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Ictal MEG onset source localization compared to intracranial EEG and outcome: Improved epilepsy presurgical evaluation in pediatrics

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Summary

Purpose—Magnetoencephalography (MEG) has been shown a useful diagnostic tool for presurgical evaluation of pediatric medically intractable partial epilepsy as MEG source localization has been shown to improve the likelihood of seizure onset zone (SOZ) sampling during subsequent evaluation with intracranial EEG (ICEEG). We investigated whether ictal MEG onset source localization further improves results of interictal MEG in defining the SOZ.

Methods—We identified 20 pediatric patients with one habitual seizure during MEG recordings between October 2007 and April 2011. MEG was recorded with sampling rates of 600 Hz and 4000 Hz for 10 and 2 minutes respectively. Continuous head localization (CHL) was applied. Source localization analyses were applied using multiple algorithms, both at the beginning of ictal onset and for interictal MEG discharges. Ictal MEG onsets were identified by visual inspection and power spectrum using short-time Fourier transform (STFT). Source localizations were compared with ICEEG, surgical procedure and outcome.

Key findings—Eight patients met all inclusion criteria. Five of the 8 patients (63%) had concordant ictal MEG onset source localization and interictal MEG discharge source localizations in the same lobe, but the source of ictal MEG onset was closer to the SOZ defined by ICEEG.

Significance—Although the capture of seizures during MEG recording is challenging, the source localization for ictal MEG onset proved to be a useful tool for presurgical evaluation in our pediatric population with medically intractable epilepsy.

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Keywords

ictal MEG; interictal MEG discharge; source localization; presurgical evaluation; surgical outcome

1. Introduction

For medically intractable partial epilepsy, surgical treatment resulting in resection of the seizure onset zone (SOZ) can achieve the primary therapeutic goal of seizure freedom with minimal side effects (Engel et al., 1993; Cohen-Gadol et al., 2004). The standard for determining the SOZ is intracranial recording after intracranial EEG (ICEEG) electrode placement. Magnetoencephalography (MEG) source localization, sometimes termed magnetic source imaging (MSI), can aid in determining locations for ICEEG electrode placement. (Knowlton et al., 2009; Stefan et al., 2011). MEG has been shown to be a useful diagnostic tool for presurgical evaluation of medically intractable epilepsy in children (Verrotti et al., 2003; Tovar-Spinoza et al., 2008). Noninvasive localization of the sources of MEG epileptiform discharges, which may or may not be detected with simultaneous EEG, can be used effectively for epilepsy surgery planning in conjunction with detailed anatomical magnetic resonance imaging (MRI) and functional imaging studies (Rosenow and Lüders, 2001; Seo et al., 2011).

There are several challenges in localization or even lateralization of the SOZ with scalp-EEG recordings in the pediatric population. In children, extratemporal epilepsy is more common than temporal lobe epilepsy (Holmes, 1996; Leiphart et al., 2001). In extratemporal pediatric epilepsy, interictal EEG findings are often multifocal or generalized. This phenomenon is typically seen in malformations of cortical development (MCD), the most common pathological diagnosis in children with refractory partial epilepsy who go on to epilepsy surgery (Palmini et al., 1991; Hirabayashi et al., 1993; Raymond and Fish, 1996; Mathern, 2009). Children with age-related epileptic spasms may also have multifocal or generalized localization on scalp EEG (RamachandranNair et al., 2008; Asano et al., 2005). Additionally, the high prevalence of cases where there is no apparent MRI lesion (so-called “nonlesional”) and “multilesional” cases such as tuberous sclerosis complex (TSC) increases the need for localization with other technologies such as MEG (Jansen et al., 2006; Xiao et al., 2006; Bollo et al., 2008; Canuet et al., 2008; Sugiyama et al., 2009).

Since the first report of ictal activity recorded with a multichannel MEG system with localization of the dipoles confirmed by intraoperative electrocorticography (ECoG) recording (Stefan et al., 1992), there have been increasing numbers of studies reporting ictal MEG with high-resolution whole head MEG systems. These MEG studies describe successful localization of seizures with a single equivalent current dipole (ECD) model (Shiraishi et al., 2001; Tilz et al., 2002; Eliashiv et al., 2002; Assaf et al., 2003). However, several studies reported that the ictal MEG occasionally failed to localize the SOZ (Shiraishi et al., 2001; Eliashiv et al., 2002; Tilz et al., 2002). Possible explanations for this failure were (1) the early spikes of an ictal MEG may have low signal-to-noise ratio (SNR), lowering the localization precision, and (2) source localization with the single ECD model may be misleading (Kobayashi et al., 2005).

In recent years, a number of forward solution methodologies for MEG source localizations, that model extended sources and do not require the investigator to choose *a priori* the number of separate sources to be localized, have been developed. These newer source localization algorithms include, among others, minimum norm estimation (Hamalainen and Ilmoniemi, 1984), low-resolution electromagnetic tomography, LORETA (Pascal-Marqui,

1994), standardized low-resolution electromagnetic tomography, sLORETA (Pascual-Marqui, 2002), multi-resolution focal underdetermined system Solution, MR-FOCUSS (Moran et al., 2005), multiple signal classification, MUSIC (Moshier et al., 1992), MEG beamformer (Robinson and Vrba, 1998; Sekihara et al., 2002; Van Drongelen et al., 1996; Van Veen et al., 1997; Brookes et al., 2007) and dynamic Statistical Parametric Maps, dSPMs (Dale et al., 2000; Tanaka et al., 2009).

We hypothesized that source localization of the ictal onset during MEG recording would provide more precise prediction of the SOZ location compared to MEG source localization for interictal discharges, especially for patients who do not have well-defined focal seizure onset on scalp EEG or who have multiple independent interictal discharge types.

This study was designed to investigate retrospectively whether ictal MEG onset source localization would have any additional benefit to interictal MEG source localization in defining the SOZ for presurgical evaluation in pediatric epilepsy.

2. Method

2.1 Patient population

We identified 20 pediatric patients diagnosed with intractable epilepsy who had both interictal discharges and also had at least one habitual seizure during MEG recordings between October 2007 and April 2011 at Cincinnati Children's Hospital Medical Center. Patients were then screened for additional inclusion criteria: completion of non-invasive presurgical evaluation (long term video-scalp EEG monitoring, FDG-PET, ictal/interictal SPECT and SISCOM if both ictal and interictal SPECT were available), surgical resection, and post-surgical follow up period of at least 6 months.

2.2 MEG/EEG data acquisition

MEG was recorded with a whole head CTF 275-Channel MEG system (VSM MedTech Systems Inc., Coquitlam, BC, Canada) with sampling rates of 300 Hz or 600 Hz and 4000 Hz for 10-minute and 2-minute recordings respectively, for a total of at least 40 minutes for each patient. Scalp-EEG was recorded simultaneously at the same settings as MEG with the VSM MedTech system with 23 scalp electrodes placed according to the International 10–20 system with the addition of ECG electrode. For each patient, three fiducial points at the nasion, left and right preauricular locations were marked with a pen and photographed. Then fiducial sources (head coils) were placed at the three locations. Head position relative to the magnetometer array was recorded at the beginning and end of each recording segment with the head coils, and the CTF head localization software for 300 Hz and 4000 Hz sampling rate dataset and continuous head localization was applied for the 600 Hz sampling rate datasets. Only recordings with less than 5 mm head movement were accepted. Sedation was achieved for two patients through general anesthesia with dexmedetomidine and for one patient through supervised conscious sedation with chloral hydrate after sleep deprivation. The other 5 patients were partially sleep deprived the night before the MEG study and spontaneously attained stage II sleep during the recording.

2.3 MEG data analysis

All the original simultaneous EEG and MEG recordings were first visually reviewed for interictal and ictal epileptiform discharges. Sections of the recording with muscle artifact were identified by visual inspection and excluded from further analysis. For the first part of the analyses, Curry 6 (Compumedics Neuroscan, Charlotte, NC) was used. Individual spikes and ictal onset were identified in sections of the simultaneous EEG/MEG signals. High pass filters were applied to reveal fast activity, if present. The particular frequency bandwidth

was chosen after first reviewing the power spectrum using short-time Fourier transform (STFT) of each section of event in a wide bandwidth and then stepwise narrowing the bandwidth to better discern the frequency of the earliest spectral power change. Principal component analysis (PCA) followed by independent component analysis (ICA) was applied to evaluate the possible number of components in each spike signal above the background noise level. The analysis time range was selected at onset of MEG interictal spikes and ictal onset in order to have sufficient data sampled and SNR required for the algorithms, while limiting source localization to the earliest activity in the epileptiform discharges.

The realistic volume conductor model was created from the patients' individual MRI automatically or manually as a 3-compartment boundary element model (BEM) (Fuchs et al., 2001); an anatomically constrained linear estimation approach was applied, assuming the sources are distributed in the cerebral cortex (Dale and Sereno, 1993). The multiple source localization methods applied to each patient's recordings included: 1) single equivalent current dipole (ECD) which is the only clinically accepted method, 2) a distributed dipole: standardized low resolution brain electromagnetic tomography (sLORETA), and 3) a dipole scan algorithm: multiple signal classification (MUSIC) for the particular frequency bandwidth of each MEG ictal onset and interictal discharges. The specific frequency bands, identified by the above method for each ictal onset and interictal discharges individually, were used for the source localizations using each of the three algorithms: ECD, MUSIC and sLORETA. Also, a fourth algorithm that can model multiple and extended sources, a beamformer source localization method, the synthetic aperture magnetometry with excess kurtosis statistic (SAM(g^2)), was applied to the same spikes and ictal onsets that were free of muscle artifact (Robinson, et al, 2002, 2004). Both ictal and interictal MEG source localization results were conducted as a part of the presurgical evaluation, and influenced the planning of ICEEG electrode placement.

2.4. MRI Acquisition

Three-dimensional T1-weighted Magnetization-Prepared Rapid Acquisition Gradient Echo (MP_RAGE) sequences with 1 mm thickness slices were obtained for all patients with MRI scanners (3T, Siemens Medical Solutions, Malvern, PA or Intera Achieva 3.0 T, Philips Medical System, Andover, MA). Three fiducial markers (MRI compatible circular targets) were placed at the same three surface locations marked during the MEG recordings for co-registration of MEG and MRI.

2.5 Intracranial EEG recording

The intracranial EEG electrodes were placed based on the consensus decision from the multimodality presurgical evaluation described earlier. The ICEEGs were recorded with a sampling rate of 2000 Hz per channel (Stellate, Montreal Quebec, Canada). The recordings were performed referentially with a scalp electrode as a reference but subsequently referenced to two quiet intracranial electrodes.

ICEEG recordings were continued until at least three of the patients' habitual seizures were captured. The seizure onsets were visually determined as the initial ICEEG pattern changes that were clearly distinguished from background activities and physiological status changes (Gotman et al., 1993) and that were followed by the same clinical onset in seizure semiology observed by video scalp EEG monitoring.

2.6 Surgical Outcome

Surgical outcome was measured at 6 months, one year and 2 years following the epilepsy surgery using modified Engel classification (Engel, 1987). Patients with less than six months of follow up were excluded.

2.7 Analysis of Concordance and Statistics

The concordance of interictal and ictal MEG source localization with ICEEG-defined SOZ were evaluated on three levels: hemispheric lateralization, lobar localization and sublobar localization. The cerebral lobes can be quite large compared to the SOZ size. For this paper we added an additional sublobar level of smaller regions (e.g., mesial vs. lateral) that we felt would be important for planning surgical placement of grids (see Table 1 for description of regions). MEG localizations were described as either concordant or discordant with the ICEEG location at each level. If bilateral interictal MEG discharges were found roughly equally from side to side, this was considered discordant for the purpose of the analysis. If interictal MEG discharges were multifocal or bilateral but predominant in one hemisphere, then the concordance decisions were made based on the predominant side. This weighted localization was also applied to lobar and sublobar localizations.

This study was approved by the Institutional Review Board at Cincinnati Children's Hospital Medical Center.

3. Results

3.1 Patient inclusions

Twenty patients had at least one seizure during MEG recording, but only 13 had a six month follow-up after surgery. Of those patients who met the six month follow-up inclusion criterion, eight patients had resective surgery. The mean follow-up duration after surgery was 1.5 years (range: 0.9 – 3.2 years). All but one had ICEEG monitoring; the other patient underwent a left temporal lobectomy without ICEEG. Two of the 8 resective surgery patients had their first surgery as a focal resection but recurrent seizures developed. Therefore these two patients had functional hemispherectomy as a second and final procedure. Five patients had sufficient follow up but did not go on to resective surgery: three had no surgery; one had complete corpus callosotomy, and one had vagus nerve stimulator (VNS) implantation (Fig. 1).

3.2 Comparison of source localization between ictal MEG onset and interictal MEG discharges in the 8 patients having resective surgery

For each patient, interictal source localizations were similar among the ECD model and the three different extended source algorithms. All source localizations for each patient showed lobar concordance across algorithms. Ictal source localizations were similarly concordant across algorithms; and all but one (patient 7) had lobar concordance. There was no clinically significant difference in the localization with the ECD and extended source models also in the initial onset for ictal MEG. Five of the 8 (63%) patients had ictal MEG onset source localization and interictal MEG discharge source localizations in the same lobe and same hemisphere with similar but slightly different localization (Table 1). Four of these five patients with concordant interictal and ictal MEG source localization went on to have ICEEG monitoring. In these four patients, MEG ictal onset source localizations were much closer to ICEEG onset compared to MEG interictal source localizations (Fig. 2). The other three patients (37%) had bilateral independent MEG interictal discharges, and the current dipole sources were likewise independently localized in either hemisphere. In two of these three patients, the predominant source lateralization for interictal spikes was on the same side as the initial ictal MEG onset. However, even though the predominant lateralization was concordant for hemisphere, the sources were not usable for lobar localization, as they were multifocal throughout that hemisphere (Table 1).

3.3 Ictal MEG source localization in non-localizing scalp EEG

For the eight patients, the seizures that were captured on MEG study were localizing on scalp EEG in only three cases. The remaining five patients' seizures, which clinically were tonic seizures, demonstrated diffuse bilateral paroxysmal onset on scalp EEG. In these five patients with diffuse scalp EEG onset, ictal MEG onsets were all lateralizing to the eventual surgical side, and all but one were localizing on a lobar level.

3.4 Comparison of ictal onset and interictal discharge MEG source localization and ICEEG

For these seven patients (see Fig. 1), concordance of source localization of ictal MEG onset and interictal MEG discharges was compared with ICEEG SOZ. Using ICEEG as the gold standard, we found that ictal MEG improved the precision of presurgical SOZ localization, particularly at the sublobar level, compared to interictal MEG. Interictal MEG discharges were useful for lobar localization but tended to show a wider distribution (patients 1–3). In patients with bilateral multifocal interictal MEG discharges, those interictal discharges were predominant in the operated hemisphere, but lobar localization was not possible (patient 4 and 5). Ictal MEG in the same group with bilateral multifocal interictal discharges yielded good lobar localization compared to eventual surgical site (Table 2).

3.5 The relationship between ictal MEG onset/interictal MEG discharge source localization and surgical outcome

We observed that there is a high correlation between MEG source localization and surgical outcome (Table 1). When the ictal MEG source localization and interictal MEG discharge source localization showed agreement with respect to lateralization and lobar localization and only one type of seizure semiology was present, the surgical outcome was excellent. Four out of 5 patients who met this criteria were Engel Class 1 with at least six months follow up (one had re-operation with functional hemispherectomy for Rasmussen Encephalitis). One patient with ictal and interictal MEG concordance was not seizure free, but this patient experienced significant improvement of seizures (Engel Class II) despite having multiple seizure types. This patient had diffuse bilateral paroxysmal ictal onset based on scalp EEG, but lateralized to the side of eventual surgery based on ictal MEG source localization. While the ictal MEG was lateralizing, the lobar localization varied depending on which algorithm was used. This patient underwent right lateral frontal corticectomy and SMA resection, but likely had a larger epileptogenic zone, portions of which were not removed by resection.

On the other hand, in patients who had ictal MEG onset lateralizing or even localizing, but more than two types of seizure semiology and bilateral interictal MEG source localization, there was a trend toward unfavorable surgical outcome. For patient 4 (Fig. 3), pathology after the first surgery showed extensive FCD along with microcystic encephalomalacia with neuron loss. With recurring seizures after the first surgery, the patient had a functional hemispherectomy and became seizure free. For patient 7, the sources of interictal MEG discharges were equally distributed in both hemispheres. However, ictal MEG demonstrated lateralization, contributing to the surgical decision in this patient. The seizure outcome was improved compared to prior to surgery. In this limited sample of two patients, the presence of two or more seizure types and bilateral interictal MEG discharges was associated with more diffuse pathology and a poor prognosis for seizure freedom from a limited resection. (Figure 3 here)

4. Discussion

In recording and analyzing multiple seizures, we found ictal MEG to be superior to scalp EEG for lateralization and localization. The eight patients' initial ictal MEG onsets were

identified by examining the spectral power in multiple overlapping bandwidths with STFT. The earliest consistent change in spectral power was then further evaluated with ICA of the signal to be certain at least one consistent source could be discerned above the background noise level. The spectral power changes in the MEG initial ictal onset could be detected even when scalp EEG did not show clear ictal onset. In most prior studies of ictal MEG localization, patients had complex partial seizures with either minimal clinical change, subtle changes such as arrest of activity, brief lapse of consciousness, or no identifiable clinical change (Stefan et al., 1992; Manoharan et al., 2007; Shiraishi et al., 2001). During seizures with minimal visually observable movement, patients may nonetheless make subtle head movements that could blur source localizations if included in the ictal onset signal. Because our system recorded continuous head localization (CHL), we were able to identify precisely the time point when the patient began head movement near the clinical onset of simple and complex partial seizures. This capability allowed us to study two additional kinds of ictal events: brief tonic seizures with short time duration between ictal signal onset and movement, and seizures with focal MEG signal onset but rapid propagation to paroxysmal bilateral high amplitude diffuse discharges.

This study represents a progression in technique in analyzing ictal MEG, relying upon analysis of change in spectral power over time at ictal onset rather than at a single time point (e.g., spike peak) with a source localization algorithm. Prior studies of ictal MEG onset used the single ECD model, which can localize a single discrete source when the signal to noise ratio (SNR) is fairly high. We found ictal onset patterns varied considerably from patient to patient but included low amplitude faster frequency rhythmic discharges, the leading edge of which is more detectable using spectral analysis. In this study, we evaluated the spectral power at ictal onset to discover the frequency bandwidth that showed the earliest signal change that also demonstrated good SNR evaluated with principal component analysis (PCA) and/or independent component analysis (ICA). This bandwidth often required high pass filter setting greater than the conventional 1 Hz.

We did not find a significant difference between the ECD model and the extended source localizations algorithms that we used. The lack of difference may be because we chose to look very early in the ictal onset at the first detectable change in spectral power. At this time point the ictal source may still be fairly focal and reasonably well-modeled with the standard ECD algorithm.

Ictal MEG represents a potential advantage over interictal MEG in defining the seizure onset zone. This is particularly true in nonlesional and multi-lesional patients, which comprise a large group of children with intractable epilepsy. In pediatric intractable partial epilepsy, interictal discharges are often multifocal or diffuse; interictal MEG source localizations in these cases are often bilateral. In our study, there were three patients who had bilateral independent and diffuse interictal discharges based on MEG source localization, as well as one patient with interictal discharges with widespread sources throughout one hemisphere (see Table 1). In these cases we found ictal MEG source localization, in addition to the other noninvasive presurgical testing, contributed to the surgical plan, whereas interictal MEG source localization would have argued more for avoidance of resective surgery or a hemispheric procedure. These results were validated by good lobar and often sublobar concordance with the SOZ determined by ICEEG.

Recent studies regarding MEG, EEG or MEG/EEG simultaneous source localization have been compared to ICEEG recordings to confirm accuracy, since the intracranial EEG is considered the gold standard (Stefan et al., 1992, 1993, 1994, 2003; Otsubo et al., 2001a, 2001b; RamachandranNair et al., 2007; Wheless et al., 1999). In our patient sample, ictal MEG proved better than interictal MEG in showing concordance with ICEEG of the SOZ at

the sub-lobar level. We also followed the surgery and surgical outcome as another means for estimating the predictive value of ictal MEG onset. Lobar concordance between interictal and ictal MEG resulted in excellent seizure outcome.

There are several limitations to this study. Even though we recorded and evaluated ictal MEG in 20 patients, when we applied the requirement of ECoG confirmation of SOZ and at least 6 months post-surgical follow-up, our study population became eight patients. So our overall conclusions, though very positive, must remain modest and describe potential clinical benefit of recording ictal MEG. Also the study is limited by its retrospective design. Since several noninvasive tests are used to make the surgical plan, it is not possible at this time to determine the exact contribution of ictal MEG data to the plan for the craniotomy location, grid placement or eventual resection. There may always be limitations to the value of ictal MEG onset localization, the most important of which relates to undersampling of seizures and seizure types (Sanker et al., 2005; Gelžinien et al., 2008). In children with multiple seizure types and bilateral interictal MEG discharges, we demonstrated a relatively poor seizure outcome. This is a consequence of multiple factors, including the inability to safely resect the SOZs in patients with multiple seizure types, which may begin independently bilaterally or involve eloquent areas in some patients. The MEG recording length and the need for strict head immobility to establish an adequate SNR remain significant limitations, especially in the pediatric population.

We found that initial ictal MEG onset provides useful additional information for surgical evaluation. Although capturing seizures during MEG recording is challenging, the source localization for the initial ictal MEG onset is a very useful tool for presurgical evaluation for medically intractable epilepsy patients, especially in our pediatric population, many of whom had “nonlesional” epilepsy based on anatomical MR imaging. Ictal MEG demonstrated good concordance with the SOZ as defined by the current gold standards: ICEEG and surgical outcome. A prospective design in a larger number of patients may better define the role of ictal MEG in surgical planning. Further study is needed to determine the role of ictal MEG in replacing intracranial recording in selected patients.

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Figure 1. Diagram of selection of patient criteria. Right column (blue) represents number of patients with exclusion criteria.

Figure 2.

Patient #1- Initial ictal MEG onset and interictal MEG discharge source localization with different algorithms, intracranial EEG (ICEEG) findings and surgery. (A) The EEG recordings, which recorded synchronously with MEG, showed unclear EEG seizure onset followed by background attenuation with muscle artifacts. Bandwidth was set as 3–70 Hz. (B) Short-time Fourier Transform (STFT) applied to MEG identified the power spectrum that revealed the initial MEG ictal onset. High pass filter was applied as 40 Hz. Source localization for the initial ictal MEG onset using (C1) sLORETA and (D1) MUSIC, showing the focal and similar location close to motor cortex area anatomically. Source localization for an interictal discharge using (C2) sLORETA and (D2) MUSIC, showing wider variation

in peak and distribution. (E) Intracranial EEG (ICEEG) findings and surgery. (E1) Overlaid grid placement for invasive presurgical evaluation with the peak of distribution of the initial MEG ictal onset on 3D reconstructed brain based on the patient's own MRI. (E2) The overlaid MRI with actual resection area (yellow), reconstructed from the patients' own post-operative MRI. (E3) Resective surgical plan (blue) and functional mapping result: motor cortex (hand/arm: red circle, face: blue circle), language (Broca's: green circle), and sensory cortex (hand: purple rectangular) on the intra-operative picture.

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Figure 3.

Patient #5 – Initial MEG onset source localization and its propagation. (A) EEG recordings, recorded synchronously with MEG, showed bilateral diffuse high amplitude burst followed by background attenuation and muscle artifacts. (B) Short-time Fourier Transform (STFT) applied to MEG identified the power spectrum that revealed the initial ictal MEG onset. High pass filter was applied as 35 Hz. (C1–3) Initial ictal MEG onset source localizations and its propagation with sLORETA and (D1–3) with MUSIC.

Table 1

Comparison of source localizations between ictal MEG onset and interictal MEG discharge, other clinical factors, and surgical outcome.

Pt. No.	Ictal MEG onset SL	Clinical semiology on MEG recording	Ictal scalp-EEG phenomena	Interictal MEG discharge SL	MRI	ICEEG ictal onset	#of seizure semiologies	Surgery	Duration of follow-up (yrs)	Outcome	Pathology
1	L mes T	head turn to R, 2GTC	theta rhythmic	L lat T	TSC	L mes T	1	LT lobectomy	3.2	1	TSC, MTS
2	L inf. post F	Right facial twitching	Epilepsia Partialis Continua	L lat F	L inf F opercular P inf pre& post central gyri	L inf. post F	1	L inf post F → L fH	2.9	3 → 1 *	Rasmussen Encephalitis
3	L post F	Eye to R	Theta rhythmic	L lat F	Normal	L post F	1	L post F corticectomy	2.6	1	FCD
4	R ant F	head turn to L, L eye lid fluttering	Diffuse bilateral paroxysmal onset	Bilateral: R > L (LF, RH- post T, F, P)	R F encephalomalacia w/ gliosis	RF	4	RFT lobectomy & P corticectomy → R fH	1	4 → 1 *	F: FCD type IIA & Microcystic encephalomalacia with neuron loss T: FCD type IIA
5	L post-mes F	R arm elevation	Diffuse bilateral paroxysmal onset	Bilateral: L > R (L post-mes F, RF)	Mild cerebral/cerebellar volume loss	L post-mid F	2	LF partial lobectomy	1.7	3	FCD, probable Palmini type IB
6	L mes T	Chewing movement, head to R	Diffuse bilateral paroxysmal onset	L lat T	Normal	N/A	1	LT lobectomy	1.5	1	FCD IA & MTS
7	L post T (ECD, STORETA), mid (MUSIC)	Tonic sz	Diffuse bilateral paroxysmal onset	Bilateral: L = R (LR FC)	Normal	L post F, P, O	3	LFP corticectomy	0.9	3	FCD Type IB
8	R post F	L arm stiffening	Diffuse bilateral paroxysmal onset	R post F, R ant P	Normal	P post F	1	R lat F conticectomy & SMA resection	1.1	2	F: FCD type IIA SMA: Type IB

Pt. = patient, SL = source localization, ICEEG = intracranial EEG, L = left, R = right, mes = mesial, lat = lateral, post = posterior, ant = anterior, mid = midline, T = temporal, F = frontal, P = parietal, H = hemisphere, fH = functional hemispherectomy, SMA = supplemental motor area, TSC = tuberous sclerosis complex, MTS = mesial temporal sclerosis, FCD = focal cortical dysplasia, SMA = supplemental motor area, sz = seizure, 2GTC = secondary generalized tonic clonic seizure,

* = patient who had second surgery due to poor outcome from the 1st surgery

Table 2

Lateralization/localization concordance between each source localization; ictal MEG onset and interictal MEG discharge with ictal onset of ICEEG. The highest level of concordance is shown.

Source localization Patient No	Interictal MEG discharges	Initial ictal MEG onset
1	lobar	sub-lobar
2	lobar	sub-lobar
3	lobar	sub-lobar
4	hemispheric	lobar
5	hemispheric	lobar
7	discordant	hemispheric
8	hemispheric	sub-lobar