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Stereoelectroencephalography in presurgical assessment of MRI-negative epilepsy

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According to most existing literature, the absence of an MRI lesion is generally associated with poorer prognosis in resective epilepsy surgery. Delineation of the epileptogenic zone (EZ) by intracranial recording is usually required but is perceived to be more difficult in 'MRI negative' cases. Most previous studies have used subdural recording and there is relatively less published data on stereoelectroencephalography (SEEG). The objective of this study was to report the experience of our group in using SEEG in presurgical evaluation, comparing its effectiveness in normal and lesional MRI cases. One hundred consecutive patients undergoing SEEG for presurgical assessment were studied. Forty-three patients out of one hundred (43%) had normal MRI and 57 (57%) had lesional MRI. Successful localization was achieved with no difference between these two groups, in 41/43 (95%) normal MRI and in 55/57 (96%) lesional MRI cases ($P = 1.00$). Surgery was proposed in 84/100 patients and contra-indicated in 16/100 with no significant difference between lesional and MRI-negative groups ($P > 0.05$). At 1 year follow-up, 11/20 (55%) of those having undergone cortectomy in the MRI-negative group and 21/40 (53%) in the lesional MRI group were entirely seizure free ($P > 0.05$) and these proportions were maintained at 2 years follow-up. Significant improvement in seizure control (ILAE outcome groups 1–4) was achieved in >90% cases with no difference between groups ($P > 0.05$). Of MRI-negative cases that underwent surgery, 10/23 (43%) had focal cortical dysplasia. This series showed that SEEG was equally effective in the presurgical evaluation of MRI-negative and lesional epilepsies.

Keywords: stereoelectroencephalography (SEEG); depth electrodes; intracranial EEG; epilepsy surgery

Abbreviations: OP = opercular frontal cortex, DLPF9/46 = dorsolateral prefrontal cortex, Brodmann area 9/46; PSMA = preSMA; CG 24 = cingulate cortex Brodmann 24; TP = temporal pole; STG = superior temporal gyrus; Am = amygdala; MTG = middle temporal gyrus

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Introduction

Current practice in epilepsy resective surgery generally relies heavily on the identification of radiologically visible lesions considered likely to be responsible for the epilepsy (Polkey, 2004). The absence of a lesion visualized by MRI has been previously shown to relate to poorer prognosis in resective epilepsy surgery, both for temporal (Berkovich *et al.*, 1995) and extra-temporal cases (Zentner *et al.*, 1996; Smith *et al.*, 1997; Mosewich *et al.*, 2000; Jeha *et al.*, 2007). Despite major advances in neuroimaging, MRI-negative cases still account for up to a quarter of all those presenting for pre-surgical evaluation (Berg *et al.*, 2003). Although some authors previously considered it unhelpful to pursue presurgical assessment in this situation (Scott *et al.*, 1999), it is however increasingly recognized that certain MRI-negative cases, while among the most challenging in terms of presurgical assessment, are indeed surgically

treatable with satisfactory and sometimes excellent outcomes (Alarcon *et al.*, 2006). This has been highlighted in a number of recent series (Cukiert *et al.*, 2001; Siegel *et al.*, 2001; Hong *et al.*, 2002; Chapman *et al.*, 2005; Cohen-Gadol *et al.*, 2005; Lee *et al.*, 2005; Alarcon *et al.*, 2006). The possibility of avoiding invasive monitoring in certain cases of MRI-negative focal epilepsy has been proposed (Wennberg, 2005), particularly in carefully selected cases of temporal lobe epilepsy (Sylaja *et al.*, 2004) and the ultimate goal may indeed be to achieve 'totally non-invasive investigation' in as many patients as possible (Knowlton, 2004). However the need for intracranial recording in the vast majority of MRI-negative cases is generally accepted (Lee *et al.*, 2005). Successful determination of the epileptogenic zone (EZ) is generally considered to be more difficult in MRI negative cases, which is almost certainly a contributing factor to the poorer surgical outcome observed in many (Siegel *et al.*, 2001; Blume *et al.*, 2004). Most recent studies have been based on the majority of patients being investigated with invasive monitoring using subdural grids, subdural strips or a combination of subdural recording and some depth electrodes. The majority of these previous series of MRI-negative cases focus on those patients who were ultimately selected for surgery, that is, those in whom localization by these means of intracranial recording was successful; there is therefore a relative paucity of data on the overall yield of intracranial exploration in such cases.

Stereoelectroencephalography (SEEG) (Bancaud *et al.*, 1965; Talairach *et al.*, 1974; Chauvel *et al.*, 1987) differs in certain respects from other intracranial recording methods such as subdural grids. In particular, deep structures and buried cortex, which are not readily accessible by subdural or cortical methods of recording, can be accessed, and EEG data is obtained simultaneously from superficial and deep brain structures. As the precise position of each electrode contact is determined, a dynamic three-dimensional temporo-spatial picture of epileptic activity may be reconstructed. This aspect makes SEEG ideally suited to the study of the relations between structures involved in seizure production and propagation, and, building on the initial concept proposed by Bancaud *et al.* (1965), has made possible the development of the now widely accepted network model of seizure organization (Chauvel *et al.*, 1987; Wendling *et al.*, 2003; Bartolomei *et al.*, 2005). From this point of view the role of SEEG in presurgical assessment continues to evolve (Bartolomei *et al.*, 2005 [1]). The SEEG exploration is well tolerated by the majority of patients and overall complication rates of SEEG are reported as being of the order of 5% (Guenot *et al.*, 2001; Cossu *et al.*, 2005). This compares similarly to recent studies using predominantly subdural mats or strips (Alarcon *et al.*, 2006), and is somewhat less than studies of subdural grids showing overall complication rates of around 13% even for recent series from a major centre (Hamer *et al.*, 2002). The perception by some authors that depth electrodes are 'more invasive' than subdural methods of recording (Alarcon *et al.*, 2006) (and therefore less desirable than subdural recording) could therefore be questioned.

The SEEG method was developed before the era of magnetic resonance imaging and as such the original cases explored were indeed 'MRI-negative' as often no structural imaging was available. We wish in particular to pose the question of whether SEEG is equally as effective in MRI-negative cases as in cases with lesional MRI. Our aim is to report the experience of our group in using SEEG in the context of pre-surgical evaluation, examining the clinical usefulness of this method in localizing the epileptogenic zone, influencing clinical decision-making regarding surgery, and subsequent surgical outcome.

Patients and methods

From February 2000 to May 2006, 100 consecutive patients underwent SEEG in the Epilepsy Unit, Hôpital de la Timone, Marseille, France. This centre is specialist in surgical assessment and receives tertiary referrals from other epilepsy surgery centres as well as direct referrals from primary and secondary care centres. All of these patients were referred for consideration of surgical treatment for drug-resistant partial epilepsy.

Prior to selection for SEEG, a phase of thorough non-invasive pre-surgical assessment was carried out, including detailed clinical history focussing particularly on seizure semiology, and a period of surface video-electroencephalographic (EEG) recording, to permit analysis of habitual seizures and interictal EEG. All patients underwent MRI that was interpreted by experienced neuroradiologists as well as being reviewed by the epilepsy team.

The MRI specifications evolved during the study period. From 2000 to 2005, the MRI protocol consisted of: transverse diffusion images, transverse T2-weighted images, coronal T1-weighted inversion recovery images, coronal fluid-attenuated inversion recovery (FLAIR) images and a three-dimensional T1-weighted acquisition (Raybaud *et al.*, 2001). Acquisition plans were referred to the bi-hippocampal plane for the transverse acquisitions and to the AC–PC plane for the coronal and axial acquisition. Reconstructions of the 3D T1 images were adapted to the type of epilepsy. MRI examinations were performed on a 1.5-Tesla Symphony machine (Siemens Medical Systems, Erlangen, Germany), with a 4-channel head coil being used from 2000 to 2005; from January 2006 onwards a 12-channel head coil was used. In this latter part of the study period the multi-channel head coil allowed the use of matrix acquisition, isotropic 1 mm 3D T1 images, with reasonable acquisition time especially for inversion-recovery, FLAIR and 3D sequences (overall MRI examination lasting approximately 25 min).

A different neuroradiologist was responsible for overseeing technical parameters and for interpreting the images before and after August 2004.

Functional neuroimaging was also performed in all cases, including single photon emission computerized tomography (SPECT) and/or positron emission tomography (PET). Some patients also underwent magnetic resonance spectroscopy (MRS) (Guye *et al.*, 2005) and/or functional MRI with language activation (fMRI). In 32/43 (74%) of the MRI-negative and 38/57

(66%) of the lesional MRI cases, high-resolution EEG (HR-EEG) with source localization was carried out; some patients also had magnetoencephalography (MEG) within the context of a research protocol. Neuropsychology assessment was routinely performed.

We identified patients as 'MRI negative' from data collected retrospectively and prospectively in a database. This group was defined as those patients in whom standard quality structural cerebral MRI as defined above was considered to be normal by the neuroradiologist and the epilepsy team, at the time of decision to pursue invasive recording. This included re-review of standard MRI and/or repeated imaging in the light of obviously focal abnormalities on functional imaging or after video-EEG recording and the assumption made about the likely EZ location. The obvious limitations of the term 'MRI-negative' are acknowledged and will be discussed later.

Forty-three of the 100 cases were thus considered to have normal MRI and 57/100 to have lesional MRI.

Most cases also underwent additional morphometric analysis of cortical anatomy performed using raw MRI data within a computer model research tool (Mangin *et al.*, 2004), at the time of planning the electrode implantation. In some this data pointed to the possibility of a subtle cortical anomaly, in which cases the planned SEEG implantation took account of this. Research using this as yet unvalidated tool is ongoing and more detailed descriptions of these cases will be reported separately at a later date. In the course of comprehensive presurgical evaluation, non-invasive investigations were therefore directed at obtaining as much information as possible that might help with formulating the eventual hypotheses of seizure organization, including the extensive search for any lesion that might be related to the epileptogenic zone.

Patients were selected for SEEG exploration depending on the conclusion following non-invasive investigations: where the ensemble of non-invasive data led to the formulation of a single hypothesis regarding the likely localization and extent of the EZ, and where no contraindications were present, surgery was carried out directly without invasive recording. Indeed of all cortectomies performed for epilepsy in the same time period, approximately two-thirds were carried out without prior SEEG exploration (the majority of these being 'lesional MRI' cases). However where a surgical decision was not able to be made based purely on non-invasive data (in other words where non-invasive data were unable to distinguish between 2 or more clearly formulated hypotheses), SEEG exploration was proposed, with the planned electrode implantation designed to refute or confirm these hypotheses. SEEG was thus performed on ~20% of all patients undergoing video-EEG recording in the context of possible pre-surgical evaluation during this time period. This step of patient selection for SEEG and planning of electrode position, based on the hypotheses formulated from all available non-invasive data, forms a crucial part of the investigation process and likely determines to a large extent the eventual likelihood of successful exploration.

All patients gave their informed consent prior to exploration. SEEG recordings were performed using intracerebral multiple contact electrodes (10 to 15 contacts, length: 2 mm, diameter: 0.8 mm, 1.5 mm apart) placed intracranially according to Talairach's stereotactic method (Talairach *et al.*, 1992). The positioning of electrodes was established in each patient based upon available non-invasive information and hypotheses about the localization of the epileptogenic zone. The implantation accuracy was peri-operatively controlled by telemetric X-ray imaging. A post-operative computerized tomography (CT) scan without contrast was used to verify the absence of bleeding and the location of each recording lead. Following the recording period of 3–9 days, intracerebral electrodes were then removed and an MRI performed, permitting visualization of the trajectory of each electrode. Finally, CT-scan/MRI data fusion was performed to anatomically and precisely locate each contact along the electrode trajectory (see Bartolomei *et al.*, 2004 for further description).

Statistical analysis was performed in order to compare the data between the two groups using an analysis of variance (ANOVA) for quantitative data and Chi square (or Fisher's exact test when appropriate) for qualitative data. A P-value <0.05 was considered to be statistically significant.

Follow-up information was determined from out-patient visits, patient telephone calls and telephone calls to referring physicians.

Localization and organization of epileptogenic zone as defined by SEEG

The EZ is defined as the region of primary organization of seizures (Bancaud *et al.*, 1965). Seizure onset recorded using SEEG is often characterized by a high frequency low amplitude rapid discharge (beta and gamma range) (Bancaud *et al.*, 1965; Wendling *et al.*, 2003), often preceded by changes in pre-ictal activity (repetitive spikes and/or slow wave activity in the same region) (Gavaret *et al.*, 2004), and followed or not by more clonic activity. However other patterns of ictal discharge also exist. The temporal relation of the electrical and clinical changes is crucial, in that by definition ictal discharge always occurs prior to the onset of clinical ictal symptoms and signs, in order to be confident that the region of seizure onset has been correctly identified. Where a seizure occurs without clear SEEG evidence of an ictal discharge preceding the first clinical sign, it can thus be concluded that no electrode has been placed within the appropriate structure involved in the EZ. In some such circumstances the EZ cannot fully delineated.

Surgical strategy based on SEEG findings

Identification of the eventual cortical region to be resected may be a complex process, requiring consideration of the whole electroclinical picture (non-invasive and invasive data). This takes account of not only the EZ as defined by SEEG but also the irritative zone (IZ) (characterized by the region of interictal spikes as well as consideration of PET and SPECT data) and the lesional zone (LZ) (characterized by EEG features of interictal slow wave activity, and also reflected in MRI, PET and SPECT abnormalities). Definition by SEEG is clearly dependent upon the position of electrodes, the sampling of particular brain regions and systems having been chosen according to the hypotheses formulated following the non-invasive phase of assessment. The planned resection is informed by the exact position of SEEG electrodes, which are stereotaxically placed and whose location can be reconstructed using the patient's 3D MRI. A zone or region is not defined by a single electrode; estimation must be made of the extent of activity, based on the activity in adjacent electrodes and knowledge of the electrophysiological patterns of activity and propagation in different cerebral systems or structures (Talairach *et al.*, 1974).

The 'MRI-negative' ($n=43$) and 'lesional MRI' ($n=57$) groups were broadly similar in the proportion of males/females, age range, duration of epilepsy and the number of electrodes implanted, with no statistically significant difference (Table 1).

Table 1 Comparison of characteristics of the two groups at the time of implantation, MRI-negative ($n = 43$) and lesional MRI ($n = 57$)

Characteristics	MRI-negative group ($n = 43$)	Lesional MRI group ($n = 57$)	
Age range in years (median)	8–62 (24)	8–56 (31)	ANOVA $P = 0.12$ (NS)
Range of duration of epilepsy in years (mean)	1–50 (17)	6–47 (20)	ANOVA $P = 0.16$ (NS)
Ratio M:F	18:25 (42% male)	26:31 (45% male)	Chi square $P = 0.42$ (NS)
Unilateral: bilateral implantation	15:28	31: 26	Chi square $P = 0.02$
Range of number of electrodes implanted (mean)	5–15 (10)	5–16 (9)	ANOVA $P = 0.07$ (NS)

NS = non-significant.

The MRI-negative group had proportionally more bilateral implantations ($P = 0.02$).

The provisional localizations of epilepsy as determined following non-invasive investigation, and prior to SEEG, are shown in Table 2.

The group was notably heterogeneous. The majority of MRI-negative cases were extra-temporal and frontal lobe epilepsies accounted for 60% of this group (26/43). Conversely, 40% of the lesional group consisted of temporal lobe epilepsies compared with 12% in the normal MRI group. This is likely to partly reflect the various aetiologies implicated in the different groups; for example many of the temporal lobe epilepsy cases showed some radiological evidence of temporal lesion associated with other non-concordant data, necessitating intracranial exploration.

The difference in case-mix also reflects evolution of the referral pattern to our service with more of the extra-temporal and MRI negative cases having been explored in the latter part of the study period. For example in approximately the first half of the series, only 15 of the 56 patients explored from 2000 to 2002 were considered to have normal imaging (27%). In the second half of the series however, 28/44 (64%) patients explored from 2003 to 2006 had normal imaging.

Table 2 Preliminary diagnosis after non-invasive phase of investigation

Likely localization of epilepsy as determined prior to SEEG	MRI-negative group (% of group)	Lesional MRI group (% of group)
Temporal lobe epilepsy	5 (12)	23 (40)
Temporo-perisylvian epilepsy	3 (7)	3 (5)
Temporo-frontal epilepsy	2 (5)	4 (7)
Operculoinsular epilepsy	2 (5)	2 (4)
Frontal lobe epilepsy	26 (60)	14 (25)
Occipital lobe epilepsy	3 (7)	5 (9)
Parietal lobe epilepsy	1 (2)	4 (5)
Temporo-parieto-occipital junction epilepsy	1 (2)	2 (4)
Total	43	57

Table 3 Results of SEEG in determining EZ in each group, MRI-negative ($n = 43$) and lesional MRI ($n = 57$)

	MRI-negative ($n = 43$)	Lesional MRI ($n = 57$)	
Unilateral EZ identified permitting surgical decision	33	52	
Bilateral or multifocal EZ identified	8	3	Fisher's exact test $P = 0.05$
EZ not adequately determined	2	1	Fisher's exact test $P = 1.00$
Failure to record due to complication at time of implantation	0	1	
Total	43	57	

Results

Localization of the epileptogenic zone (EZ) with SEEG

The results show that the vast majority of patients in the present series had successful localisation of the EZ using SEEG. This was not significantly different between the MRI-negative and lesional MRI groups (Table 3).

The type of organization of the EZ varied between cases. Most showed unilateral organization involving several structures that were not necessarily contiguous but known to be closely functionally connected (for example, see Fig. 1). Some cases had bilateral organisation, involving bilateral homotopic regions at seizure onset. Only rarely did we observe very local organization restricted to closely neighbouring structures. By definition, no localization differed greatly from the provisional pre-SEEG diagnosis, as electrode placement had been chosen to confirm or refute the main hypotheses of EZ localization; if these hypotheses had been completely wrong then the SEEG would have been entirely non-conclusive. The localization of the EZ for each patient as determined by SEEG is given in the Tables A1 and A2 of the Appendix.

One patient in the lesional MRI group did not have SEEG recording due to the complication of a haematoma at the time of electrode implantation (discussed later). Only three inconclusive results were obtained following SEEG recording, two in the MRI-negative group and one in the lesional MRI group. In each of these cases, although the EZ was not felt to have been adequately defined in its totality, there was however sufficient indication of

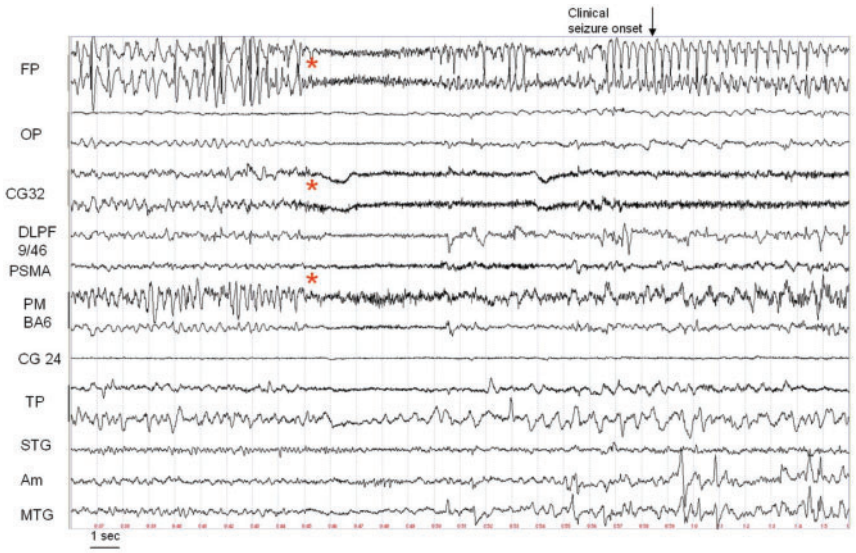

Fig. 1 Seizure recorded with SEEG in a patient with frontal lobe epilepsy (patient 44, Appendix Table A2), showing a representative sample of EEG channels recording within the right frontal and temporal lobes. Following an increase in preictal spike activity (in the first 9 s of the EEG trace shown here), a rapid (gamma range) ictal discharge (marked * on the diagram) is seen simultaneously in certain leads of electrodes exploring the frontopolar (FP) cortex, anterior cingulate region (CG32) and premotor lateral cortex (PMBA6). The electrical seizure onset therefore simultaneously involves areas that are spatially separate but functionally connected. The first clinical sign occurs 13 s after the onset of the fast discharge. OP = opercular frontal cortex; DLPF9/46 = dorsolateral prefrontal cortex, Brodmann area 9/46; PSMA = preSMA; CG 24 = cingulate cortex Brodmann 24; TP = temporal pole; STG = superior temporal gyrus; Am = amygdala; MTG = middle temporal gyrus.

multi-focality to make further attempts at SEEG localization inadvisable as eventual surgical treatment would be contra-indicated. One patient in the series (normal MRI group) underwent two SEEG explorations: the first had partially localised the EZ but showed that some seizures arose outside the structures explored; the second SEEG showed conclusive evidence of a bifocal organization.

Complications of SEEG

Three complications occurred in this series of 100 cases, of which 2 led to a neurological deficit. One patient developed a local haematoma at an electrode site that caused a focal motor upper limb deficit. The deficit partially resolved over several months. One other patient developed an intracranial haematoma at the time of implantation requiring abandonment of the procedure; no further attempt was made and no SEEG recording was carried out in this single case. This patient has a residual moderate hemiparesis. The third patient developed an extradural haemorrhagic collection at the first attempt at implantation, requiring surgical intervention. This particular patient had previously had very mild functional abnormalities of blood clotting attributed to sodium valproate. A second successful implantation was subsequently performed.

Decision following SEEG

As the EZ could be satisfactorily defined in the majority of both MRI-negative and lesional MRI cases, a high yield of either focal localization or clear evidence of multi-focality leading to surgical contraindication was obtained in this series (Table 3). In some cases with a unilateral EZ, surgery was also considered contraindicated due to major involvement of functional cortex. The SEEG was therefore clinically useful in making a definitive treatment decision in the majority of cases in both groups (Table 4), allowing some form of surgical treatment to be offered in 79% of the normal MRI group and 88% of the lesional MRI group, with no statistically significant difference between these (Chi square $P = 0.55$).

The surgical treatment offered depended upon the characteristics of each case. The majority of cases were suitable for tailored cortical resection. In some patients a gamma knife (GK) radiosurgical procedure was proposed (see Tables A1 and A2 for details of these cases, e.g. radiosurgical anterior callostomy; treatment of a surgically inaccessible region such as the insula; patient preference in some TLE cases).

Four patients who were considered suitable for conventional surgery subsequently chose to delay surgical treatment or declined intervention. In two of these this was due to a relative improvement in epilepsy control and in one due to other health problems; one patient no longer wished to pursue surgical treatment.

Surgical outcome

As the time course of post-operative evolution of GK treatment differs markedly from that of cortectomy, and as the numbers with adequate follow-up are small, the results

Table 4 Surgical decision following SEEG

	MRI-negative ($n = 43$)	Lesional MRI ($n = 57$)
Cortectomy already performed	25	42
Gamma knife radiosurgery already performed	4	6
Surgical treatment contra-indicated	9	7
Surgery awaited	2	1
Patient declined or wished to postpone surgery	3	1

of the 10 patients who underwent a GK procedure have been separated from the analysis of outcome. We therefore report outcome data on 60 of the original 100 explored patients, who have undergone resective cortectomy and in whom at least 1 year follow-up is available (20 in the MRI negative group and 40 in the lesional MRI group).

Outcome has been assessed using the International League Against Epilepsy (ILAE) classification (Wieser *et al.*, 2001), with a score assigned at the 1-year and 2-year post-operative assessment based on presence or absence of seizures and their frequency relative to the pre-operative status. Class 1 outcome is defined as complete seizure freedom with no auras [therefore being equivalent to the '1a' outcome of the Engel classification (Engel *et al.*, 1993)]. Range of duration of follow-up was 6–55 months (mean 28 months) in the MRI negative group and 6–67 months (mean 38 months) in the lesional MRI group. The relatively shorter follow-up for the MRI-negative cases reported here relates to the fact that the majority of the MRI negative cases were explored in the latter part of the 6-year study period, many during 2005 and 2006. As this difference in follow-up period is significant between the two groups, we have chosen to compare all patients at the same post-operative time intervals of 1 and 2 years (Tables 5 and 6), accepting that the numbers are obviously smaller in the normal MRI group at the 2-year assessment. The most recent follow-up data for each patient is also listed in Tables A1 and A2 of the Appendix.

The present results indicate that there is no significant difference between the MRI-negative and lesional MRI groups, in the proportion of cases that are seizure free or that have had significant improvement following surgery (Tables 5 and 6), either at 1 or at 2 years post-cortectomy. Seizure freedom rates (Class I ILAE) are 55% in the MRI-negative group and 53% in the lesional MRI group at 1 year, while more than 90% of patients in each group have had significant improvement in seizure control (ILAE outcome groups 1–4). These proportions remain similar at the 2-year follow-up.

Histopathology

Of 67 patients having undergone cortectomy, histopathology results were available in 23/25 MRI negative patients having undergone cortectomy and in 40/42 operated lesional MRI patients. In addition, one patient in the lesional MRI group who underwent GK radiosurgery had had a prior biopsy of the lesion (DNET). In four operated patients, histopathological analysis was not available for technical reasons (for example in cases of temporal lobe resection using aspiration of mesial structures). Histopathology data are therefore provided for a total of 64 patients.

Ten out of 23 patients of the MRI-negative group (43%) proved to have Taylor's type focal cortical dysplasia (FCD) (Table 7). Two MRI-negative patients had pathological evidence of hippocampal sclerosis despite the absence of definite imaging abnormality. Eleven MRI-negative cases showed evidence of gliotic change but no specific evidence of tumour, dysplasia or neuronal migration disorder.

Table 5 Surgical outcome (ILAE class) at 1 year in patients having undergone cortectomy

ILAE class	Normal MRI	Lesional MRI	
Class 1 (seizure free)	11	21	Chi square $P = 0.43$
Class 2 (auras only)	2	3	
Class 3 (1–3 seizures days/year; ± auras	1	9	
Class 4 (4 seizure days/year to 50% reduction from baseline)	5	5	
Class V (<50% reduction)	1	2	
Total	20	40	

Table 6 Surgical outcome (ILAE class) at 2 years in patients having undergone cortectomy

ILAE class	Normal MRI	Lesional MRI	
Class 1 (seizure free)	9	17	Chi square $P = 0.19$
Class 2 (auras only)	1	1	
Class 3 (1–3 seizures days/year; ± auras)	1	12	
Class 4 (4 seizure days/year to 50% reduction from baseline)	1	4	
Class V (<50% reduction)	2	1	
Total	14	35	

Discussion

This study reports our group's experience of using SEEG in a consecutive series of pre-surgical epilepsy patients requiring invasive exploration, comprising a high proportion of MRI-negative cases. The present study illustrates that, combined with thorough non-invasive assessment, SEEG can be equally effective in MRI-negative and lesional

Table 7 Available histopathology results for the 2 groups

	Normal MRI	Lesional MRI
Focal cortical dysplasia (Taylor type)	10	11
DNET and other cortical malformations	0	7
Hippocampal sclerosis	2	2
Gliosis/non-specific findings	11	19
Other	0	2
	23	41

MRI cases. Given the high proportion of clinically useful results obtained following SEEG, particularly the large number in whom some form of surgical treatment could be offered (79% in the normal MRI group and 88% in the lesional MRI group), it seems that patient selection for exploration in this series was satisfactory. This is an important aspect given the risks of invasive exploration as well as issues of cost-effectiveness. The patient population presented here reflects a complete series of consecutively explored patients, representative of our centre's practice as it has evolved over a 6-year period; other aspects of investigation have also necessarily evolved over the same period, notably MRI. The case-mix is therefore heterogeneous and comprises a high proportion of cases that can be considered complex (e.g. presence of extensive lesion; extra-temporal cases with normal MRI) including patients referred from other epilepsy surgery centres. Indeed, surgery had previously been considered contraindicated by other epilepsy surgery teams in 10 of the operated cases presented here. That subsequent resective surgery could be offered to the majority of patients in the present study may seem evident, given that patients were indeed selected with this ultimate goal; however such a rate of subsequent surgical treatment has not automatically been found in some previous series. For example Siegel and colleagues (2001) achieved localization of the EZ in 37/43 patients (86%), using mainly subdural grids, but only 25/43 patients (58%) were deemed to have a 'focal' epilepsy likely to be amenable to surgical treatment. The authors acknowledged that it is important to try to further reduce the failure rate due to 'sampling error' of the exploration.

In terms of surgical outcome in the present study, over 50% of the operated patients in each group became completely seizure free and over 90% of each group had significant improvement in seizure control, with no significant difference between groups. We chose to use the ILAE method of classification in which 'Group 1' patients are strictly seizure-free with no auras. If the Engel method of classification is used to assess outcome in the present study, 13/20 in the MRI-negative group (65%) and 24/40 in the lesional group (60%) have Class I outcome. It is indeed recognized that studies using Engel's classification tend to report higher rates of 'seizure freedom' than those using other forms of classification (Tellez-Zenteno *et al.*, 2005). Comparison with other studies is therefore clearly difficult given the issues of heterogeneous patient groups, different methods of exploration and different surgical outcome measures used. We also acknowledge the importance of longer term follow-up, particularly in view of recent reports of high rates of relapse in patients with normal MRI following frontal lobe surgery (Jeha *et al.*, 2007). Recognizing these limitations of possible comparison, the seizure freedom rate of 55% (or 65% Engel's Class I) obtained in the present MRI-negative group compares well with overall rates of between 40 and 50% patients in Engel Class I found in the majority of other studies of MRI-negative cases comprising mixed temporal and extra-temporal cases (Siegel *et al.*, 2001; Blume *et al.*, 2004; Lee *et al.*, 2005; Tellez-Zenteno *et al.*, 2005). However the high rates of seizure-freedom found in the present study for MRI negative cases are particularly notable considering that three quarters of these were extra-temporal epilepsies, as previous authors have reported poorer outcomes in MRI-negative extra-temporal cases than either 'non-lesional' temporal epilepsies or extra-temporal epilepsies with lesional MRI (Blume *et al.*, 2004; Tellez-Zenteno *et al.*, 2005; Alarcon *et al.*, 2006). In terms of the lesional MRI group, while comparison with other studies remains difficult as mentioned above, outcome is in keeping with previous series of mixed temporal and extra-temporal cases that have undergone intracranial recording (Siegel *et al.*, 2001; Lee *et al.*, 2005; Alarcon *et al.*, 2006). Lesional cases requiring intracranial exploration are a different population from those that can be operated directly. In such cases in the present study the SEEG was performed in order to define the extent of the EZ and its relation to the lesion and to decide whether an absolute surgical contra-indication existed. In some, the results of the exploration were such that a partial resection was proposed with the consideration that, although the chances of obtaining complete seizure freedom were low, the possibility of significantly improving very disabling epilepsy merited surgical intervention.

Earlier SEEG series (Bancaud *et al.*, 1965; Talairach *et al.*, 1974, 1992) demonstrated surgical outcomes comparable with many modern series; in effect these were cases that were correctly localized independently of structural imaging abnormalities. This aspect was also recently illustrated in a study of cerebral dysplastic lesions that were successfully localized using SEEG, with the majority of patients having been investigated before the era of modern brain imaging (Chassoux *et al.*, 2000). An important feature of earlier SEEG series was a relatively high proportion of extra-temporal epilepsy cases, in contrast to the general emphasis on temporal lobe surgery in recent decades. The role of SEEG in the context of modern pre-surgical evaluation has evolved, taking account of the great advances made in non-invasive investigations (particularly MRI), and the method is always used within the context of a full non-invasive work-up leading to clear hypotheses to be tested by intracranial electrode placement. This process of

formulating and testing hypotheses is essentially the same whether or not a visible lesion is present.

The definition of 'MRI negative' is somewhat controversial, as the ability to detect subtle lesions varies according to the techniques used, this being itself an area of extremely rapid current development (Knowlton, 2004; Koepp and Woemann, 2005). Overall, more advanced techniques may show abnormalities in around half of patients in whom conventional MRI is negative, but such abnormalities may not be concordant with other patient data (Koepp and Woermann, 2005). In addition, lack of large series of surgical outcome data means that the clinical implications of advanced imaging techniques, when used to identify potentially operable lesions in epilepsy patients with conventionally normal imaging, are somewhat unclear: ever more sensitive imaging methods carry the risk of increasingly identifying clinically innocuous lesions for which surgery may be unhelpful or even detrimental (Koepp and Woemann, 2005) and results must always be interpreted in the light of the clinical picture and other investigation findings. There are therefore likely to be natural limits to the ability of better imaging techniques alone to improve epilepsy surgical outcome and the need for invasive recording in certain cases is likely to persist. Better knowledge of seizure organisation has been suggested as an essential step to future progress in epilepsy surgery (Bartolomei *et al.*, 2005 [1]; Luders and Schuele, 2006). In addition clearer indications of whether some cases are better suited to certain methods of exploration could help improve patient selection for invasive exploration.

It is of interest that 43% of the MRI-negative cases for whom histopathology results were available showed focal dysplasia, as it is well-known that small dysplastic lesions may be difficult to detect using conventional high-resolution MRI (Duncan, 1997; Lee *et al.*, 2001; Knowlton, 2004; Lüders and Schuele, 2006). Several previous studies have found a high incidence of cortical dysplasia in patients with normal MRI who have subsequently been operated (Hong *et al.*, 2002; Cossu *et al.*, 2005; Lee *et al.*, 2005; Nobili *et al.*, 2006; Jeha *et al.*, 2007). All cases of cortical dysplasia in the present study, whether associated or not with a visible lesion, had significant improvement in seizure frequency following surgery. Indeed of the eight patients with focal cortical dysplasia and adequate follow up in the MRI-negative group, 6/8 were seizure free at 1 year. Of these eight normal MRI cases with FCD, seven had frontal lobe epilepsy and one had occipito-temporal epilepsy. While these numbers are small, these results are in marked contrast to a recent study of operated FLE cases explored using subdural grids (Jeha *et al.*, 2007), in which 11/12 patients with normal MRI plus malformations of cortical development (MCD) relapsed following surgery (the majority relapsing within the first six post-operative months), thus leading to the authors' conclusion that such patients formed the group with the overall worst surgical prognosis. The results of the present study may therefore offer an alternative to this rather pessimistic view. Our findings seem much closer to the findings of an Italian SEEG study (Nobili *et al.*, 2006), which found very good rates of persistent seizure freedom in a group of frontal lobe epilepsy patients: of nine who had normal imaging and evidence of dysplasia on histopathology, six became seizure-free following surgery. It is known that dysplasias are often located in regions that are difficult to satisfactorily record using subdural techniques, such as mesial cerebral structures and the fundus of sulci, and the advantage of SEEG in permitting direct intralesional recording in such cases has been documented (Chassoux *et al.*, 2000). In our cases of focal dysplasia, characteristic interictal surface and depth EEG abnormalities were often present, in keeping with previous observations (Chassoux *et al.*, 2000; Gavaret *et al.*, 2006; Lüders and Schuele, 2006). Finding better ways of identifying the group of likely radiologically 'invisible' cortical dysplasias may therefore represent a reasonable target in terms of future study, and the particular role of SEEG in exploring this group merits further study.

Supplementary material

Supplementary material is available at *Brain* online.

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Appendix

Table A1 Localization of EZ in 43 lesional MRI patients (numbered according to chronological order of SEEG exploration)

Patient number	Sex	Age at time of SEEG (years)	Duration of epilepsy at time of SEEG (years)	Likely diagnosis before SEEG	Laterality of EZ	Structures involved in EZ	Conclusion/clinical decision after SEEG	Histopathology	Duration of follow-up post surgery (months)	Outcome of surgery ILAE class 1 year	Outcome of surgery ILAE class 2 years	Most recent available outcome ILAE class
15	F	42	23	FLE	R	Right temporal pole, right posterior orbitofrontal cortex	Cortectomy	Gliosis	36	1	1	1
17	F	23	16	Occipital epilepsy	R	Lateral occipital cortex (BA 5), posterolateral temporal neocortex	Cortectomy	Dysplasia	49	2	1	1
20	F	20	15	FLE	R	Right dorsolateral premotor region (BA 6)	Cortectomy	Dysplasia	55	1	2	1
21	F	35	5	TLE	Bilateral	Right and left amygdalohippocampic regions	EZ localised but surgery contraindicated	Not operated	–	–	–	–
27	F	13	9	FLE-PM	L	Dorsolateral aspect of left premotor region (BA 6)	Cortectomy	Dysplasia	24	1	1	1
30	F	8	7	FLE-C	R	Right lower prerolandic region (F3, face region)	Cortectomy	Gliosis	28	4	5	5
35	F	18	7	Temporo-perisylvian epilepsy	Bilateral	Implication of right temporal region but some seizures suggestive of occipital onset	EZ incompletely localised by SEEG; no further attempt as evidence of multi-focality	Not operated	–	–	–	–
37	M	37	19	TLE	Bilateral	Right and left amygdalohippocampic region	EZ localised but surgery contraindicated	Not operated	–	–	–	–
39	M	34	19	TLE	L	Left amygdalohippocampic structures	Cortectomy	Hippocampal sclerosis	48	1	1	1
41	M	43	35	Temporo-perisylvian epilepsy	R	Anterior and posterior regions of right superior temporal gyrus	Cortectomy	Gliosis	50	1	1	1
43	F	17	12	FLE-C	L	Left dorsolateral prefrontal and premotor cortex (BA 9/46, BA 8)	Cortectomy	Dysplasia	42	3	4	4
45	M	33	17	FLE-PM	R	Right dorsolateral prefrontal cortex (BA 32 and BA 9/46)	Cortectomy	Dysplasia	36	1	1	1
49	F	15	9	Occipital epilepsy	R	Right supracalcarine and infracalcarine occipital cortex and fusiform gyrus	Cortectomy	Gliosis	38	1	1	5
54	M	31	25	FLE	R	Right mesial prefrontal cortex (BA 24 and BA32), posterior orbitofrontal cortex, temporal pole	Cortectomy	Dysplasia	41	1	3	3
56	F	43	12	TPOJ epilepsy	R	Right lateral temporal cortex, particularly superior temporal gyrus	Cortectomy offered but declined by patient	Not operated	–	–	–	–
58	F	33	30	TLE- mesiolateral	L	Left amygdalohippocampic region and temporal pole	Cortectomy	Hippocampal sclerosis	35	4	5	5
59	F	20	17	FLE-PM	L	Left operculoinsular region and left posterior orbitofrontal region	EZ localised but surgery contraindicated	Not operated	–	1	1	–
62	F	29	18	Temporo-frontal epilepsy	L	Left amygdala, temporal pole and basal temporal regions	Cortectomy offered but the patient wishes to wait	Not operated	–			–
63	M	9	7	FLE-PF	R	Right dorsolateral prefrontal region (intermediate frontal sulcus)	Cortectomy	Dysplasia	40	1	1	1
64	M	29	16	FLE	Bilateral	Right temporal pole and left operculo-insular region	EZ localised but surgery contraindicated	Not operated	–	–	–	–
65	F	18	8	FLE-PM	L	Lateral part of left BA 6, SMA, anterior cingulate gyrus	EZ localised but surgery contraindicated	Not operated	–	–	–	–

66	M	26	16	FLE	L	Left insulo-opercular region, posterior fronto-orbital region and temporal pole	EZ localised but surgery contraindicated	Not operated	–	–	–	–
70	M	13	2	FLE-PF	L	Left supplementary motor area, mesial aspect	Cortectomy offered but the patient wishes to wait	Not operated	–	–	–	–
71	M	28	24	Temporo-perisylvian epilepsy	R	Right superior temporal gyrus and right amygdalohippocampic region	Cortectomy	Not available	24	4	4	4
72	M	42	28	TLE	R	Right mesial temporal structures and basal temporal structures	Cortectomy	Not available	24	2	2	2
73	F	17	14	FLE	L	Left dorsolateral premotor and prefrontal regions (preSMA, 9/46); cingulate cortex	Cortectomy	Dysplasia	24	1	1	1
74	F	62	34	Temporo-frontal epilepsy	R	Right amygdalohippocampic region, entorhinal cortex and temporal pole; posterior part of superior temporal gyrus	Cortectomy	Gliosis	18	4	–	4
75	F	23	16	FLE	Bilateral	Bilateral prefrontal and premotor regions	EZ localised but surgery contraindicated	Not operated	–	–	–	–
76	M	31	16	FLE-PF	L	Prefrontal and premotor regions involving both lateral and medial aspects of left frontal lobe, and left anterior temporal region, with very rapid involvement of right frontal regions	Cortectomy	Gliosis	18	5	–	5
77	F	25	20	FLE	L	Left premotor, dorsolateral prefrontal cortex; anterior cingulate region	Cortectomy	Gliosis	19	4	–	4
79	M	21	4	FLE-PF	Bilateral	bilateral prefrontal regions, particularly mesiobasal aspect	GK (anterior callosotomy)	Not available	21	4	–	4
81	F	16	10	FLE	Bilateral	Dorsolateral aspect of right and left premotor and precentral frontal regions	GK	Not available	18	5	–	5
82	F	26	16	Parieto-central epilepsy	R	Paracentral lobule, mesial aspect	GK	Not available	9	–	–	N/A
84	F	22	20	FLE-PM	R	Extensive involvement of right premotor regions (lateral and mesial)	Cortectomy	Gliosis	8	–	–	3
85	F	32	25	FLE-PF	R	Right paramedian prefrontal region, anterior and posterior regions of superior frontal sulcus	Cortectomy	Gliosis	18	1	–	1
86	M	25	10	Operculoinsular epilepsy	R	Right insular region and posterior part of right superior temporal gyrus	GK	Not available	4	–	–	N/A
90	M	51	50	FLE	R	[Right frontal and right temporal]	EZ localised but surgery contraindicated	Not operated	–	–	–	–
92	F	26	23	Occipital epilepsy	L	Left infra- and supracalcarine occipital regions, lateral parietal cortex	Cortectomy	Gliosis	9	–	–	4
94	M	52	35	FLE-PF	Bilateral	Temporal pole, orbitofrontal cortex	EZ localised but surgery contraindicated	Not operated	–	–	–	–
95	M	8	7	Operculoinsular epilepsy	R	Right insula, perisylvian region	GK	Not yet operated	–	–	–	–
96	F	35	23	FLE	L	Left orbitofrontal cortex, perisylvian region	Cortectomy	Dysplasia	1	–	–	N/A
97	M	18	11	FLE	R	Right prefrontal region	Cortectomy	Gliosis	6	–	–	1
98	F	28	11	FLE	R	Right pre-SMA, medial prefrontal cortex	Cortectomy	Dysplasia	12	–	–	2

BA = Brodmann's area; DNET = dysembryoplastic neuro-epithelial tumour; EZ = epileptogenic zone; FLE = frontal lobe epilepsy; FLE-PF = prefrontal frontal lobe epilepsy; FLE-PM = premotor frontal lobe epilepsy; FLE-C = precentral frontal lobe epilepsy; GK = gamma knife radiosurgery; L = left; MCD = malformation of cortical development; R = right; TLE = temporal lobe epilepsy; TPOJ = temporo-parieto-occipital junction.

Table A2 Localization of EZ in 57 lesional MRI patients (numbered according to chronological order of SEEG exploration)

Patient number	Sex	Age at time of SEEG (years)	Duration of epilepsy at time of SEEG (years)	Likely diagnosis before SEEG	Laterality of EZ	Structures involved in EZ	Conclusion/clinical decision after SEEG	Histopathology	Duration of follow-up post surgery (months)	Outcome of surgery ILAE class 1 year	Outcome of surgery ILAE class 2 years	Most recent available outcome ILAE class
1	F	26	6	TPOJ epilepsy	G	Left mesial temporal and temporobasal regions	GK	Not available	65	4	4	4
2	F	18	10	Temporo-perisylvian epilepsy	G	Extensive involvement of left TPOJ, anterior and basal mesial temporal regions and superior temporal gyrus	EZ localised but surgery contraindicated due to wide involvement of language areas	Not operated	–	–	–	–
3	F	27	11	FLE-PF	G	Mesial aspect of left prefrontal region (BA 32) and mesial orbitofrontal region	Cortectomy	Dysplasia	42	2	1	1
4	M	48	15	FLE	D	Right posterior and mesial orbitofrontal region with rapid widespread propagation to amygdala and posterior frontal regions	EZ localised but surgery contraindicated	Not operated	–	–	–	–
5	M	22	18	TLE	D	Right amygdala, hippocampus and temporobasal regions	GK	Not available	67	2	3	1
6	F	43	7	TLE	D	Right amygdala, anterior and posterior hipocampus	Cortectomy	Gliosis	56	2	3	3
7	F	30	20	TLE	G	Widespread involvement of right mesial temporal and temporobasal structures particularly posterior hippocampus, amygdala, entorhinal cortex; early propagation to TPOJ	Cortectomy	Gliosis	60	1	1	1
8	F	25	20	TLE	D	Perilesional area (right temporal lobe) extending to STG and posterior temporoparietal region (BA 22)	Cortectomy	Ectopic neurones suggestive of MCD	33	1	1	1
9	M	29	15	TLE	G	Left hippocampus, amygdala and entorhinal cortex with early propagation to STG and TPOJ	Cortectomy	Gliosis	66	1	1	3
10	F	44	24	TLE	G	Left hippocampus, temporal pole and STG	Cortectomy	Gliosis	60	1	1	1
11	M	34	6	Mesiolateral TLE	D	Right lateral temporobasal region, mesial temporal and entorhinal structures	Cortectomy offered but declined by patient	Not operated	–	–	–	–
12	M	47	45	FLE-PF	D	Complex EZ with 2 independent "starter zones": right mesial prefrontal region (BA 32 and 24); right frontal operculum (BA 44)	Cortectomy (right mesial prefrontal region)	Dysplasia	60	1	1	1
13	F	30	28	Mesial TLE	G	Left anterior hippocampus; rapid widespread involvement of limbic system	Cortectomy	Gliosis	56	2	1	1
14	F	31	28	TLE	Bilateral	Perilesional area (right parieto-occipital junction); rapid involvement of bilateral posterior cingulate regions	GK	Not available	54	4	4	5

16	F	29	28	Mesial TLE	D	Right amygdala and hippocampus with rapid spread to temporal neocortex	Cortectomy	Gliosis	40	1	1	1
18	M	8	1	TLE	G	Left mesial temporal limbic structures	Cortectomy	Dysplasia	53	1	1	1
19	F	40	38	Occipital epilepsy	G	Bilateral parieto-occipital regions, including region anterior to left-sided lesion	Cortectomy	DNET	38	5	5	5
22	M	20	6	Occipital epilepsy	D	Right mesial occipital structures, particularly supracalcarine cortex	Cortectomy	Gliosis	34	3	3	3
23	F	38	13	Temporo-perisylvian epilepsy	G	Left mesial temporal structures with secondary spread to left lateral temporal structures	Cortectomy	Not available	56	3	3	1
24	M	37	11	FLE	G	Left dorsolateral prefrontal region (BA9) as well as mesial prefrontal structures and left frontal opercular region (perilesional)	Cortectomy	Gliosis	42	1	3	3
25	M	31	26	TLE	D	Right amygdala and hippocamus	Cortectomy	Gliosis	38	1	3	1
26	F	25	20	FLE	G	Left precentral and premotor regions including BA 6	Cortectomy	Dysplasia	26	4	4	4
28	M	15	9	Mesial TLE	G	Left posterior hippocampal region with propagation to temporo-occipital region	Cortectomy	DNET	60	1	1	1
29	M	31	17	Temporo-perisylvian epilepsy	D	Right STG with spread to mesial temporal structures	Cortectomy	Gliosis	42	1	1	1
31	M	15	12	FLE-C	D	Right mesial perirolandic regions with propagation to premotor regions	GK	Not available	38	4	5	5
32	M	43	18	Temporo-frontal epilepsy	Multifocale	Onset in several different perilesional areas (nodular hetreotopia) as well as implication of right mesial temporal structures	GK offered but declined by the patient	Not operated	–	–	–	–
33	M	24	22	Temporo-frontal epilepsy	G	Left anterior temporobasal and mesial temporal structures including perilesional zone; implication of thalamus	Cortectomy	Not available	51	1	3	3
34	M	33	16	FLE	Bilate	Extensive bilateral involvement of premotor regions (dorsolateral and medial)	EZ localised but surgery contraindicated (bilateral EZ)	Not operated	–	–	–	–
36	M	31	14	TLE	D	Left amygdala and hippocampus	Cortectomy	Gliosis	36	3	3	4
38	F	55	1	TLE	G	Onset left mesial temporal region with early propagation to temporal neocortex and insula	GK	Not available	30	3	3	3
40	F	29	25	FLE-PF	G	Principally perilesional area within left mesial prefrontal region	Cortectomy	Dysplasia	37	1	1	3
42	M	31	19	FLE-PF	G	Left mesiobasal prefrontal regions, orbitofrontal cortex and temporal pole	Cortectomy	Gliosis	40	1	1	1

(continued)

Table A2 Continued

Patient number	Sex	Age at time of SEEG (years)	Duration of epilepsy at time of SEEG (years)	Likely diagnosis before SEEG	Laterality of EZ	Structures involved in EZ	Conclusion/clinical decision after SEEG	Histopathology	Duration of follow-up post surgery (months)	Outcome of surgery ILAE class 1 year	Outcome of surgery ILAE class 2 years	Most recent available outcome ILAE class
44	F	41	16	FLE-PF	D	Right, frontopolar, orbitofrontal and dorsolateral premotor region	Cortectomy	Not operated	–	–	–	–
46	M	15	1	TLE	G	Left anterior hippocampus and temporobasal regions	Cortectomy	Hippocampal sclerosis	49	3	3	3
47	M	29	27	Occipital epilepsy	D	Right occipital cortex including perilesional region	Cortectomy	Dysplasia	30	4	4	4
48	F	29	18	Parietal epilepsy	D	Right superior parietal cortex and right perisylvian region	Cortectomy	Rosenthal fibres, gliosis	36	2	4	4
50	M	23	20	Lateral TLE	D	Right STG including perilesional region with spread to perisylvian region and insula	Cortectomy	DNET	42	3	3	1
51	F	36	32	TLE	D	Right mesial temporal structures	Cortectomy	Gliosis	45	3	3	3
52	M	22	21	TLE	D	Widespread involvement of right mesial and lateral temporal structures	Cortectomy	Astrocytoma	28	1	1	1
53	F	39	24	Mesiolateral TLE	D	Right mesial temporal structures with early spread to opercular and insular regions	Cortectomy	Gliosis	36	1	1	1
55	F	35	33	Mesial TLE	D	Right mesial temporobasal structures (entorhinal cortex closely connected to anterior hippocampus)	Cortectomy	Dysplasia	45	3	2	4
57	M	35	32	Mesial TLE	G	Left anterior mesial temporal structures	Cortectomy	Hippocampal sclerosis	29	1	1	1
60	F	17	9	Occipital epilepsy	D	Right perilesional region (V5) and posterior temporal region	Cortectomy	Dysplasia	42	3	3	1
61	F	13	11	TPOJ epilepsy	G	Left mesial temporal structures and temporal pole	Cortectomy	Neuronal migratio disorder	38	1	1	1
67	F	34	25	FLE-C	D	"Bifocal" organisation: right Hesch's gyrus and 2nd independent ZE (different seizure type) involving perisylvian structures and orbitofrontal cortex	Cortectomy	Gliosis	35	4	4	4
68	M	29	28	FLE-C	G	Left frontal opercular and basal central regions	GK	Not available	N/A	N/A	N/A	N/A
69	F	42	1	Mesiolateral TLE	G	No SEEG recording obtained	–	Not operated	–	–	–	–

78	F	26	21	Temporo-frontal epilepsy	D	Onset right amygdala and temporal pole, propagation to ipsilateral prefrontal and mesial occipito-parietal regions	Cortectomy	Dysplasia	15	1	–	1
80	F	34	22	Parietocentral epilepsy	D	Right perilesional area (parietal cortex)	Cortectomy	Gliosis	15	1	–	1
83	F	50	36	Parietal epilepsy	D	Right perilesional area (superior interparietal sulcus)	Cortectomy	Dysplasia	14	1	–	1
87	M	32	16	FLE	G	Left temporal pole with rapid propagation to orbitofrontal cortex, prefrontal anterior cingulate region (BA 32) and SMA	Cortectomy	Gliosis	12	4	–	4
88	M	16	13	Operculoinsular epilepsy	G	Perilesional region (left parietal operculum) with propagation to lateral frontal opercular region	Cortectomy	Neuroepithelial angiocentric tumour	12	5	–	5
89	F	36	26	Parietal epilepsy	D	Right mesial parietal region	Cortectomy	Dysplasia	6	–	–	1
91	M	26	17	Operculoinsular epilepsy	D	Right operculo-insular region	EZ incompletely localised by SEEG	Not operated	–	–	–	–
93	F	42	26	Occipital epilepsy	D	Right perilesional area (right occipital cortex) with rapid propagation to parietal regions and homotopic contralateral regions	GK	Not available	9	–	–	5
99	M	56	47	Temporo-frontal epilepsy	D	Right basal temporal cortex and amygdala	Cortectomy	Gliosis	6	–	–	N/A
100	F	15	12	FLE-PM	G	Left mesial precentral region (hand motor area)	Limited cortectomy	Not yet operated	–	–	–	–

BA = Brodmann's area; DNET = dysembryoplastic neuro-epithelial tumour; EZ = epileptogenic zone; FLE = frontal lobe epilepsy; FLE-PF = prefrontal frontal lobe epilepsy; FLE-PM = premotor frontal lobe epilepsy; FLE-C = precentral frontal lobe epilepsy; GK = gamma knife radiosurgery; L = left; MCD = malformation of cortical development; R = right; TLE = temporal lobe epilepsy; TPOJ = temporo-parieto-occipital junction.