Forward and inverse solutions for EEG/MEG source reconstruction

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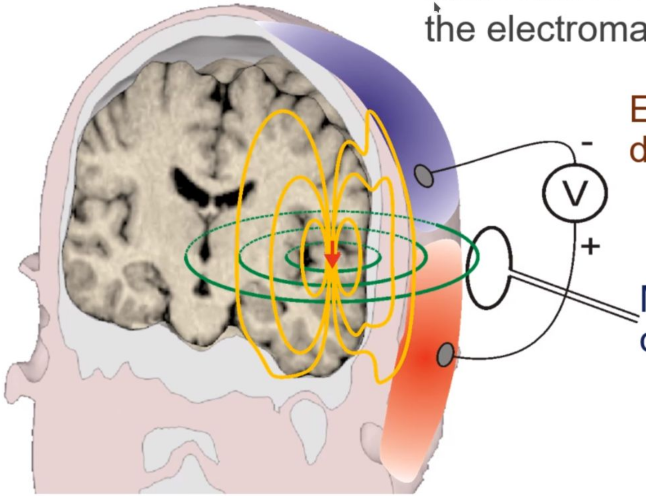
MEGIN

MEG/EEG signals measurement

MEG and EEG track electric brain activity by measuring the electromagnetic fields generated by neurons



EEG = measuring the potential differences on the scalp

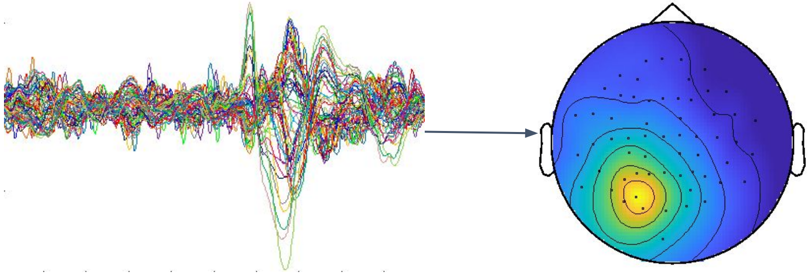
MEG = measuring neuromagnetic fields outside of the head

EEG

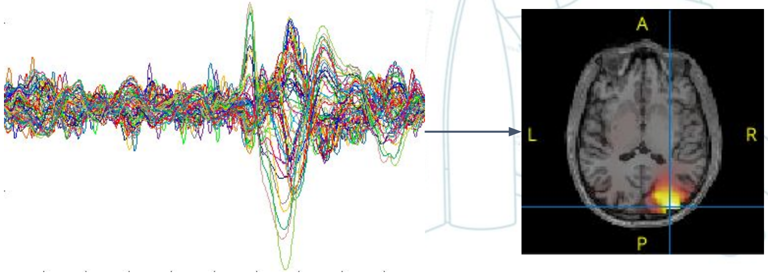
MEG + EEG

Sensor-level vs. source-level analysis

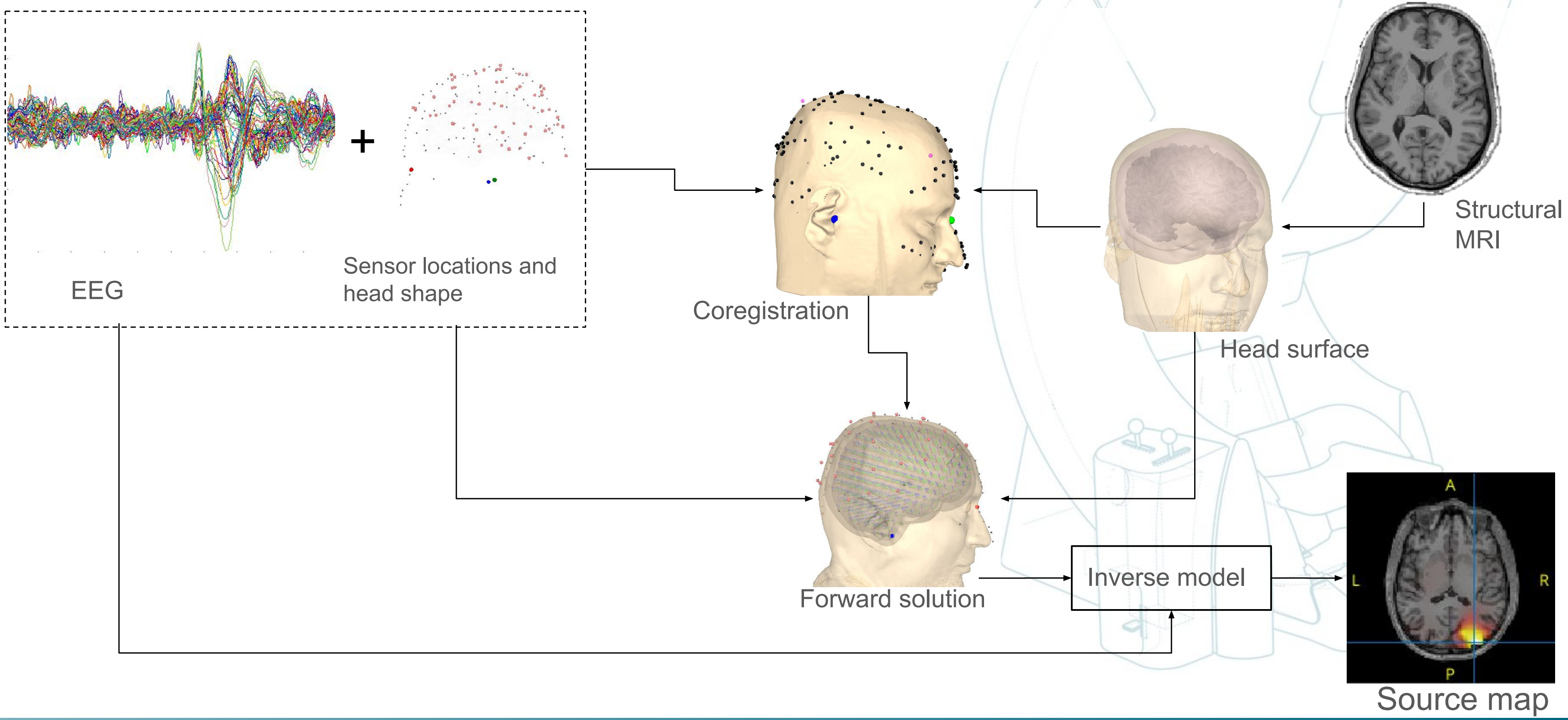
- Often simple and fast and generally involve fewer steps.
- Doesn’t require brain anatomical information.
- Robust but lower spatial accuracy.



- Involves multiple steps, turning the analysis workflow more complex and time-consuming.
- Often require anatomical information of patient’s head.
- Various influencing factors.

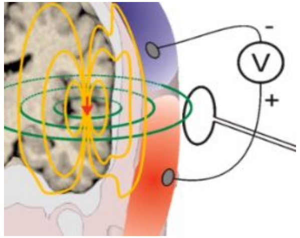


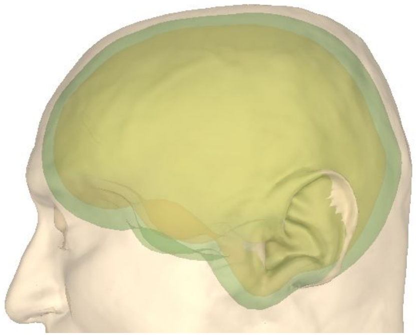
A typical workflow for EEG source imaging

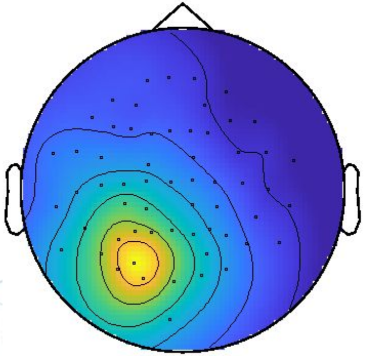


Forward and inverse models: simplified

Forward model







Inverse model

Need of forward solution for EEG analysis

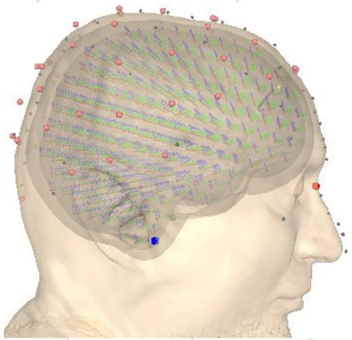
Forward model/solution is a key ingredient in EEG (or MEG) source localization, enabling *inverse methods* to estimate brain activity from recorded EEG signals.

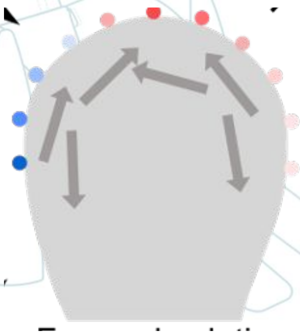
Purpose: To predicts the electrical potentials at scalp electrodes for a known brain source activity, e.g. a dipole.

Inputs: Requires a head model, a source model, and sensors position. Structural MRIs are often utilized for head and source model.

Computation: Solves Maxwell’s equations (quasi-static approximation) to estimate how currents propagates through brain tissues to the scalp.

Output: Produces a lead field matrix that maps each source’s contribution to each EEG electrode.





Forward model formulation

The EEG forward model can be written as:

$$V = L.J$$

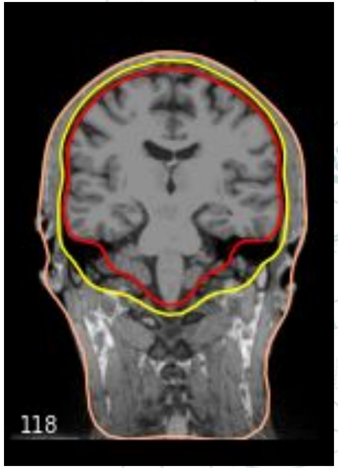
where,

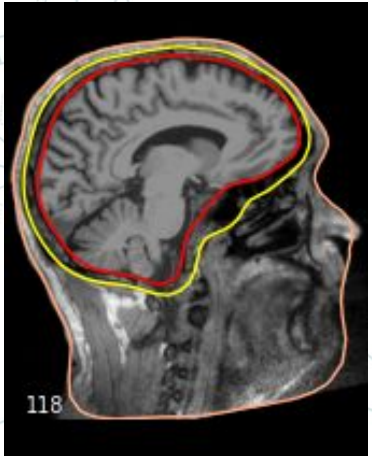
- **V**: Sensor data (EEG signals)
    - shape: [#channels x times]
- **L**: Leadfield matrix (describes how sources project to sensors)
    - shape: [#channels × 3 x #sources]
- **J**: Source currents (dipole amplitudes at each source location)
    - shape: [3 x nsources]

Use of structural MRI from subject's head

- **Need:** To define head compartments and source space.

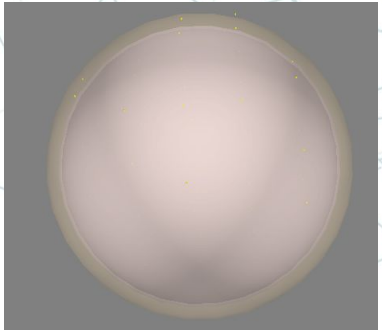
- T1-weighted structural MRIs are often used.
- Various MRI processing software can be used to segment the MRI and reconstruct the head surface, e.g., FSL, Freesurfer, and SPM.
- Improve localization accuracy; however it poses additional cost.
- Also intersecting surfaces are a major challenge in EEG source imaging.



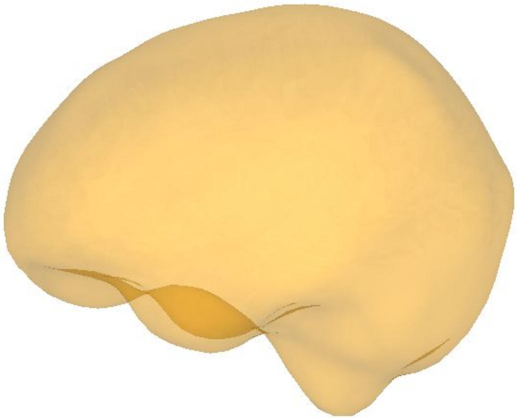


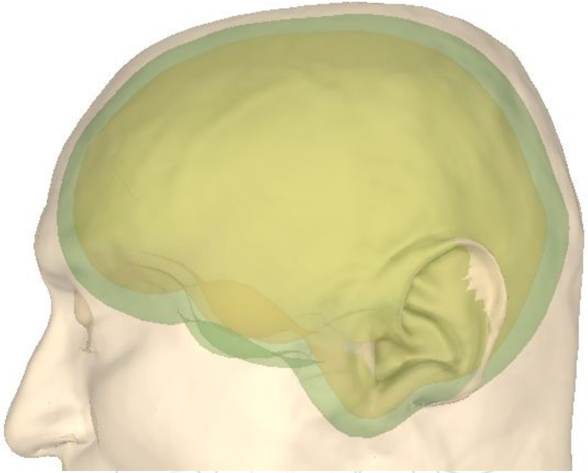
Volume conductor model *aka.* head model

- **Physical representation of head tissues**: Models the head as a set of compartments with distinct-conductivities.
- **Includes geometry and conductivity**: It accounts for the shape and size of head structures, as well as their anisotropic or isotropic conductivity properties.
- **Realistic or simplified**: Can be modeled with a single or multiple compartments. It may be a simple spherical model and realistic models BEM or FEM.



Single or multiple compartment conductor model?

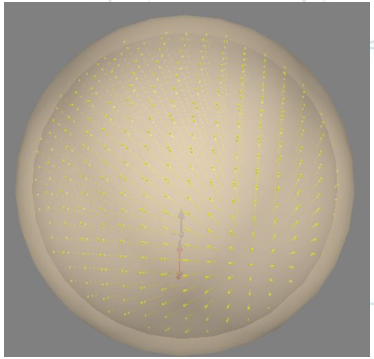




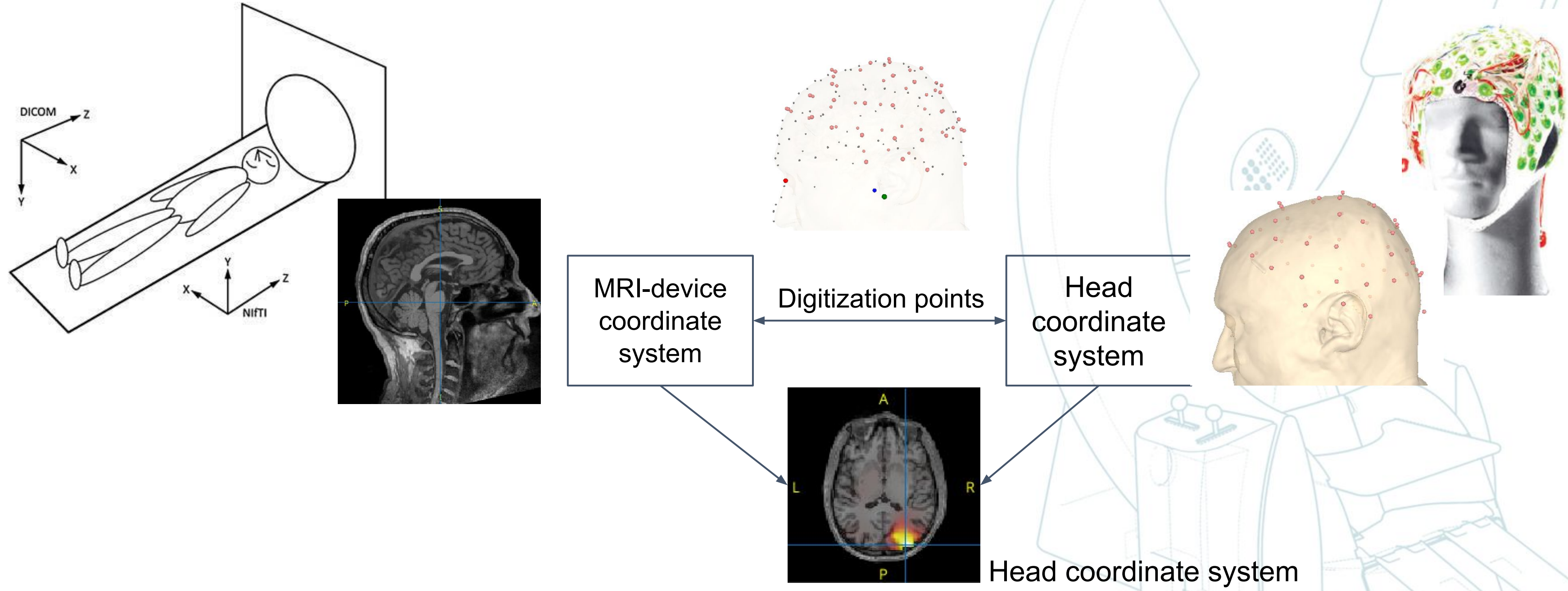
- Often used and sufficient for MEG
- EEG source reconstruction often requires a multiple compartment head model

Source models

- Dipolar sources, placed within the brain boundary.
- They represent the locations and orientations of the neural sources).
- Could be either a 3D grid (*volume source model*) or constrained to the cortical surface (*cortically-constrained source model*).



Digitization and coregistration



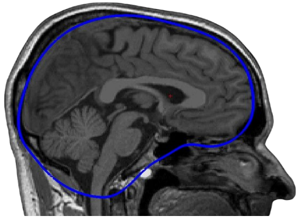
Jaiswal, et al. (2023). On electromagnetic head digitization in MEG and EEG. *Scientific Reports*, *13*(1), 3801.

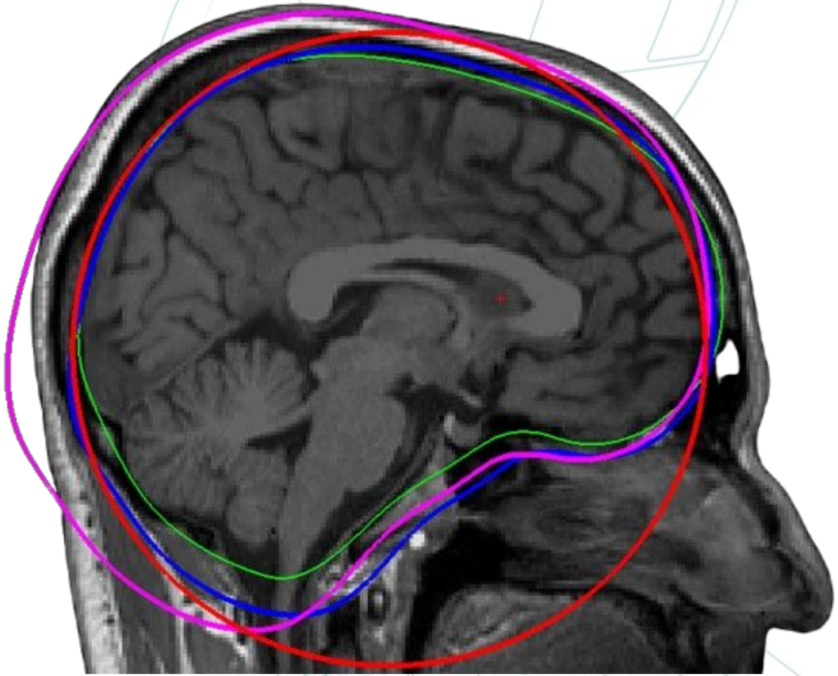
Challenges with using individual MRIs with EEG

- Additional time, cost and logistics.
- Additional data processing.
- Pediatric and metal-implanted patients often excluded
- Occasionally insufficient quality
  - Deformed scalp surface may affect coregistration.
  - Automatic segmentation leads to incorrect / intersecting surfaces

Alternative approaches to individual MRIs

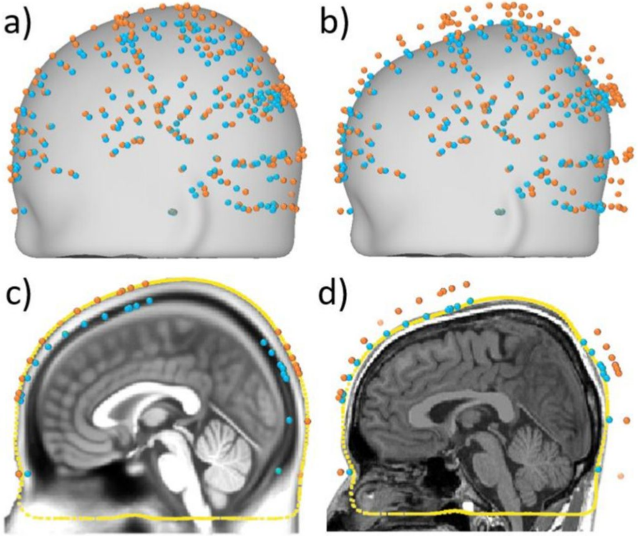
- Sphere model
- Template MRI
- Scaled template MRI

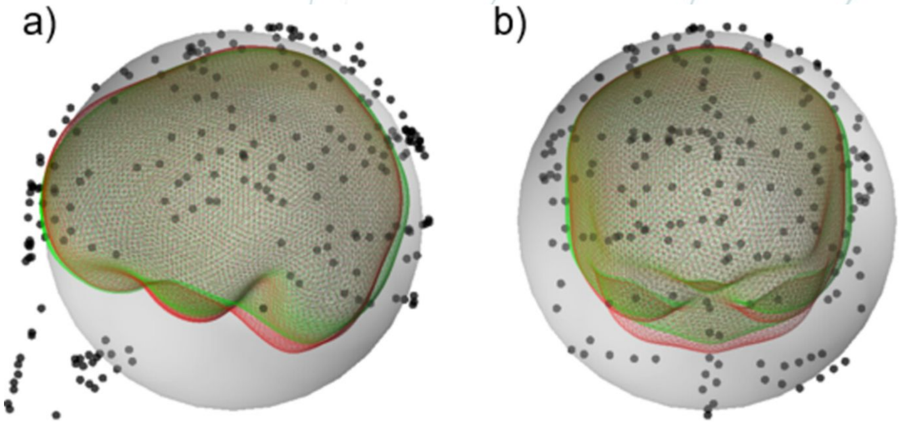




Inner skull surface from individual MRI

Using MRI templates and pseudo-MRI

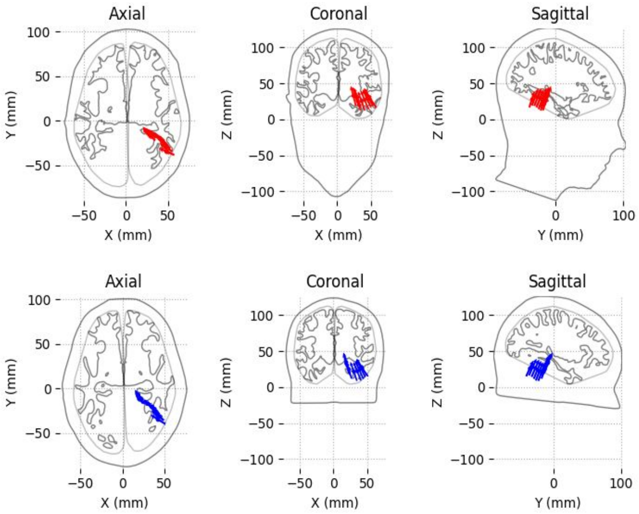




Jaiswal, et al. (2025). **Pseudo-MRI Engine** for MRI-Free Electromagnetic Source Imaging. *Human Brain Mapping*, *46*(2), e70148.

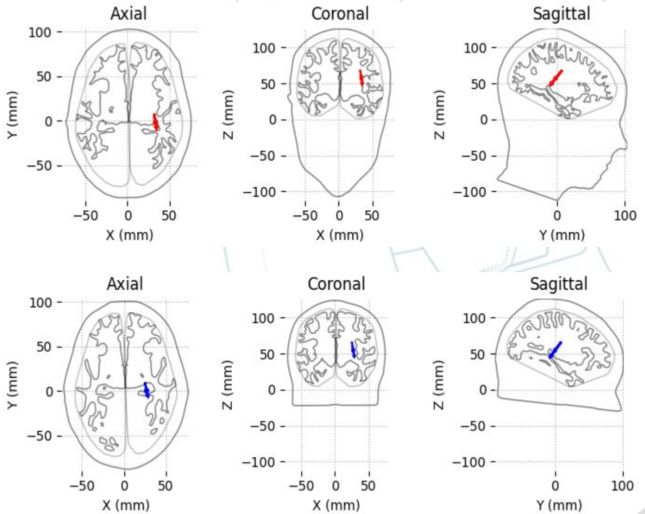
EEG source reconstruction with pseudo-MRI *

- Simulated spikes

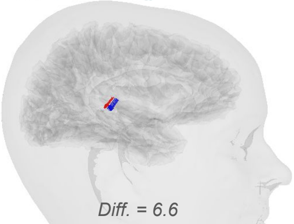


	real MRI	*pseudo-MRI*
Location	43.0, -23.0, 29.0	37.0, -23.0, 24.0
Orientation	-0.4, 0.3, 0.84	-0.4, -0.4, -0.8
Amplitude	89 nAm	91 nAm
GOF	63.3	63.8
Loc. error	15.2 mm	13.1 mm

- Binaural auditory (tone) stimulus



	real MRI	*pseudo-MRI*
Location	33.0, -2.0, 57.0	27.0, 0.0, 55.0
Orientation	0.1, -0.6, -0.8	0.2, -0.6, -0.8
Amplitude	23 nAm	23 nAm
GOF	67.8	70.0



Diff. = 6.6 mm

** Study in progress (Pseudo-MRI in EEG source imaging)*

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Inverse methods

The inverse methods for computing a source reconstruction can be divided into three categories:

- **Dipole fitting**: using an overdetermined model with a few sources
  - Single dipole fitting
  - Sequential dipole fitting
- **Scanning**: computed independently on each point of a source model
  - dynamic imaging of coherent sources (DICS)
  - linear constrained minimum variance (LCMV)
- **Distributed source modeling**: using an underdetermined distributed source model)
  - minimum norm estimation with and without noise regularisation (MNE)
  - minimum norm estimation using eLORETA

Inverse modeling

- **Goal**: To estimate the location, orientation, and strength of neural sources in the brain that produce the recorded EEG signals.
- **Ill-posed problem:** The inverse problem is ill-posed, means there is no unique solution without additional constraints.

  Why? Because there are **more unknowns** (sources) than equations (EEG sensors); which make the problem **ill-posed**, as many different J can explain the same V in ***V = L.J***

- **Prior constraint:** Prior knowledge (e.g., sources only on cortex, fixed orientations) helps reduce ambiguity and improve accuracy.
- **Different inverse methods:** Various methods including beamforming, sLORETA, eLORETA, MNE, and sparse solvers, follow unique assumptions.

Let’s see how we do it in FieldTrip!

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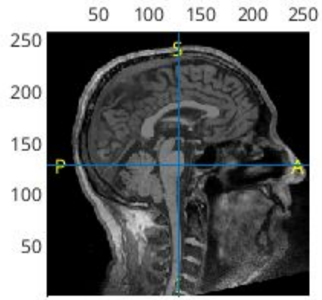
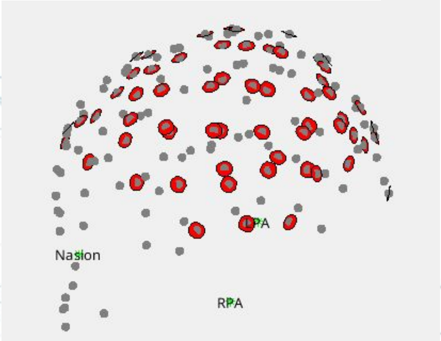
Read MRI data and sensor position

```
mri = ft_read_mri(mri_fname);
ft_sourceplot([], mri)
```

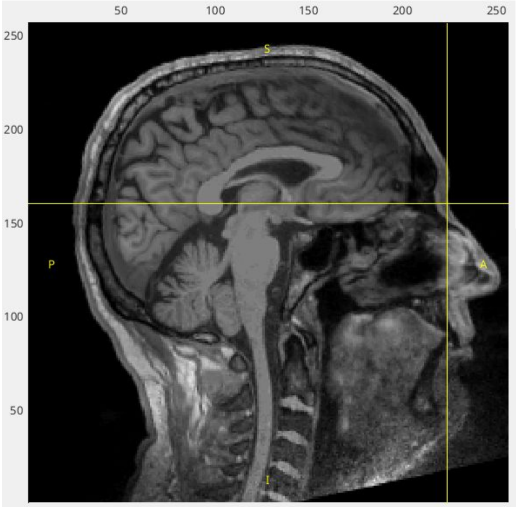


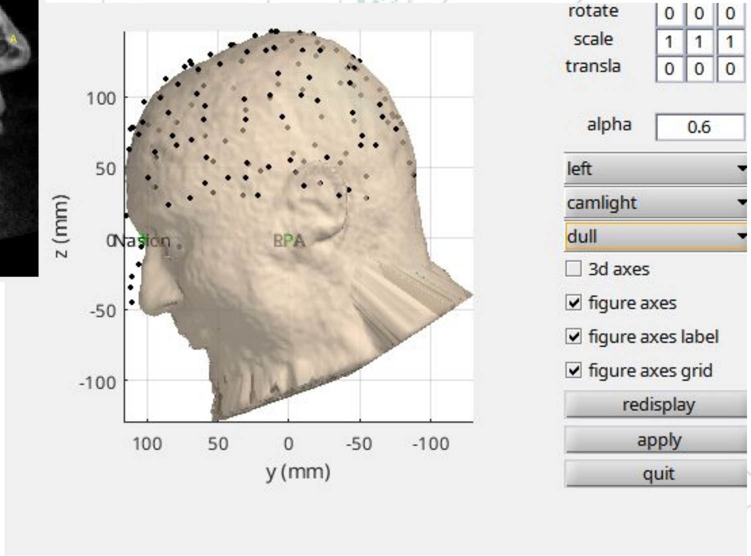

```
ft_plot_sens(raw_clean.elec, 'label', 'off',...
 'elecsize', 1, 'elecshape', 'circle',...
 'facecolor', 'red');

hsps = ft_read_headshape(eeg_filename);
ft_plot_headshape(hsps, 'vertexcolor', 'gray',...
 'vertexsize', 15)
```



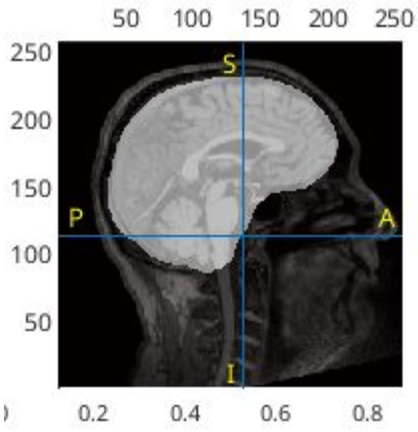
Coregistration

- Interactive mode
- Headshape-base

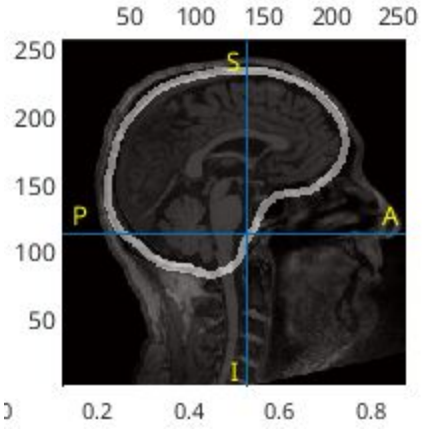




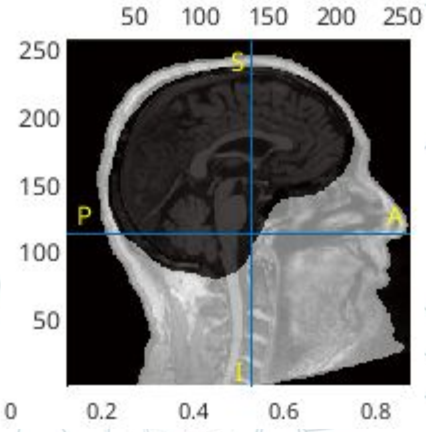
Segmentation of MRI



brain



skull



scalp

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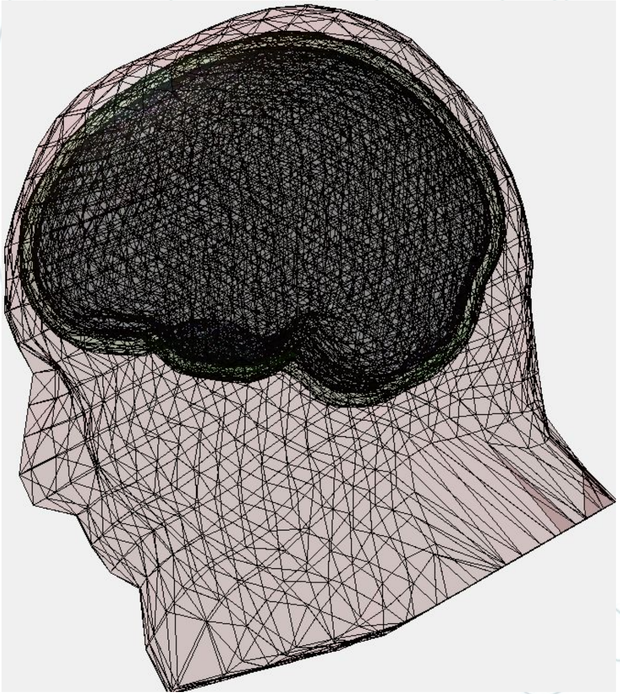
Head model preparation

```
% Prepare triangular mesh
cfg          = [];
cfg.method = 'projectmesh';
cfg.numvertices = [3000 2000 1000];
cfg.tissue = {'brain', 'skull', 'scalp'};
mesh         = ft_prepare_mesh(cfg,segmri);

% compute the 3-compartment conductor model
cfg                = [];
cfg.method         = 'dipoli';
cfg.tissue         = {'brain', 'skull', 'scalp'};
cfg.conductivity = [0.33 0.0125 0.33];
headmodel          = ft_prepare_headmodel(cfg,
mesh);
```



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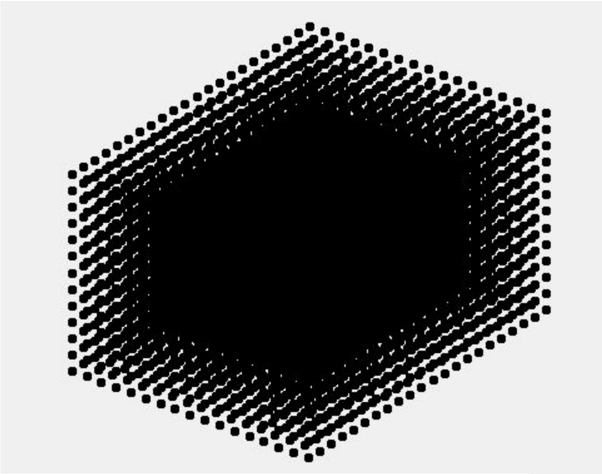
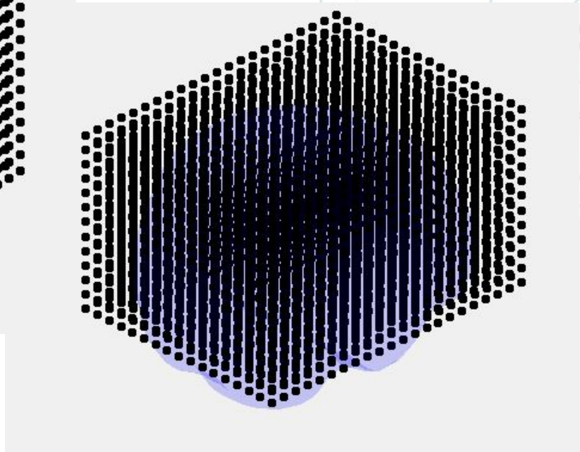
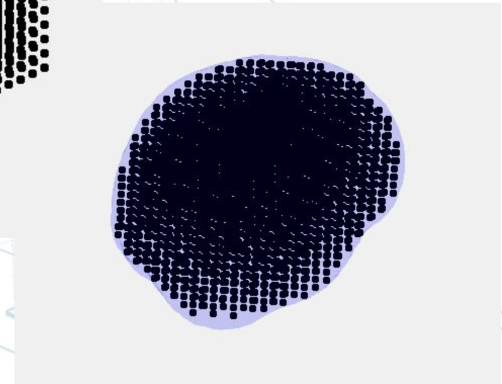
Source model computation



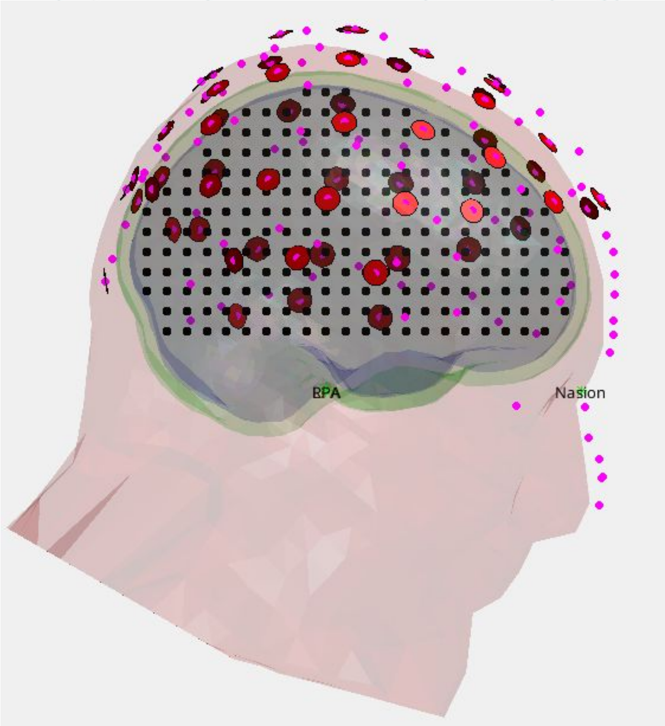




```
cfg                     = [];
cfg.elec                = elec_m;
cfg.headmodel           = headmodel;
cfg.grid.resolution     = 8/1000;
cfg.grid.unit           = 'm';
cfg.inwardshift         = 2/1000;
src_v                   = ft_prepare_sourcemodel(cfg);
```

Check if coordinate frames and units are identical

```
figure,
ft_plot_mesh(headmodel.bnd(1), 'facecolor', 'r',...
 'edgecolor', 'none', 'facealpha', .1)
ft_plot_mesh(headmodel.bnd(2), 'facecolor', 'g',...
 'edgecolor', 'none', 'facealpha', .1)
ft_plot_mesh(headmodel.bnd(3), 'facecolor', 'b',...
 'edgecolor', 'none', 'facealpha', .1)
ft_plot_sens(elec_m, 'label', 'off', 'elecsize', .01,...
 'elecshape', 'circle', 'facecolor', 'red');
ft_plot_headshape(hsps, 'vertexcolor', 'm',...
 'vertexsize', 15)
ft_plot_mesh(src_v.pos(src_v.inside,:),...
 'facecolor', 'c', 'vertexsize', 20)
rotate3d, camlight, view(90,0)
```



Computing the forward solutions

```
cfg                   = [];
cfg.elec              = elec_m;
cfg.headmodel         = headmodel;
cfg.grid              = src_v;
cfg.channel           = raw_clean.label;
cfg.normalize         = 'yes';
cfg.backproject       = 'yes';
cfg.senstype          = 'EEG';
cfg.unit              = 'm';
leadfield             =
ft_prepare_leadfield(cfg, raw_clean);
```

```
disp(leadfield)

              dim: [17 22 13]
              pos: [4862×3 double]
             unit: 'm'
           inside: [4862×1 logical]
              cfg: [1×1 struct]
        leadfield: {1×4862 cell}
            label: {60×1 cell}
  leadfielddimord: '{pos}_chan_ori'
```

Thanks for your attention!

MEGIN