Localization accuracy of electric and magnetic source imaging in epilepsy with a 3D printed human head phantom

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Background and Aim

- **Electric and magnetic source imaging** (ESI/MSI) play a critical role in the presurgical evaluation of patients with focal drug resistant epilepsy (DRE).
- A growing body of in-vivo studies[1,2] has investigated **ESI/MSI** in the presurgical evaluation of patients with DRE by evaluating their **clinical utility** and **localization accuracy**.
- In-vivo studies lack a **solid ground truth** for the exact location of the epileptic focus since scalp electroencephalography (EEG) and magnetoencephalography (MEG) recordings are rarely performed **simultaneously** with intracranial EEG (iEEG), and thus may capture different underlying sources.
- An effective way to validate the **localization accuracy** of ESI/MSI is through **head-shaped phantoms** resembling the **electromagnetic properties** of human head.
- Here, we report the **design**, **fabrication**, and **testing** of a **three-layer** human head **phantom**. The phantom can produce realistic **interictal epileptiform discharges** (IEDs) recorded from drug resistant epilepsy patients and assess the ability of **ESI/MSI** to localize **cortical** and **deep** brain sources.

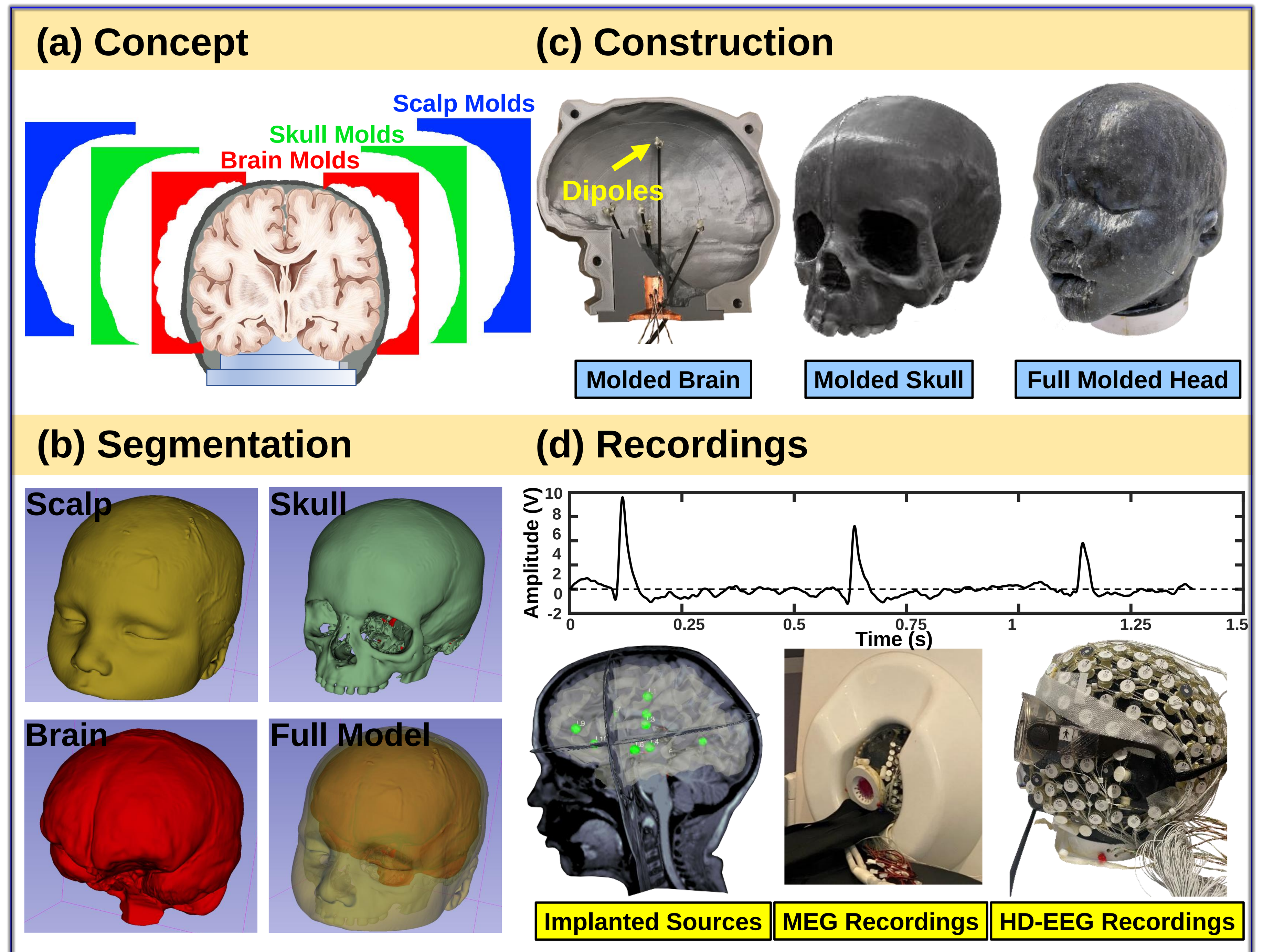

Figure 1: Fabrication process and source stimulation of the three-layer human head phantom. (a) Phantom fabricated by sequential casting of brain, skull and scalp layers with uniform conductivity around central base. **(b)** CT-derived segmentation of layers. **(c)** Brain mold with central base and rod-mounted dipoles; silicone/CCF skull layer cast around brain; finished phantom with skin/scalp layer. **(d)** Stimulation signal obtained from iEEG recordings of left temporal lobe of male, 17-year-old drug resistant epilepsy patient, band pass filtered between 1 to 70 Hz to include interictal epileptiform discharges in a time span of 1.4 s. Signal was then regenerated and replayed through individual embedded dipoles using a waveform generator.

Methods

- The 3-layer phantom was created by molding the brain layer with embedded dipoles, then sequentially overmolding the skull and scalp layers with silicone/chopped carbon fiber (CCF) mixtures of different conductivities.
- The concept behind the phantom's design was to pour these materials inside molds, which had the shape of the brain, skull, and scalp.
- **10 dipolar sources** embedded in **each hemisphere** represent conditions of varying source localization difficulty (e.g., cortical, subcortical, and deep brain sources).
- We recorded **simultaneous MEG and HD-EEG** (1 KHz sampling rate) while dipolar sources were activated through a waveform generator.
- Using computed tomography of the phantom, we marked the locations of the embedded sources.
- Finally, we performed source localization at the peak of each spike using equivalent current dipole (ECD) (Goodness of Fit > 90%) using Brainstorm.
- Source localization errors were calculated as the average distance of Brainstorm-calculated dipole positions from the CT-derived embedded source positions.

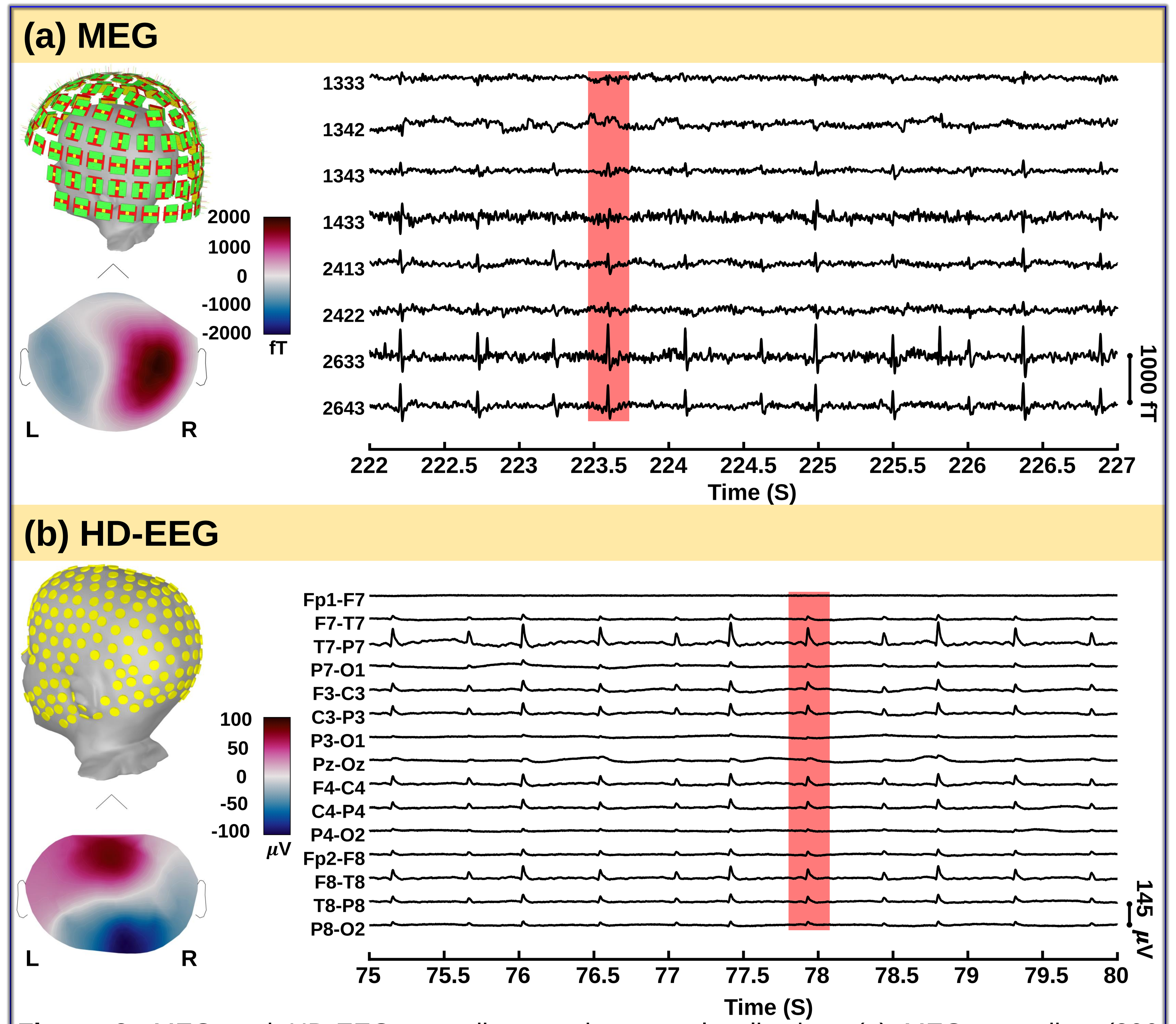

Figure 2: MEG and HD-EEG recordings and source localization. (a) MEG recording (306 sensors) and the helmet placement on the head with the topography of the highlighted spike event. (b) The bipolar montage view of HD-EEG recording (256 channels) and the HD-EEG cap placement on the head with the topography of the highlighted spike.

Results

- **Realistic IEDs** in terms of **amplitude**, **duration**, and **morphology** were obtained in both **MEG** and **HD-EEG** recordings.
- For MEG data, two dipolar sources placed close to the **left insula** and **right brainstem** had a localization error of **8.6 ± 0 mm** and **8.6 ± 2.9 mm**, respectively.
- For HD-EEG data, the dipolar source placed close to the **right brainstem** had a localization error of **11.4 ± 0 mm**.

Conclusion

- Based on advances in **3D printing** technology and bioengineering concepts, we present here for the first time a three-layer human head phantom that resembles the **electromagnetic properties** of the **human head**.
- The phantom is capable of generating artificial signals that have the morphological characteristics of actual IEDs.
- Other types of brain signals such as **epileptic seizures**, **ripples**, and **fast ripples** can be fed to the phantom.
- Such technology can allow the reliable assessment of the localization abilities of **MEG** and **HD-EEG** in different clinical scenarios.

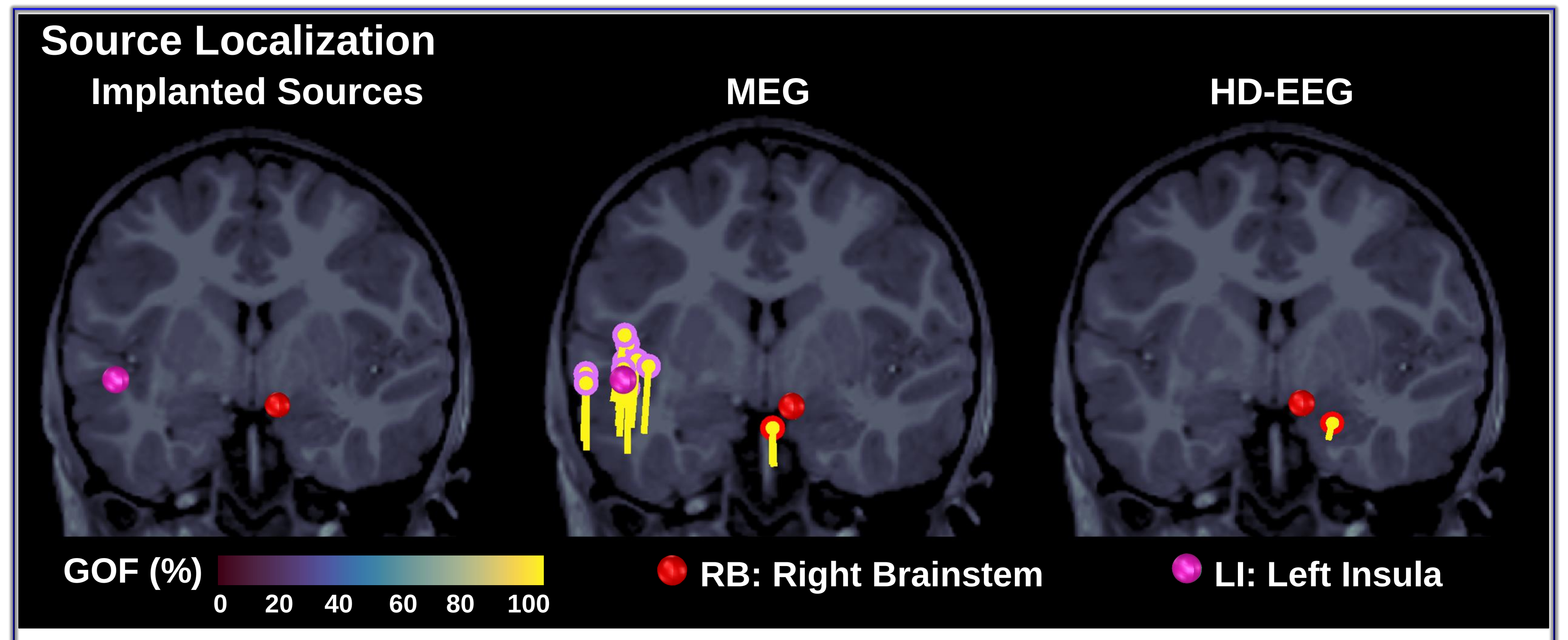

Figure 3: Two implanted sources in the vicinity of left insula and right brainstem are marked and their respective dipole source localizations for MEG and HD-EEG recordings are depicted. The phantom's head model was computed using the three-layer Boundary Element Model (BEM) in Brainstorm for source localization of MEG and HD-EEG recordings.

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References

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