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Effect of epilepsy magnetic source imaging on intracranial electrode placement

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Abstract

Objective—Intracranial electroencephalography (ICEEG) with chronically implanted electrodes is a costly invasive diagnostic procedure that remains necessary for a large proportion of patients who undergo evaluation for epilepsy surgery. This study was designed to evaluate whether magnetic source imaging (MSI), a non-invasive test based on magnetoencephalography source localization, can supplement ICEEG by affecting electrode placement to improve sampling of the seizure onset zone(s).

Methods—Of 298 consecutive epilepsy surgery candidates (between 2001–2006) 160 cases were prospectively enrolled on the basis of insufficient localization from seizure monitoring and MRI results. Prior to presenting MSI results, decisions were made as to whether to proceed with ICEEG, and if so, where to place electrodes such that the hypothetical seizure onset zone would be sampled. MSI results were then provided with allowance of changes to the original plan.

Results—MSI indicated additional electrode coverage in 18 of 77 (23%) ICEEG cases. In 39% percent (95% CI: 16.4, 61.4) seizure onset ICEEG patterns involved the additional electrodes indicated by MSI. Sixty-two patients underwent surgical resection based on ICEEG recording of seizures. Highly localized MSI was significantly associated with seizure-free outcome (mean=3.4 years, minimum > 1 year) for the entire surgical population (n=62).

Interpretation—MSI spike localization increases the chance that the seizure onset zone is sampled when patients undergo ICEEG for presurgical epilepsy evaluations. The clinical impact of this effect—improving diagnostic yield of ICEEG—should be considered in surgery candidates

that do not have satisfactory indication of epilepsy localization from seizure semiology, EEG, and MRI.

Keywords

magnetic source imaging; epilepsy; surgery; magnetoencephalography

Introduction

The surgical treatment of epilepsy is unique for its potential of a nearly curative impact on a lifelong disabling neurological disease.¹⁻³ The primary goal of evaluation for surgical candidates is to determine if seizures arise from a single part of the brain, and if so, where. Although electroencephalography (EEG) is the primary tool used to directly implicate a brain region involved in generation of seizures, numerous imaging technologies have been developed to aid identification of epileptogenic pathology. Indeed, arguably the greatest impact on the epilepsy surgery evaluation since EEG has been the development of high-resolution magnetic resonance imaging (MRI). Localized scalp EEG findings that are concordant with imaging evidence of epileptogenic lesions allow many patients to have surgical resection without further testing.⁴ This additional testing includes intracranial EEG (ICEEG), a form of EEG that uses chronically implanted electrodes on or within the brain to record spontaneous seizures such that precise epilepsy localization can be determined for ultimate surgical planning.

One of the greatest challenges of ICEEG is determining where to place electrodes.⁵ In any given case only a small fraction of the total cerebral cortex can be sampled, for the extent of electrode coverage is limited by safety and other practical concerns. Often, the very reason ICEEG is considered necessary is due to the poor localization of non-invasive tests. Thus, a conundrum is created for deciding where and what type of ICEEG electrodes should be implanted. The stakes are high for these decisions. ICEEG studies include non-trivial medical risks and expense.^{1, 6} Additionally, wrong decisions can lead to false positive and false negative measurements—either incorrect localization (and related surgery) or inappropriate exclusion from surgery. Attempt to rectify indeterminate results by adding or changing electrode placement requires additional surgical risk that may be prohibitive.⁷ A final result can often be pressure to go ahead with some type of surgical resection with only limited localization data. This is not an uncommon scenario for patients with severely uncontrolled epilepsy for whom “doing nothing” after such extensive evaluation seems unacceptable in the perceived context of having “little to lose.”

Magnetoencephalography (MEG) based source localization, also called magnetic source imaging (MSI), is a non-invasive tool that can be used to three-dimensionally localize epilepsy related disturbances of cerebral activity. Limitations exist and assumptions about the source(s) of interest are required; but in appropriate cases, MEG spike source localization can be technically accurate and predictive of both ICEEG seizure localization and seizure-free outcome following surgery.⁸⁻¹² This study was designed to examine whether MSI may influence ICEEG electrode implantation such that epilepsy localization yield, and ultimately surgical decision-making, may be improved.

Patients and Methods

Patients, ICEEG, and surgical decision-making

Patients completing scalp video-EEG (VEEG) seizure monitoring at the UAB Epilepsy Center (including The Children's Hospital of Alabama, TCH) between August 2001 and March 2006 were screened. Inclusion and exclusion criteria are detailed in a previous report.

10 In summary, toward the larger goal of this work, enrollment was designed to select and study a group of patients that could be generalized to a population typically evaluated with ICEEG in most epilepsy centers (see Figure). A total of 298 patients with medically intractable partial epilepsy were considered for the study at the time of surgery conference presentation within the enrollment period. Of these, 138 (46%) were excluded due to the following reasons: 95 (32%) met the specific exclusion criteria of epilepsy not requiring additional testing for surgical-decision making, 25 (8%) potentially qualifying candidates were not identified before decision-making about ICEEG, 13 (4%) were considered to be unlikely surgical candidates or by patient choice held up further surgical evaluation, and 5 (2%) had incomplete or absent presurgical data sets. The study population was identified mainly by exclusion of patients with mesial temporal lobe epilepsy (MTLE) characterized by localized scalp VEEG (including supportive semiology) and concordant evidence of unilateral hippocampal sclerosis (HS) on MRI. It was these cases that comprised the large majority of the 95 patients who were excluded and had surgery without additional testing with functional imaging.

One hundred sixty patients (mean age=27, range 1-62, 48% female) were recruited into the study (Fig.). One patient died as a result of myocardial infarction unrelated to a seizure. Two patients on further evaluation did not meet eligibility requirements. Per protocol, all enrolled cases underwent MSI. If no large structural defect was on MRI (e.g. encephalomalacia), 2-[18F]fluoro-2-deoxy-D-glucose positron emission tomography (FDG-PET) was obtained. For patients with frequent seizures upon medicine withdrawal and non-localized seizures on VEEG, attempt was made to acquire ictal single photon emission computed tomography (SPECT).

All available data for each case—history, semiology, EEG, imaging (excluding MSI), and neuropsychological testing—were presented at surgery conference_1 (see Fig.) to make two primary decisions: (1) surgical candidate or not, and (2) if surgical candidate, whether or not ICEEG would be required. Nineteen patients were recommended for surgery without ICEEG or other additional testing (except when the intracarotid amobarbital test for language and memory lateralization testing was believed to be indicated). These 19 cases had well localized VEEG with supportive imaging; the decision to recommend surgical resection was made, by design, to be independent of MSI results, which remained undisclosed at this point in the conference. Three cases had multiple subpial transection procedures and one had a vagal nerve stimulator implantation without further evaluation. Of the remaining 134 patients, 57 were not recommended for further surgical evaluation. This decision was based on any one or combination of the following factors that were not controlled in this study: (1) consensus that epilepsy would not be satisfactorily localized for surgical resection (based mainly on history and electroclinicoanatomic features of epilepsy gathered from VEEG and MRI), (2) existing functional imaging data insufficient to support a reasonable epilepsy localization hypothesis, (3) high likelihood that eloquent cortex overlapped with suspected epileptogenic tissue, (4) patient, patient's guardian(s), or surgeon not sufficiently satisfied with risk-benefit ratio of surgery and possible outcomes. Some patients with insufficient functional imaging data were still considered possible candidates due to strong clinical suspicion of focal epilepsy; further non-invasive data (including repeat VEEG or functional imaging, particularly ictal SPECT) was requested before final deliberation on surgical candidacy was possible. If a case had the additional studies requested, it was re-presented at a subsequent consensus conference and decision-making was reclassified if changed.

Seventy-seven patients, remaining as surgical candidates, were recommended to undergo ICEEG recordings. For these patients, MSI results continued to be withheld, and were not considered in generation of an initial hypothesis of seizure localization. A plan of ICEEG

coverage based on the initial hypothesis was documented. Of important note, one conference participant (RCK), who was responsible for all MSI analysis, was not allowed to provide input into the initial hypothesis and ICEEG plan. Subsequent to documenting this first plan of coverage, MSI results were provided, which could then only influence ICEEG sampling by indicating supplemental coverage to that already planned based on the initial hypothesis. Specifically, if the original plan did not appear to fully sample all regions of spike sources suggested by MSI, then additional electrodes were added to include these regions. No increased morbidity or mortality resulted from additional electrodes placed as part of this study.

Intracranial Electroencephalogram (ICEEG)

Intracranial electrodes were placed according to the consensus hypothesis of epilepsy localization including MSI results as described above. With subdural grid arrays and depth electrodes a surgical navigation system was used, incorporating the MEG dipole source estimates. After brain exposure, electrode placements were confirmed to cover the region(s) of dipole sources. At the time of electrode removal and surgical resection, localization of seizure onset electrodes was determined in relation to MSI spike dipole sources. For cases with subtemporal epidural or subdural strip electrodes frameless stereotaxy was not used and source agreement was determined by visual confirmation of accurate electrode placement of mesial basal and lateral regions of the middle cranial fossa on skull x-rays.

ICEEG recordings continued with the goal to capture spontaneous seizures representative of the patient's epilepsy (no minimum number of seizures was required, although, three or more seizures were recorded in the vast majority). Final surgical decisions were completed at a second consensus conference following ICEEG recordings. Patients without any seizures captured after a maximum of ten days recording did not proceed to surgical resection. Of the 72 patients who had seizures recorded with ICEEG, 62 proceeded with surgical resection. The decision of whether to go ahead with surgical resection was based primarily on acceptable seizure localization from initial ictal ICEEG patterns and agreement of clinical onset and seizure semiology. A second consideration was topographical relationship of seizure localization with 'eloquent cortex' (cortex critical for either language or primary motor and sensory functions as defined by electrocortical stimulation brain mapping). All cases were treated on an individual basis, with final surgical resection decisions influenced by the patients and their willingness to accept or not accept *potential* irreversible neurological deficits. Functional imaging results could be used to influence surgical decision-making—both location and extent of resection. No rules were applied to weighting of individual modality influence.

MSI

Continuous MEG of spontaneous cerebral activity was recorded using a whole head, 148-channel biomagnetometer system (4D Neuroimaging, San Diego, CA). EEG was recorded simultaneously using the International 10-20 system of electrode placement with FT9 and FT10 included as additional electrodes. A minimum of four 10-minute recording runs were performed unless the patient had frequent spikes (more than 40 in 10 minutes). MEG signals were recorded at 508.63 Hz sampling frequency and band pass = 1.0-100Hz, and were then digitally filtered with a band pass of 3-70 Hz for offline analysis.

One epileptologist (RCK) analyzed all aspects of the data sets. On first-pass review of the recordings, spikes were identified on EEG, and then MEG. Next, a second-pass review of the MEG data was performed using the waveform knowledge of the initial review to attempt identification of MEG-only epileptiform discharges. Single equivalent current dipole (ECD) modeling was used to estimate spike sources using FDA-approved 4D Neuroimaging

software. A single latency in the ascending phase of each discharge (usually just before the first or only peak) was chosen for analysis. If three or more contiguous latencies (minimum of 6 msec) were not stable in regard to magnetic flux patterns at the time of interest then analysis was aborted for that spike. Dipole fits were accepted if the following criteria were met: (1) a correlation coefficient of 0.95 or greater, (2) no simultaneous magnetic artifact, and (3) a 95% confidence volume less than or equal to 20 mm³. A specific criterion for signal-to-noise was not required, but all accepted dipole fits were associated with events having clearly visible signal above background activity (approximately 3-4 fold baseline activity). Spikes that were not amenable to ECD modeling (unstable or without acceptable parameters) were classified as non-localized. Spike averaging was not used in order to eliminate over simplification of inter-spike variability, particularly scatter in distribution that was used to aid representation of extent of involved cortex. Emphasized in this study is an additional scoring system used to define degree of MSI localization as a whole: 1=no spikes, 2=all or majority of spikes non-localized, 3=less than five total spikes captured and localized or multifocal localization, 4=majority of greater than five spikes localized but with distribution greater than one sub-lobar region, and 5=all of more than five spikes localized, centered in one sub-lobar region. Sublobar regions have been previously defined.¹³

Analysis and Statistics

Surgical outcome was measured with consensus between two evaluators (without knowledge of the imaging tests) using Engel Classification¹⁴ either during follow-up clinic visit or phone call. For simple proportions, confidence intervals were calculated using the Modified Wald Method. Fishers Exact test was used to analyze the 2×2 tables created for analyzing MSI localization score ≥ 5 each with seizure-free outcome (Engel class I) using two-tailed p values for each of the subgroups. Wilcoxon Signed-Ranks Test was used to test for significant difference of Engel class outcomes (I-IV) between the different patient subgroups of interest—those with and without modified ICEEG coverage due to MSI results.

Results

MSI Effect on ICEEG Electrode Placement

MSI results modified ICEEG electrode coverage in 18 of the 77 cases comprising the study cohort. MSI primarily effected topography of subdural strip and grid-array placement in frontal and extent of lateral temporal coverage (Table 1). Seven cases represented the proportion (0.39 (95%CI: 0.16, 0.61)) of the 18 patients with ICEEG recorded seizures involving the additional electrodes placed as a result of MSI influence. ICEEG interictal spikes were recorded in the additional coverage in all but one of the 18 cases.

Surgery and Outcomes

Sixty-two patients underwent surgical resection. The remaining cases were either not satisfactorily localized, seizure onset zone overlapped with functional brain tissue that if removed might cause an unacceptable neurological deficit, or no seizures were recorded during at least 7 days of monitoring. Of the 18 cases with modified ICEEG, 16 had surgical resection (Table 2). In the two that did not have surgery, one had seizures appearing to arise from orbital frontal cortex that had been covered to due to MSI results, yet was still not satisfactorily localized. The second patient had seizure localization overlapping with posterior lateral temporal language cortex, identified in a region of additional coverage indicated by MSI. Four of the 18 patients are presumed to have had surgery modified as a result of the MSI effected ICEEG electrode placement.

Surgical outcomes (based on Engel I-IV classification and Wilcoxon Sign-Ranks Test) were not significantly different between the group of patients who had additional ICEEG

electrode coverage (n=16) and the group not affected by MSI (n=46). Further, no surgical outcome difference was seen between the total ICEEG group and the group who underwent surgery without ICEEG.

Level 5 (highly localized MSI studies) were associated with seizure-free outcome ($P=0.03$) in the entire surgical cohort (n=62). For each of the smaller subgroups the association was not statistically significant (suspected type II error).

Discussion

This was a prospective observational study intended to determine the effect of MSI spike localization on ICEEG electrode placement for epilepsy surgery. Blinding was included in the design such that surgical plan of electrode coverage for ICEEG was delineated before MSI results were made available at surgery decision-making consensus conferences. Discussion of MSI results led to modification of the original ICEEG electrode coverage plan in 18 of the 77 (23%) patients that comprised the study population. In 39% of the patients with ICEEG affected by MSI, seizure onset ictal patterns involved the additional electrodes, and as a consequence, affected surgical resection. Although seizure-free outcomes were not significantly different between the subgroups of patients with or without MSI modified electrode coverage, this does not indicate that MSI has no effect on outcome. It is likely that seizure-free rates in the group with additional electrodes would have been lower if MSI had not directed additional coverage. Additionally, one case likely avoided a failed surgery because additional coverage revealed epileptogenic tissue extending into unresectable language cortex that would not have otherwise been identified. When added to the independent predictive value of seizure-free surgical outcome with highly localized MSI results, these findings provide supportive evidence for use of spike source localization to improve ICEEG localization yield and outcome.

Much of the previously published work on the role of MSI in epilepsy surgery has concentrated on comparison of spike sources with epilepsy localization measures. Many of these studies have provided a degree of validation for MSI spike localization by demonstrating colocalization with known epileptogenic tissue identified with imaging 15, ICEEG 8-10, 16, and correlation with surgical resection.11, 17, 18 This body of work supports a foundation compelling further study to determine how MSI might be used to effect clinical practice as a unique non-invasive epilepsy localization tool. Multiple points of input exist in the presurgical evaluation for such a tool. Amongst them, three of particular interest are: (1) Screening of candidates—selecting those with a reasonable likelihood of being amenable to surgical treatment, (2) improving ICEEG localization yield and accuracy, and (3) aiding non-invasive localization tests such that an increased proportion of patients may avoid ICEEG. For patients with normal or non-localized anatomic imaging and limited or non-localized scalp EEG, potential for replacing ICEEG almost certainly exists in a subset of patients with very-well localized unifocal spike sources in a location that is strongly concordant with seizure history and semiology. Work is still needed to further define the diagnostic features that accurately identify these patients so that they may avoid the risks and expense of ICEEG. In the remaining patients ICEEG will remain a requirement. Unfortunately, even in centers with extensive experience in ICEEG electrode implantation, the procedure is fraught with unsatisfactory results; the extent of electrode sampling is limited and the risk of incomplete (and inaccurate) localization is prevalent.5, 19

This study focuses on whether MSI should be used to influence ICEEG electrode implantation. A very recently published study with a similar protocol of blinding MSI prior to initial surgical decision-making surrounding ICEEG, has also addressed this important gap in knowledge.20 The results showed that MSI changed surgical decisions in 23 of 69

(33%) of patients presented for further surgical evaluation. Effects on decisions ranged from: 1) to perform fewer tests, 2) to not proceed further with surgical treatment, 3) to decrease or add intracranial electrode coverage, 4) to add intraoperative electrocorticography to surgery, and 5) to proceed with surgery (when prior to MSI surgery was not recommended). In twelve (17%) cases electrode coverage was affected. The present study demonstrated a similar impact. ICEEG electrode coverage was affected as a result of MSI in nearly a quarter of the cases; and in 39% of these patients with expanded coverage defined by MSI, ictal onset involved the additional electrodes. This observation alone is important, however, what effect this may have on diagnostic accuracy of ICEEG and subsequent surgical decision-making and outcome is most important. Neither study can directly address these issues of clinical impact because no controls or randomization were implemented to test differences in outcome measures between matched groups of surgical candidates requiring ICEEG with and without MSI effect.

Further interpretation of results must take into account other limitations. At the time of study design, knowledge of MSI interpretation—how to optimally weight different characteristics and patterns of dipole source estimates—was limited. As a result, the protocol for interpreting MSI was generally liberal. Nearly all spike sources were deemed as possibly representing epileptogenic cortex and worthy of ICEEG electrode sampling. The only exceptions were spike sources that were believed to be remote and independent of the patient's habitual recurrent seizures. Reviewing the apparent false positive results in 11 of the 18 cases without seizure onsets in MSI indicated additional electrode coverage, it is apparent that less reliable spike source estimates were given too much significance. The best examples were frontal lobe epilepsy cases in which spikes were more variable (morphologically complex and temporally unstable) with greater scatter leading to mesial frontal coverage added to an initial plan that included only sampling the dorsal lateral convexity. This issue of not knowing how to optimally interpret MSI remains an important problem to address with more systematic study of spike source reliability such that proper weighting can be used for accurate diagnostic utility, decreasing both false positives and false negatives. Although no increased morbidity or mortality resulted from additional electrodes placed as part of this study, some increased risk must be taken in to account in any analysis of clinical utility and influence decision-making.

A few studies have discussed features of spike dipole sources associated with true positives, including observations from this work. Together they indicate that uniform, single tightly clustered MEG spike sources correlate strongly with both ICEEG localization of seizures and surgery outcome.^{9, 11, 17, 21} For such cases with highly localized spikes it is reasonable to conclude that strong diagnostic weighting should be given to the MSI results to influence all aspects of surgical decision-making, including ICEEG electrode placement.

Both specificity and sensitivity issues, however, remain for MEG based spike source localization.^{15, 18, 22} Sensitivity is affected by the fixed limitation of detecting small and distant spike source generators at the scalp.²³⁻²⁶ Another issue is the problem of modeling extended sources with an equivalent current dipole model.²⁷ Beyond these limitations, the greatest difficulty might arguably be the determination of true negatives, particularly in the context of spike disturbances with complex rapid propagation, including secondary bilateral synchrony.^{28, 29} Even if the source analysis challenges of such discharges could be appropriately modeled, assessment of clinical accuracy is very problematic because many cases with complex epileptiform discharges do not complete surgical evaluation due to selection bias. This bias, which exists in all surgical series (including this study), is seemingly unavoidable, for in a study designed to minimize the selection bias an unacceptable proportion of patients would likely have to experience true negative outcomes in an elective, highly invasive treatment scenario. Further complicating the measure of

diagnostic utility is determining truth when even the “gold standard”, ICEEG, may not fully characterize the cortical source(s) of either spikes or seizures. Nonetheless, determination of true and false negatives is possible in many cases in which seizure-free outcome is not obtained in spite of apparent satisfactory localization with ICEEG and other preoperative tests. One of the most important advances for improving the clinical value of spike source localization (whether by MEG, EEG, fMRI or some combination) will be the identification of features that indicate a likely negative outcome. Although not as appealing as a positive test result, a test with strong negative predictive value could improve patient selection, decreasing cost and exposure to unnecessary risk, including ineffective surgery.

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Figure.

Diagram for evaluation and treatment pathways of all patients identified as epilepsy surgery candidates after inpatient seizure monitoring with video and scalp electroencephalography (VEEG) and brain magnetic resonance imaging (MRI) for five years (2001-2006) at the University of Alabama at Birmingham (UAB). The cohort of cases enrolled for observational study (N=160) was considered to have localization-related epilepsy that was potentially amenable to unifocal resection. Specifically excluded were patients (N=95) with clinically defined mesial temporal lobe epilepsy (MTLE) supported by localized scalp VEEG (including supportive semiology) and concordant evidence of unilateral hippocampal sclerosis (HS) on MRI and patients considered to require simple lesionectomy—both reflecting groups of patients that are widely treated without additional localization tests including seizure recordings with chronic implanted intracranial electrodes (ICEEG).

† Three patients did not complete the study: one patient died as a result of myocardial infarction unrelated to a seizure. Two patients on further evaluation did not meet eligibility requirements.

‡ Three cases had multiple subpial transection procedures and one had a vagal nerve stimulator implantation without further evaluation.

* Prior to presenting magnetic source imaging (MSI) results at “Conference 1”, decisions were made as to whether to proceed with ICEEG, and if so, where to place electrodes such that the hypothetical seizure onset zone would be sampled. MSI results were then provided with allowance of changes to the original plan.

Table 1

MSI effect on ICEEG electrode placement topography.

Case no.	ICEEG Plan	ICEEG Added Electrodes	ICEEG Seizure Localization
40	Bilateral ST strips	Right O-T depth & LT-O strips	Right MT & Right LT-O
51	Right ST strips & LT grid	Left LT, ST strips	Right LT
58	Right ST & LT strips	Right LT grid	Right LT
62	Left ST & LT strips	L OF strips	Left OF
70	Bilateral ST strips	R OF strips	Right OF
83	Right F-P grid & ST strips	Right PP strips	Right LF > AP
91	Left F-P grids & MF, OF strips	Left ST strips	Left LF (inferior)
92	Bilateral ST strips	Left LT grid	Left LT
98	Left ST & OF strips	Left LT grid	Left MT
107	Bilateral ST strips	Right LT-O strips	Right MT
120	Left LO grid & P-T strips	Left MO grid	Left MO
123	Right LO grid	Right LT-O strips	Left LO-T
129	Right LF grids & FP, OF strips	Right MF strips	Right LF
133	Left LF grids & FP strips	Left MF strip	Left LF (inferior)
142	Right LF grid & OF, FP, P strips	Right MF strips	Right LF (superior)
148	Right ST & LT strips	Right LT grid & posterior ST strip	R MT
153	Right ST & LT strips	Right LT-P grid	Right LT & Right MT
155	Left ST & LT strips	Left LT grid & posterior ST strip	Left MT

ST=subtemporal, L=lateral, M=mesial, T=temporal, F=frontal, O=occipital, P=parietal, FP=frontal polar, OF=orbital frontal.

Localization results and effect on intracranial electroencephalography and surgery in cases with magnetic source imaging modified electrode coverage.

Table 2

Case no.	Age	Onset	VEEG class	MRI class	MSI score	Seizure onsets involve added electrodes	ICEEG class	Effect on Surgery	Outcome
040	23	18	MTLE	Normal	3	Yes	Multifocal	No	III
051	9	7	LTLE	Localized	5	No	Localized	No	II
058	28	20	LTLE	NL	5	Yes	Localized	Yes	I
062	48	41	MTLE	NL	5	No	Localized	No	I
070	25	12	ExTLE	Normal	3	Yes	NL		NS [‡]
083	54	38	ExTLE	NL	3	No	Localized	No	IV
091	17	7	ExTLE	Normal	3	No	Multifocal	No	III
092	41	5	NL	Normal	4	Yes	Localized		NS [‡]
098	27	19	MTLE	Normal	3	No	NL	No	I
107	41	4	MTLE	NL	3	No	Localized	No	I
120	2	1	ExTLE	NL	5	Yes	Localized	Yes	II
123	27	11	ExTLE	Localized	4	Yes	Localized	Yes	I
129	10	5	ExTLE	Normal	4	No	Localized	No	II
133	5	2	ExTLE	Normal	4	No	Localized	No	I
142	13	1	ExTLE	Normal	4	No	Localized	No	IV
148	53	6	LTLE	NL	5	No	Localized	No	I
153	22	2	LTLE	Normal	5	Yes	Localized	Yes	I
155	27	1	MTLE	Normal	5	No	Localized	No	I

VEEG Class: MTLE=mesial temporal lobe epilepsy, LTLE=lateral temporal lobe epilepsy, ExTLE=extratemporal lobe epilepsy. MRI Class: NL=nonlocalized (includes ambiguous / large, multifocal, and questionable abnormalities). MSI Score: 3=less than five total spikes captured and localized or multifocal localization, 4=majority of greater than five spikes localized but with distribution greater than one sub-lobe region, and 5=all of more than five spikes localized, centered in one sub-lobe region. Intracranial electrode EEG (ICEEG) Class: NL=seizure onset zone not satisfactorily localized for purposes of surgical resection, Multifocal=more than one seizure onset zone. Outcome (Engel): I=no disabling seizures, II=rare disabling seizures, III=worthwhile improvement, IV=no worthwhile improvement.

[‡] NS=no surgical resection performed because seizure onset zone not satisfactorily localized (even with additional ICEEG electrodes).

[‡] NS=no surgical resection performed because seizure onset zone overlapped with language cortex.