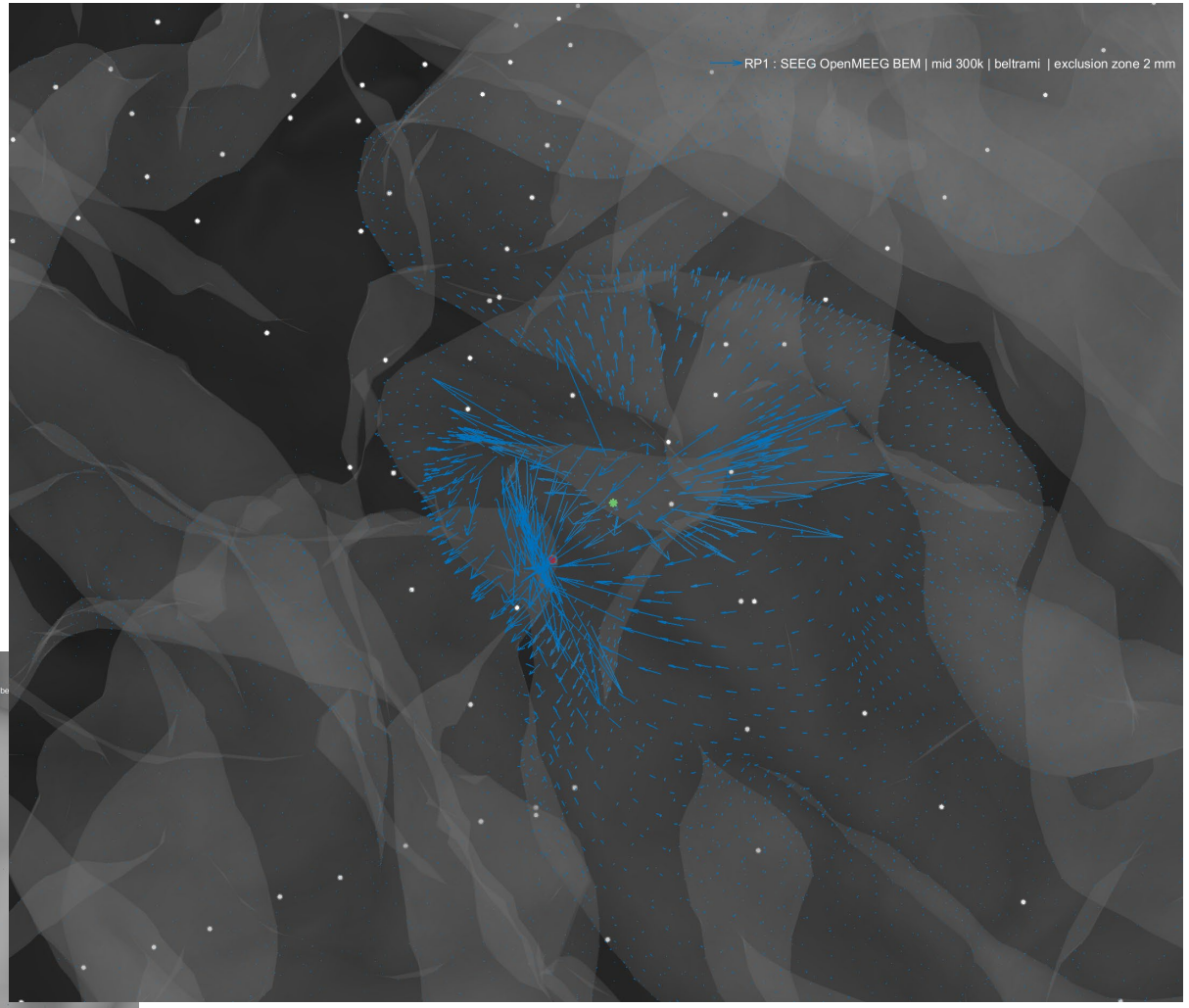

SMA
MPM
MC
ALAT

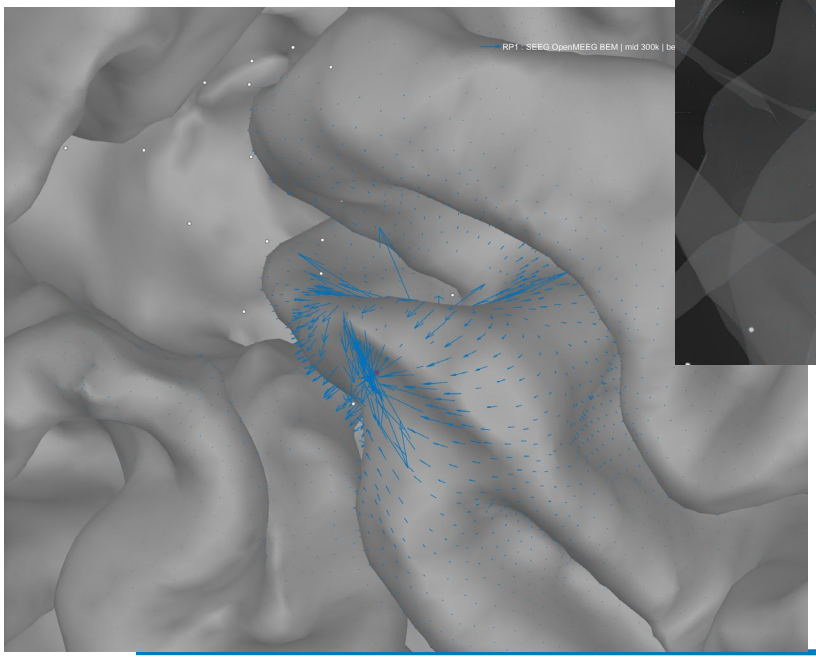
Leadfields


RP1 : SEEG OpenMEEG BEM | mid 300k | beltrami | exclusion zone 2 mm

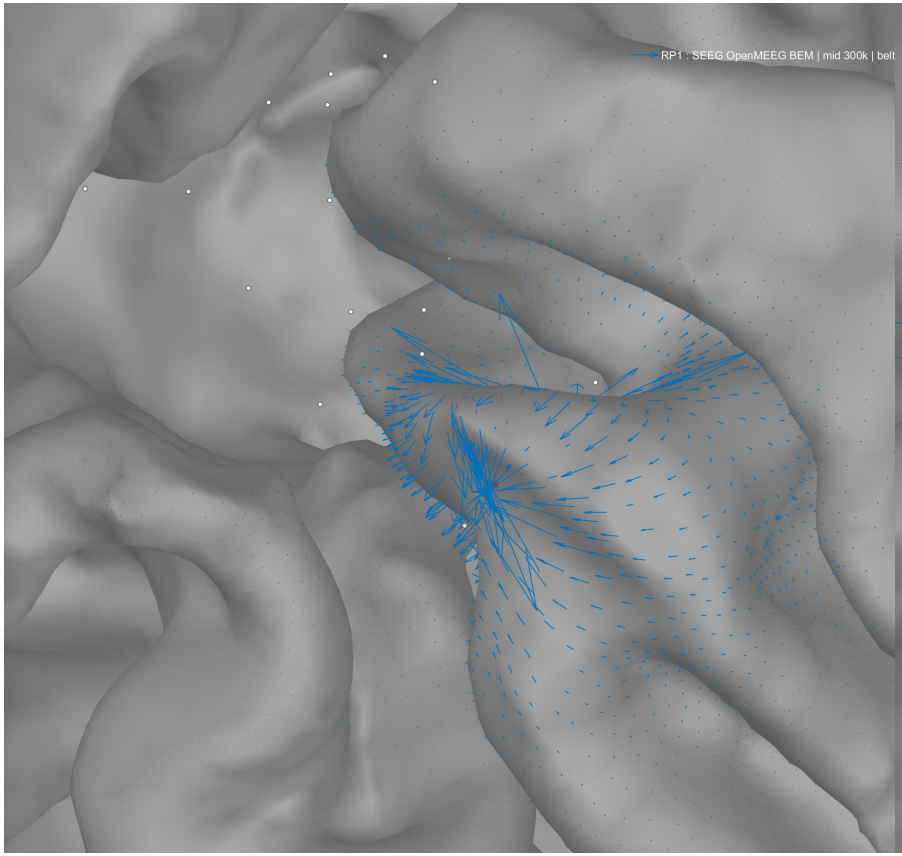

SMA
MPM
MC
ALAT

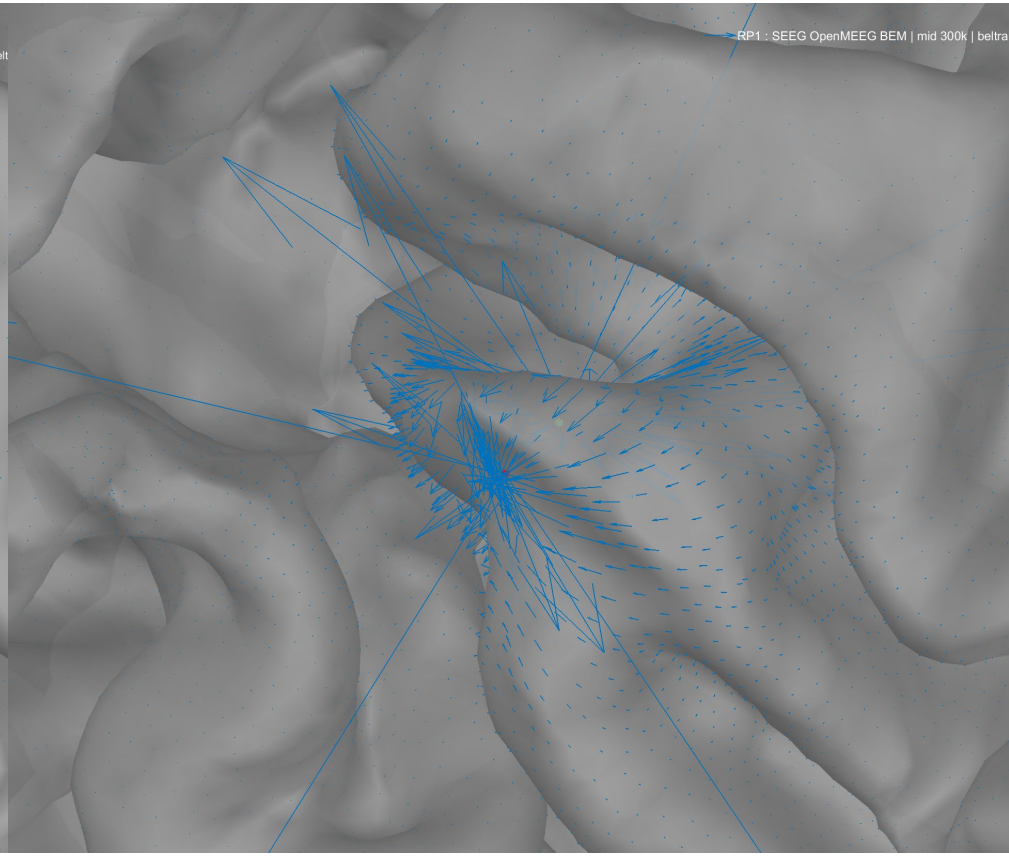
Leadfields


RP1 : SEEG OpenMEEG BEM | mid 300k | beltrami | exclusion zone 2 mm


RP1 : SEEG OpenMEEG BEM | mid 300k | be

Numeric Instabilities Need Trimming



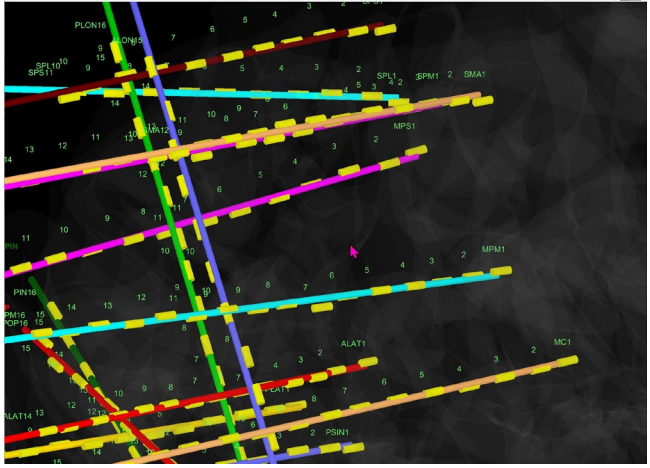


2mm Exclusion Zone

No Exclusion Zone

Stepping through Leadfields

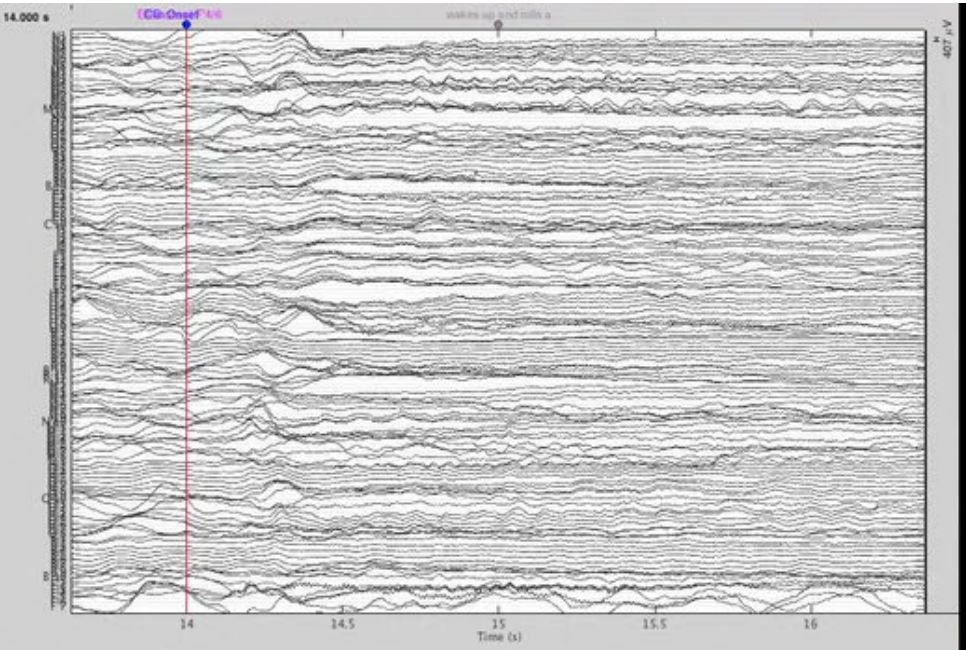
- (VLC Movie: Stepping Through)

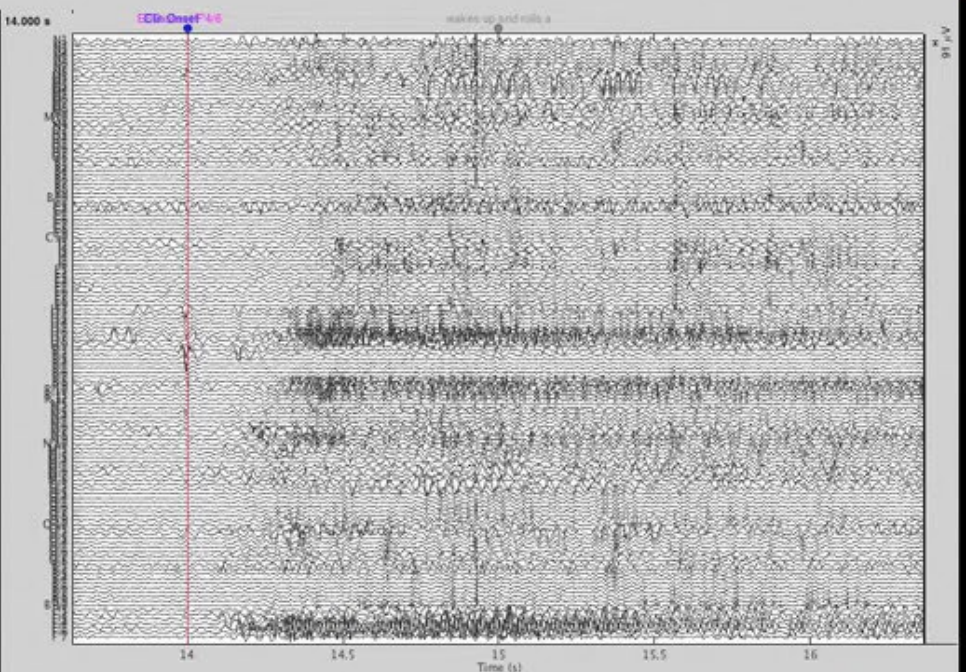


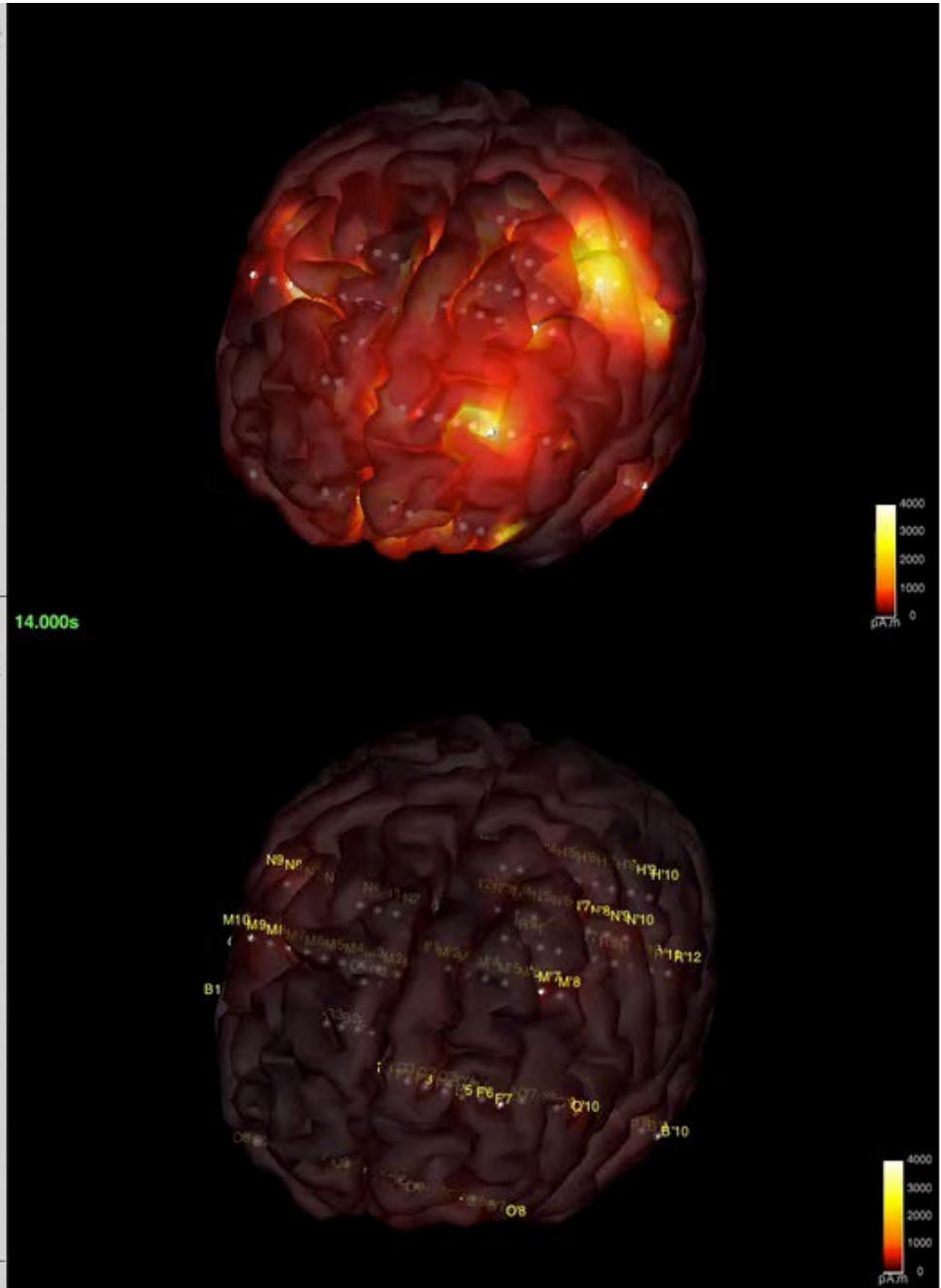
Source Imaging and Modeling

- Lead fields must be inspected for consistency
- With lead fields approved, minimum norm and its standardizations (sLORETA, dSPM, z-score) provide dynamic “heat maps”
- With good coverage (interpolation), some sources can be localized – dipole models

SZ - 1/10 speed - 2 seconds - two bands

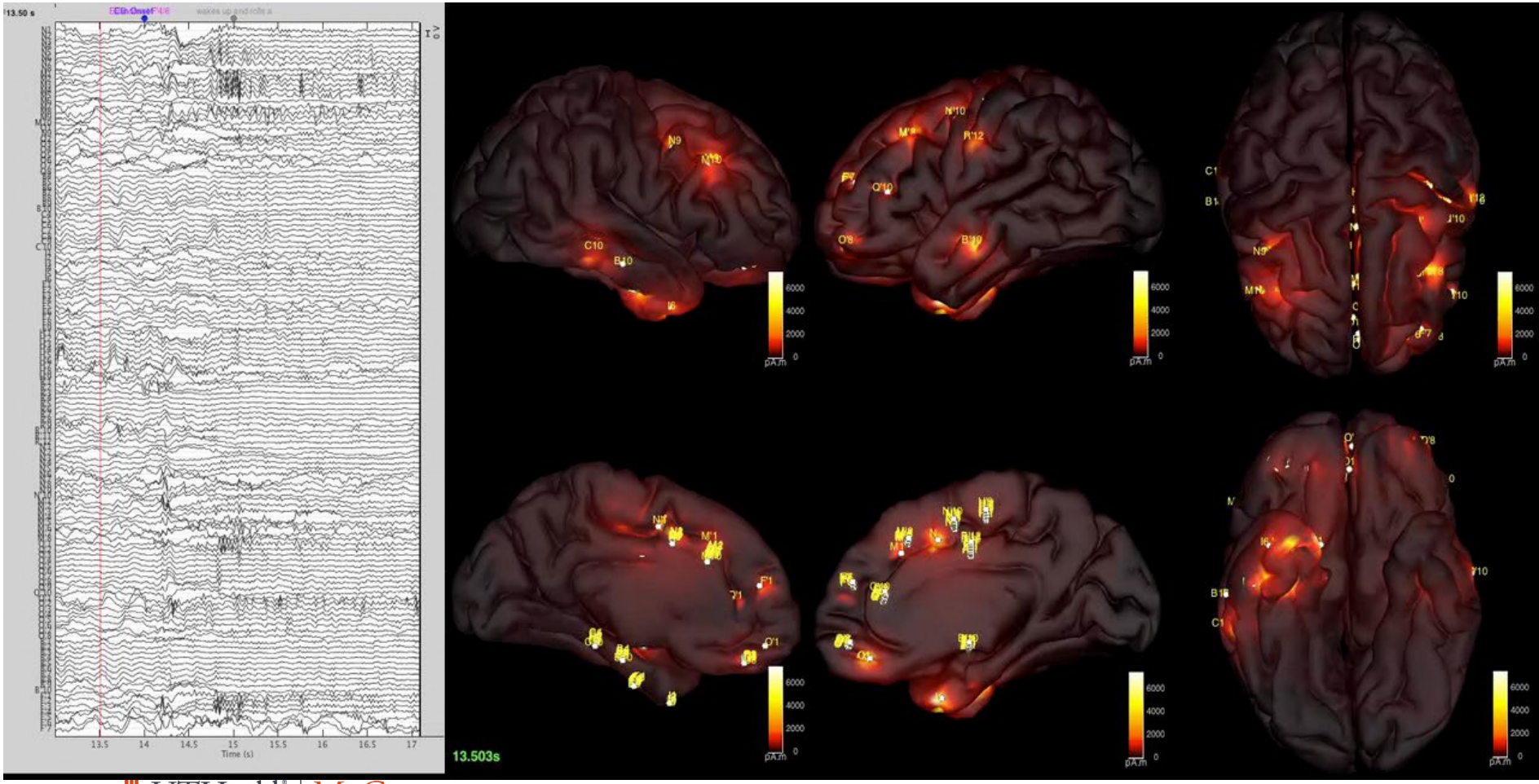




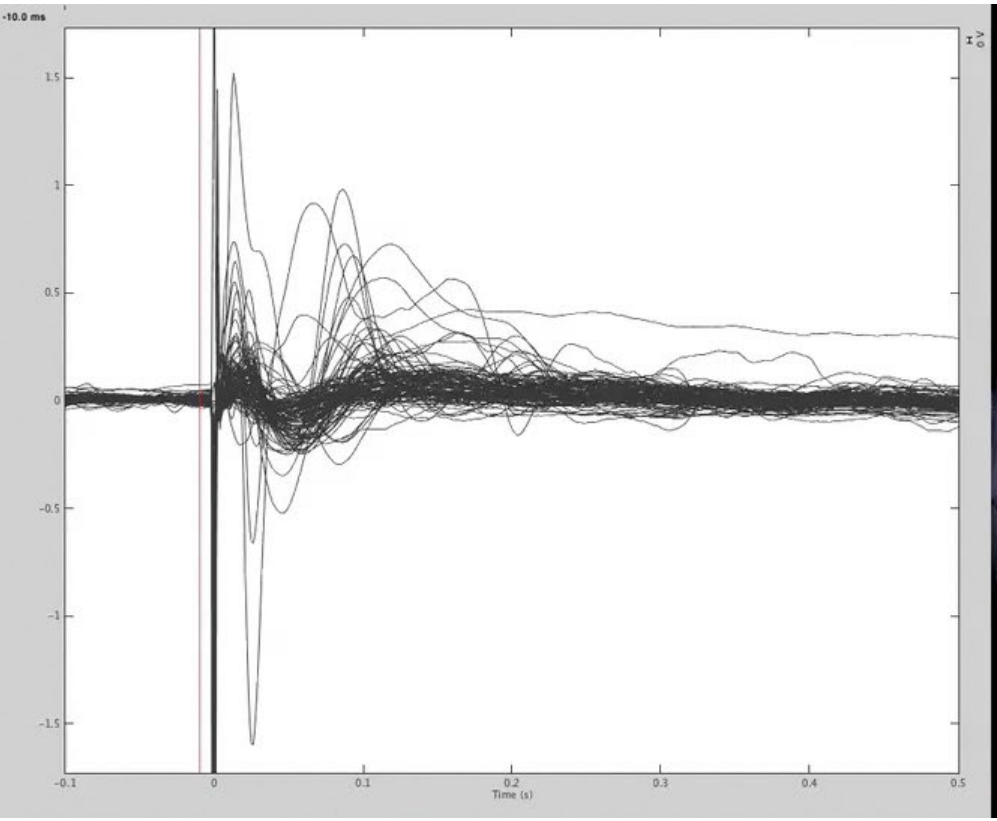


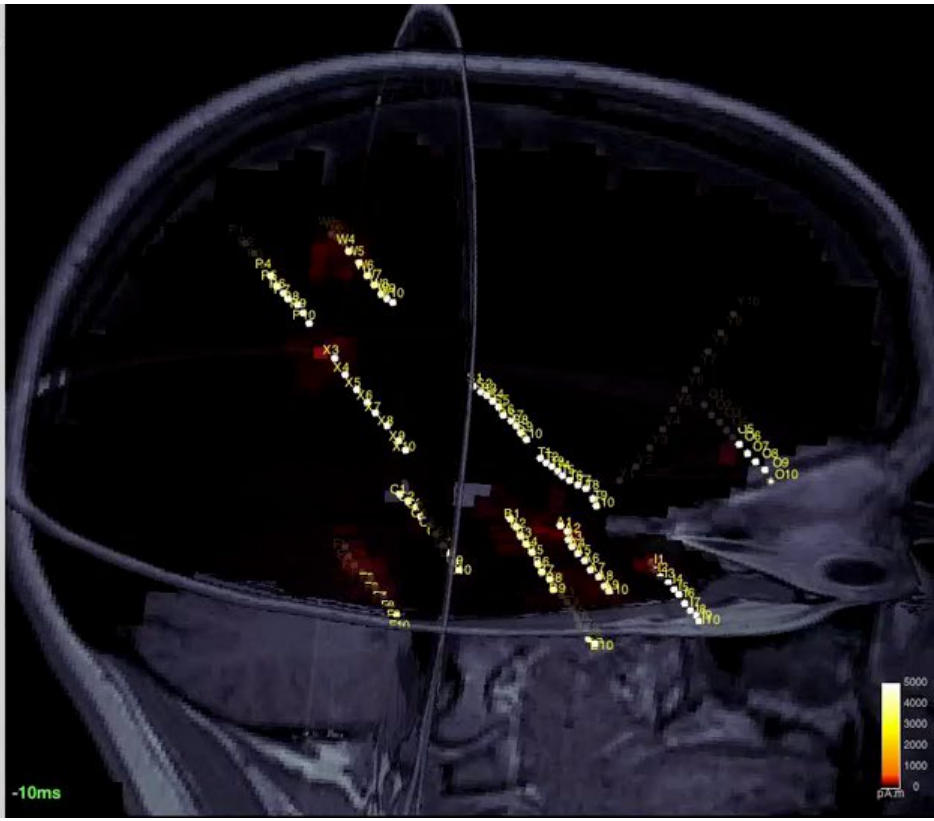
SZ Onset - Four Seconds Real-Time

- Simultaneous different views

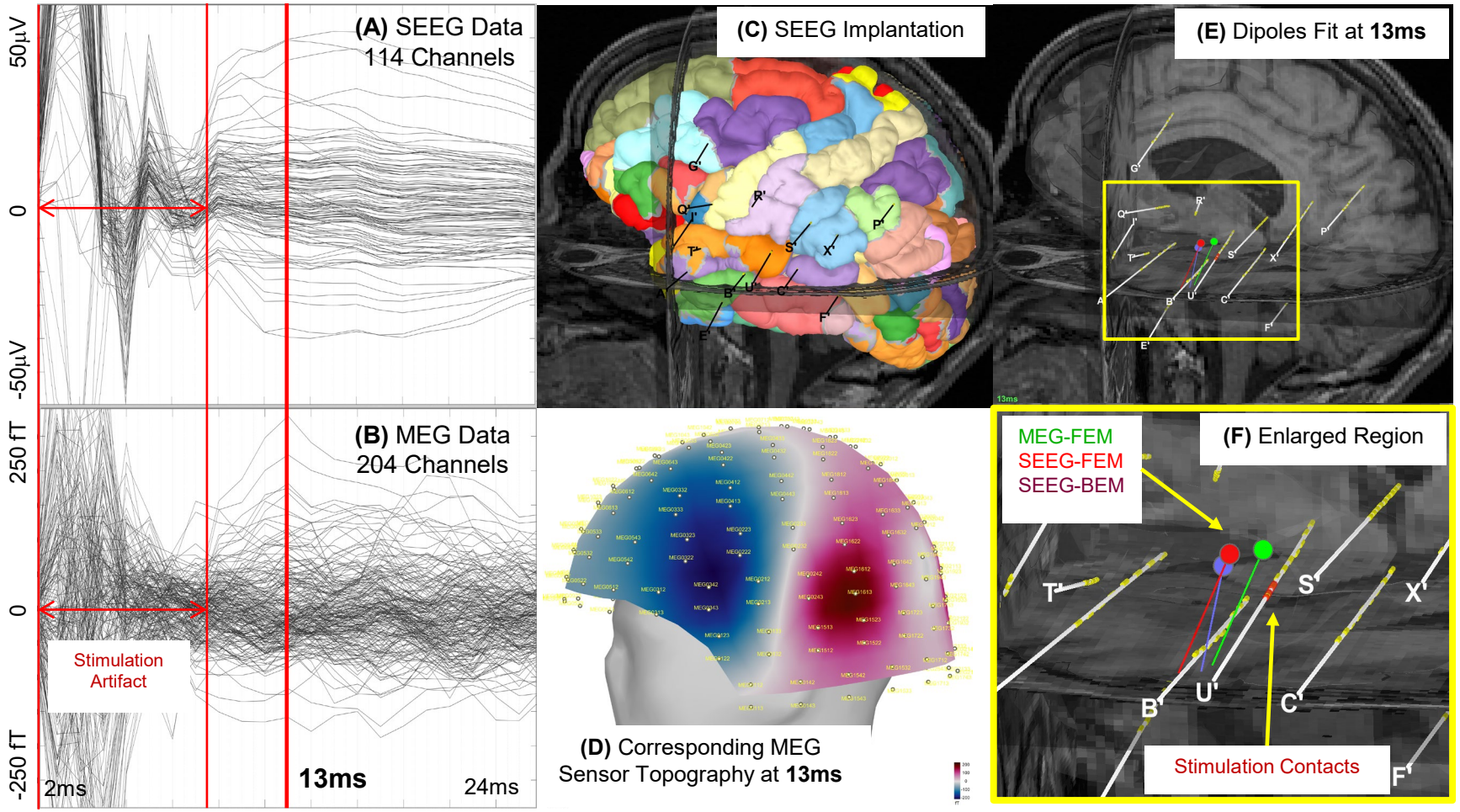


CCEPS - 1/10th real-time





MEG vs SEEG, BEM vs FEM for Dipole Localization



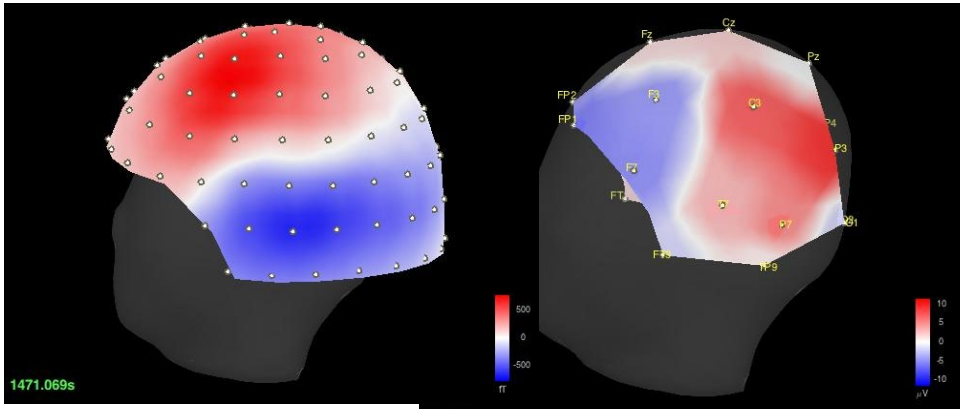
- Bipolar current stimulation at a pair of SEEG contacts produces focal early stimulus artifact and later propagating evoked response, here recorded simultaneously in (A) SEEG and (B) MEG arrays. (C) SEEG electrode locations (black) relative to the USC brain atlas coregistered to individual anatomy. (D) MEG sensor topography of the evoked response at 13ms. (E) Brain locations of dipole models: using SEEG-BEM (blue), SEEG-FEM (red) and MEG-FEM (green). (F) Enlarged view.

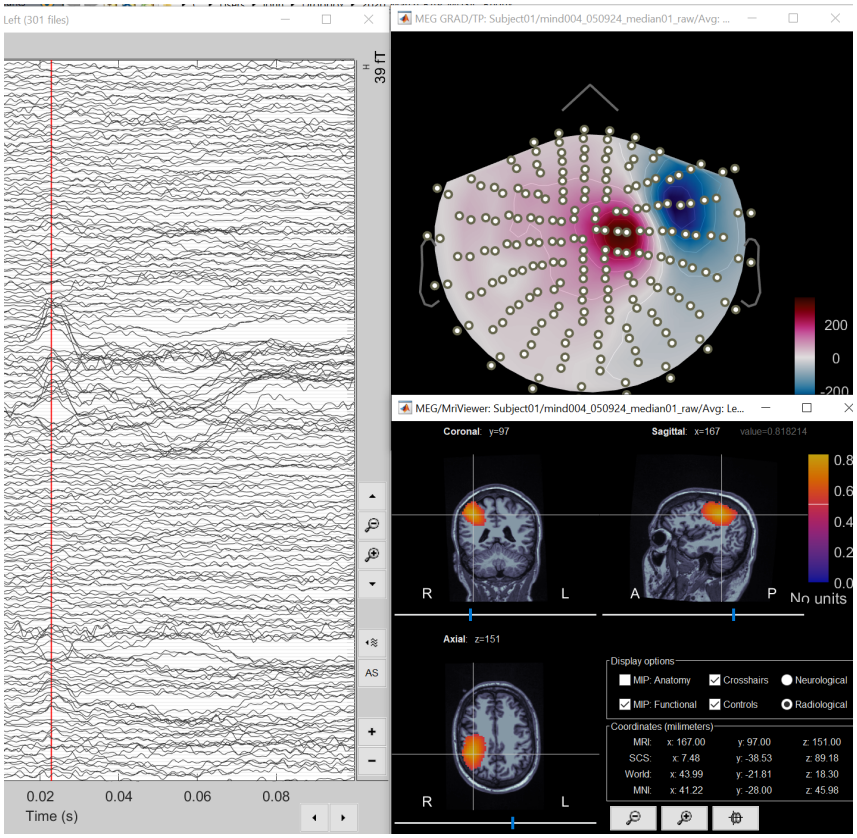
Dipole Interpretation Summary

- The Cortical Column represents a useful model of the gray matter, with EPSPs and IPSPs flowing up and down the column.
- Vertices from the tessellation of the cortex easily represent these cortical columns. In turn, these tessellations are easily joined to form patches of cortex.
- These extended sources nonetheless compress to models of point **equivalent** current dipoles (not shown today, see Jerbi 2004).
- We can directly **estimate** the location, orientation, and dipolar strength of these equivalent current dipoles.
- The true extent of the source can be **inferred** through the **Okada Constant** for source densities, about 1 nA-m per square mm.
- Minor variations in the assumed current density dramatically change this source extent, from 0.1 – 1.0 nA-m/mm^2.
- Any more sophisticated models of source extent should explicitly clarify this assumption of density.

Overall Summary

- Lead field modeling reveal how currents flow through our assumed head model and allows us to spot errors.
- Head models range from the simple sphere, overlapping spheres, boundary elements, and finite elements.
- OpenMEEG and DuneNEURO easily interfaced from within Brainstorm
- Visualization and pruning very important due to sources and sensors lying in the same space.
- Min norm “heat maps” are particularly useful in SEEG, showing dynamics effectively
- Source imaging via sLORETA standardization of the min norm effective in coming “off” the contacts and into the volume
- Source modeling such as current dipoles possible when coverage is adequate





Brainstorm Contributors

Investigators


Sylvain Baillet
MNI


Richard Leahy
USC


John Mosher
UT Houston


Dimitrios Pantazis
MIT

MEG @ McGill


Konstantinos Nasiotis
PhD student


Soheila Samiee
PhD student


Jeremy Moreau
PhD student

Key collaborators


Elizabeth Bock
MEGIN, Chicago


Guiomar Niso
Politécnica Madrid


Juan Garcia-Prieto
Martinos, Boston

Geeks


François Tadel
Software,Grenoble


Raymundo Cassani
Software, MNI


Marc Lalancette
MEG manager, MNI

SIPI @ USC


Anand Joshi
RA Professor


Hossein Shahabi
Research assistant


Takfarinas Medani
Research assistant

NIRSTORM


Christophe Grova
Concordia


Thomas Vincent
Montreal Heart Inst


Edouard Delaire
Concordia