

# Utility of electrocorticography in the surgical treatment of cavernomas presenting with pharmacoresistant epilepsy

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**ABSTRACT** – *Aim.* To describe the general aspects of cavernomas and epilepsy and review the available literature on the utility of electrocorticography (ECoG) in cerebral cavernoma surgery. *Methods.* We searched studies in PubMed, MedLine, Scopus, Web of Science, and Google Scholar (from January 1969 to December 2013) using the keywords “electrocorticography” or “ECoG” or “prognosis” or “outcome” and “cavernomas”. Original articles that reported utility of ECoG in epilepsy surgery were included. Four review authors independently selected the studies, extracted data, and assessed the methodological quality of the studies using the recommendations of the Cochrane Handbook for Systematic Reviews of Interventions, PRISMA guidelines, and Jadad Scale. A meta-analysis was not possible due to methodological, clinical, and statistical heterogeneity of included studies. We analysed six articles with a total of 219 patients. *Results.* The most common surgical approach was lesionectomy using ECoG in the temporal lobe with Engel I outcome range from 72.7 to 100%. *Conclusions.* Small controlled studies suggest that ECoG-guided resection offers the best functional results in seizure control for subjects undergoing cavernoma surgery, especially in the temporal lobe.

**Key words:** electrocorticography, cavernomas, ECOG, prognosis, EEG

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Electrocorticography (ECoG) is the practice of using electrodes placed directly on exposed cortical surface to record brain electrical activity. Wilder Penfield and Herbert Jasper introduced the procedure for localisation and treatment of epileptogenic zones between 1930 and 1950. Later, Cosimo Ajmone Marsan described the classic patterns of ictal and interictal activity recordings (Keene *et al.*, 2000). Today, ECoG is considered the *gold standard* for intraoperative determination of epileptogenic zones. ECoG has been used to localise the irritative zone and guide cortical resections, as well as to determine functional areas and establish prognosis (Keene *et al.*, 2000; San-Juan *et al.*, 2011). For a didactic review you can refer to the Seminars in Epileptology manuscript on “*Intraoperative Electrocorticography: indications, techniques and utility in epilepsy surgery*” (Yang *et al.*, 2014).

Cavernomas (CAs) are vascular malformations of the central nervous system (CNS) in which ECoG has been used to guide resections. They represent 10-15% of all vascular malformations (VM) of the CNS and are associated with seizures in 40 to 70% of cases (Arita *et al.*, 2000; Alonso-Vanegas *et al.*, 2011). Studies have evaluated the utility of ECoG in the surgical treatment of CA, showing a decrease of up to 79 *versus* 91% of patients at six months post-resection, 77 *versus* 90% at one year, and 79 *versus* 83% at two years without ECoG *versus* with ECoG, respectively (Van Gompel *et al.*, 2009). However, the utility of ECoG in epilepsy surgery with associated CAs has not been systematically analysed (Rosenow *et al.*, 2013). In this review, we briefly describe the general aspects of CAs and then focus on analysing the available literature on the utility of ECoG in cerebral CA surgery.

## Material and methods

Our systematic review was conducted according to the recommendations of the Cochrane Handbook for Systematic Reviews of Interventions (Higgins and Green, 2011), and the present report follows PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines (Moher *et al.*, 2010).

### Literature search

We searched for articles published in PubMed, MedLine, Scopus, Web of Science, and Google Scholar from January 1969 to December 2013 using the keywords “electrocorticography” or “ECoG” or “prognosis” or “outcome” and “cavernomas”. We also looked for articles in the reference lists of retrieved articles and ECoG review articles, and also contacted experts in the field.

### Selection criteria

The following criteria were adopted in order to analyse the utility of ECoG in cerebral CA surgery: (1) articles written in English or Spanish; (2) original articles with at least five patients; and (3) articles with a follow-up and evaluation using Engel scale.

We therefore excluded the following articles: review articles and articles reporting duplicate data or data extracted from original articles. In relation to the sections of general aspects of CA and principles of ECoG utility in epilepsy surgery, we followed similar criteria, except that we included review articles.

### Data extraction

For each study, two authors extracted data independently (DNCl and OBM) and two other authors (BJVA and GHI) checked data extraction. Any discrepancies were resolved by the corresponding author (DS). We developed a checklist in order to extract the following variables:

- (1) demographic and clinical characteristics, such as total sample, sex, and mean age at surgery;
- (2) study design characteristics;
- (3) treatment characteristics, type of surgery, and localisation;
- (4) iECoG technique (number and type of electrodes, duration of ECoG before and after resection [min]);
- (5) anaesthesia; and
- (6) outcome using Engel scale and/or complications.

### Quality assessment

According to the technique of Jadad *et al.* (1996), we addressed the following issues that influence data quality: (1) selective outcome reporting (we identified whether and to what extent complications and outcomes were reported and the follow-up); (2) year of publication (rare complications might take more years to be identified and reported); and (3) presence of control group, in order to distinguish between efficacy and adverse events (*i.e.* those which appear after intervention onset) and complications (*i.e.* adverse events in which causality is likely), and outcome.

Since our aim was to understand the possible utility of ECoG in epilepsy surgery with associated CA, we took a conservative approach and did not discard studies based on risk bias; instead, we undertook a separate analysis according to study quality.

### Quantitative analysis

All analyses were performed using Excel, and due to the small number of studies, we reported the

results using descriptive statistical analysis. A meta-analysis was not possible due to methodological, clinical, and statistical heterogeneity of included studies.

The next sections contain a brief review of the general aspects of CA and the principles of ECoG in epilepsy surgery, followed by a literature review related to the utility of ECoG in CA surgery.

## Part I. Basic aspects of cavernomas and principles of ECoG utility in epilepsy surgery

CAs or cerebral angiomas are low-flow VM, typically 1-2 cm in diameter (Bozinov *et al.*, 2010; von der Brelie and Schramm, 2011). According to post mortem studies, CAs represent 10-15% of VM and are encountered in 0.34-0.9% of the general population (von der Brelie and Schramm, 2011; Rosenow *et al.*, 2013). CA can occur throughout the CNS; 70-80% are supratentorial, 15-20% are infratentorial, and 5-10% are intraspinal (Campbell *et al.*, 2010). In 10-40% of cases, CAs are familial, and thus, often multiple (Chen *et al.*, 2011). Early series showed haemorrhage incidence in CA patients to be up to 65% and seizures are the most frequent clinical presentation of supratentorial CAs, occurring in 41-80% of patients with CA (von der Brelie and Schramm, 2011; Kivelev *et al.*, 2011).

The origin of cavernous malformations is still highly debated but there are a few theories to explain the underlying causes based on: 1) genetics (Bacigaluppi *et al.*, 2013); 2) radiation; and 3) origin in other vascular malformations (capillary telangiectasias) (Ardeshiri *et al.*, 2008).

### Clinical features

The clinical presentation of cavernous angiomas is widely varied and depends largely on anatomical location (Huang *et al.*, 2011; Rosenow *et al.*, 2013). The characteristic clinical triad consists of intraparenchymal haemorrhage (11-32%), seizures (38-51%), and neurological deficits (12-45%). These symptoms are directly related to initial intra- and peri-lesional haemorrhages (Huo *et al.*, 2008; Englot *et al.*, 2011).

Patients with CA have a twofold higher probability of presenting with epileptic seizures compared to patients with other VM and tumours (Kivelev *et al.*, 2011; Alonso-Vanegas *et al.*, 2011). It is estimated that close to 4% of drug-resistant seizures are caused by CAs (Sugano *et al.*, 2007). Epileptic seizures can be focal, with or without alteration of consciousness, or secondarily generalised. Seizures arise as a consequence of neural irritation, caused by microhaemorrhages containing haemoglobin degradation

products, such as haemosiderin (Baumman *et al.*, 2006; von der Brelie and Schramm, 2011). Haemorrhages can be both intra and extralesional (Campbell *et al.*, 2010). The epileptogenicity of supratentorial CAs depends on cortical, especially mesiotemporal archicortical, involvement. Exclusively, subcortical CAs are less likely to cause epilepsy. A greater diameter of the CA (>1.5 cm), multiple CAs, absence of oedema, and localisation in the left hemisphere are also associated with the occurrence of epilepsy (Kayali *et al.*, 2004; Rosenow *et al.*, 2013).

### Diagnosis

Increased availability and use of magnetic resonance imaging (MRI) has led to an increase in the diagnosis of CA (Campbell *et al.*, 2010; Rosenow *et al.*, 2013).

CAs commonly appear on MRI (T1 and T2-weighted, gradient echo and susceptibility weighted imaging sequences) as "berry or salt and pepper corn clusters" as a result of the heterogeneous ferromagnetic properties of CAs, surrounded by a high T2 signal border of perilesional gliosis. The interior appears as a reticulated core of mixed intensities reflecting the intralesional vascular channels, deoxyhaemoglobin, calcifications, thrombosed vessels, and metahaemoglobin. The perilesional halo is due to the presence of haemosiderin (Campbell *et al.*, 2010).

Computed tomography (CT) is only 30-50% specific in the detection of CAs. The lesions are observed as spherical hyperdense or mixed zones with perilesional oedema. Calcifications and a slight mass effect may be visualised (Requena *et al.*, 1991). Cerebral angiography has a low sensitivity as it detects only 10% of cases (angiographically occult VM), showing an avascular zone and displacement of adjacent venous structures in the venous phase (Requena *et al.*, 1991).

### Treatment

Management of CA is controversial and is generally based on natural history, age, lesion localisation, and surgical risk. The therapeutic options include conservative management, surgery, and radiosurgery (Kivelev *et al.*, 2011; Rosenow *et al.*, 2013).

Conservative treatment is recommended:

1) when the patient presents with multiple lesions and it is uncertain which is symptomatic; 2) the lesion is located near eloquent cortex; 3) the lesion is asymptomatic; and 4) in the event of a medical contraindication to surgery.

Surgical treatment is indicated in cases of drug-resistant epilepsy, lesions located near eloquent cortex (when the risk of rebleeding is high and using neurophysiological monitoring techniques), recurrent

haemorrhage, as well as important focal or progressive deficits and brainstem lesions (Alonso-Vanegas *et al.*, 2011). The objective of microsurgical treatment of CA is not only to improve symptomatology but also prevent further neurological deterioration due to bleeding. Surgical resection of supratentorial lesions is associated with 70-100% seizure reduction (von der Brelie and Schramm, 2011; Alonso-Vanegas *et al.*, 2011; Kivelev *et al.*, 2011).

The role of radiosurgery in the treatment of CA is controversial; it has been primarily used in CA located in the brainstem, basal ganglia, and eloquent areas of the cerebral cortex (Moreno-Jiménez *et al.*, 2008).

The surgical outcome and factors affecting seizure outcomes in patients who harbour supratentorial cavernous angiomas presenting with seizures vary (Stavrou *et al.*, 2008; Alonso-Vanegas *et al.*, 2011). One study included 60 patients with supratentorial CA; intractable epilepsy ( $n=22$ ) and sporadic seizures ( $n=38$ ) were treated by lesionectomy, extended lesionectomy, standard temporal lobectomy, and tailored resection. Of the patients with intractable epilepsy and patients with sporadic seizures, 72.7 and 89.5% achieved Engel Class I outcomes, respectively, and showed that lesionectomy alone can be considered a reasonable approach for those patients who exhibit sporadic seizures and have an extra-temporal or neo-temporal lesion. In patients with intractable epilepsy and/or mesial temporal lesions, a more invasive approach appears to achieve a better outcome (Yeon *et al.*, 2009). Some authors have found a similar Engel class I outcome and demonstrated that patients benefit significantly from early surgery and excision of the hemosiderin rim (Stavrou *et al.*, 2008). Other authors suggest that the surgical resection of CA should be considered in all patients with supratentorial CA and concomitant epilepsy, irrespective of the presence or absence of predictors for a favourable seizure outcome (Rosenow *et al.*, 2013).

Other predictors for good seizure outcome reported are age older than 30 years at the time of surgery, gross-total resection, the absence of multiple CA, surgery within one year of symptom onset, mesiotemporal CA localisation, CA size <1.5 cm, the absence of secondary generalised seizures, and medically-controlled seizures (Englot *et al.*, 2011; Rosenow *et al.*, 2013).

### Principles of ECoG utility in epilepsy surgery

ECoG has been used as a neurophysiological technique to register cerebral activity for over 40 years, as an auxiliary method in the surgical treatment of patients with medically refractory epilepsy (Keene *et al.*, 2000). Although the use of ECoG entails an inva-

sive risk, it is a useful tool to localise epileptogenic areas before and after surgery (San-Juan *et al.*, 2011). The number of patients with epilepsy considered for surgical treatment has increased over the last decades, making intraoperative ECoG an important resource to surgical success; numerous studies have demonstrated an improved prognosis in seizure outcome when surgery is guided by ECoG (Keene *et al.*, 2000; Ferrier *et al.*, 2007; San-Juan *et al.*, 2011).

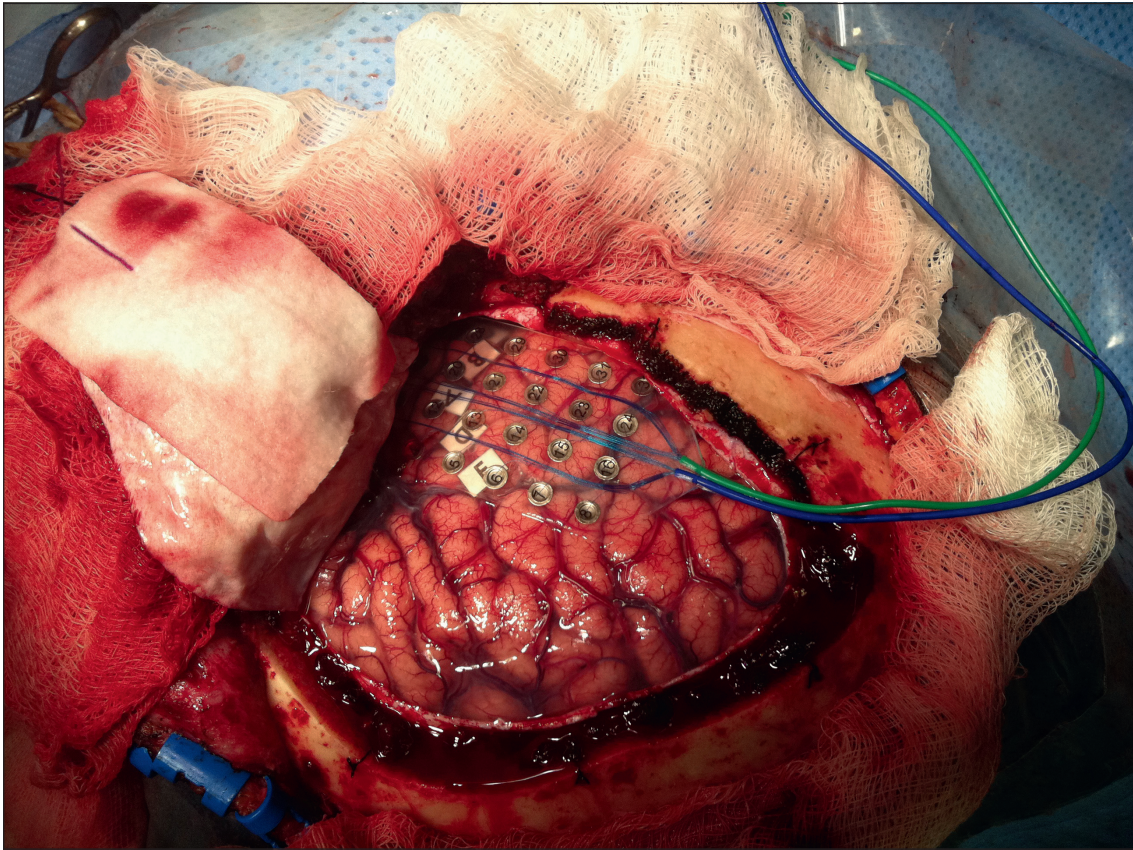
Intraoperative ECoG monitoring identifies epileptic activity in different pathologies and the ECoG pattern varies depending of aetiology (Keene *et al.*, 2000; Ferrier *et al.*, 2007; San-Juan *et al.*, 2011). ECoG registers the same brain potentials as scalp EEG without attenuation by scalp and skull tissues, which improves the amplitude and frequency spectrum, and reduces dispersion of registered potentials allowing for an improved localisation of the epileptogenic zone (Keene *et al.*, 2000). ECoG relies on interictal discharges to identify the epileptogenic zone, and ultimately depends on an adequate presurgical evaluation to determine and plan the surgical approach and ECoG recording (San-Juan *et al.*, 2011).

### ECoG procedure in epilepsy surgery

Once the dura mater has been retracted and the cortex exposed, general anaesthesia will be suspended and surface electrodes arranged in grids or strips with inter-electrode spacing of 5 to 10 mm placed over the cortex (*figure 1*) (San-Juan *et al.*, 2011). Subdural ECoG recordings are usually carried out using a 64 to 128-channel EEG monitoring system and amplifier. Signals are bandpass filtered between 0.03 and 70 Hz, sensitivity is set between 20 to 50  $\mu\text{V/s}$ , and a notch filter is set at 60 Hz. The electrode grids are placed consecutively over the cortical areas of interest. A reference electrode is placed on the mastoid, ipsilateral to the surgical field (San-Juan *et al.*, 2011).

Pre-resection ECoG is considered satisfactory if epileptiform activity is observed and there is no evidence of burst suppression. The intraoperative recordings, which usually take about 30 minutes to perform, guide the surgical steps to tailor the extension and volume or size of the cortical resection in each patient (San-Juan *et al.*, 2011).

Implantation of intracranial electrodes during ECoG may be associated with undesirable morbidity and mortality. Unfortunately, there are no data on the specific complications of ECoG. Some information on complications may be inferred from studies on chronic invasive monitoring. The most common complications during chronic recordings are cerebrospinal fluid leaks, meningitis, wound infection, haemorrhages/haematomas, transient or permanent



**Figure 1.** 32-contact grid (8×4) placed over the right temporal lobe. The letters indicate areas with interictal epileptiform discharges.

neurological deficits, and cerebral oedema. Death as a complication of intracranial monitoring is a very rare event. Therefore, the rate of complications in intraoperative ECoG is expected to be inferior to that of chronic intracranial recordings.

In summary, ECoG is considered to be a safe technique, and possible complications may be related to craniotomy and epilepsy surgery, but can rarely be attributed to the ECoG procedure itself (Fernández and Loddenkemper, 2013).

## Part II. Utility of ECoG in cerebral cavernoma surgery

We originally retrieved 20 articles related to the utility of ECoG in cerebral CA surgery. However, after excluding studies according to our selection criteria, six original articles were selected with 219 patients. Table 1 shows clinical studies of the utility of intraoperative ECoG in cerebral CA surgery. All the studies were ranked as JADDAD score 1. The most common

surgical approach was lesionectomy in the temporal lobe with Engel class I outcome range from 72.7 to 100%.

## Discussion

The first case reports published during the late 1970s–80s suggested ECoG to be a useful neurophysiological tool to guide CA resections and improve functional prognosis (Buckingham *et al.*, 1989; Kamada *et al.*, 1994). Today, some authorities consider lesionectomy sufficient for control of seizures secondary to CAs, while others consider that resection of the whole epileptogenic zone is necessary to obtain improved functional results (Zhao *et al.*, 2005; Baumann *et al.*, 2006; Yeon *et al.*, 2009). Some studies on surgical series have supported the usefulness of intraoperative ECoG in decreasing seizure frequency in CA resections, with some cases even becoming seizure-free (Cho *et al.*, 2005; Ferrier *et al.*, 2007; Sugano *et al.*, 2007; Yeon *et al.*, 2009; Van Gompel *et al.*, 2009; Sun *et al.*, 2011).

A study on ECoG discharges, including 19 patients with CA and 54 with neurodevelopmental lesions

**Table 1.** Clinical studies of the utility of intraoperative electrocorticography in cerebral cavernoma surgery (all the studies were ranked as JADDAD score 1).

**Study** *Sun et al., 2011*

No. patients with epilepsy	Mean age at surgery (years)	Sex (% males)	Study design	Type of surgery	iECoG technique (No./type of electrodes/duration of ECoG before and after resection, min)	Localisation of cavernomas	Anaesthesia
20/36	32.7	64	Cohort	Lesionectomy, Extended Lesionectomy, Extended Lesionectomy and standard temporal lobectomy	? Subdural grids and strips Pre and postoperative recordings were obtained	9 temporal lobe 9 frontal lobe 18 other lobes	?

*Complications:* 4 patients, 1 paraesthesia, 2 quadrantanopsia; 1 transient aphasia.

*Outcome:* 11 patients with non-refractory epilepsy had a class I outcome. Of the 9 patients with refractory epilepsy, 7 (77.8%) had a class I outcome, 1 (11.1%) had a class II outcome, and 1 (11.1%) had a class III outcome.

*Conclusions:* Intraoperative ECoG is an important adjunct to the careful removal of any resectable epileptic foci. The combination of iMRI and functional navigation and iECoG has been successfully used to resect the lesion, most of the non-functional haemosiderin rim and epileptogenic foci, thereby helping to avoid damage to functional areas and neurological compromise.

iECoG: intraoperative electrocorticography; iMR: intraoperative magnetic resonance.



Study Van Gompel *et al.*, 2009

No. patients with epilepsy	Mean age at surgery (years)	Sex (% males)	Study design	Type of surgery	iECoG technique (No./type of electrodes/ duration of ECoG before and after resection, min)	Localisation of cavernomas	Anaesthesia
105/173	35.4	55	Retrospective Case-control Non-randomised Non-blinded	Lesionectomy or tailored resection (anterior tetal lobectomy, and mygdalohippocampectomy)	? Subdural grids and strips Postoperative recordings were not obtained	64 temporal lobe 41 frontal lobe 14 parietal lobe 6 occipital lobe	?

*Complications:* None

*Outcome:* The use of iECoG in cases of temporal lobe cavernomas resulted in a superior seizure-free outcome: 79% vs 91% of patients at 6 months post-resection, 77% vs 90% at 1 year, and 79% vs 83% at 2 years without iECoG vs with iECoG, respectively.

*Conclusions:* The surgical removal of cavernomas most often leads to an excellent epilepsy outcome. In cases of temporal lobe cavernomas, the more extensive the iECoG-guided resection, the better the seizure outcome

iECoG: intraoperative electrocorticography.

Study Yeon *et al.*, 2009

No. patients with epilepsy	Mean age at surgery (years)	Sex (% males)	Study design	Type of surgery	iECoG technique (No./type of electrodes/ duration of ECoG before and after resection, min)	Localisation of cavernomas	Anaesthesia
60	5.4	62	Cohort with a Control group Non-randomised Non-blinded	Lesionectomy, Extended lesionectomy, Standard temporal lobectomy and tailored resection	? Subdural electrode plates Pre and postoperative recordings were obtained	17 temporal lobe 29 others 4 multiple	?

*Complications:* In the lesionectomy group; 6 patients hypesthesia, aphasia, upper extremity monoparesis and hemiparesis. In the extended lesionectomy group; 2 patients shoulder weakness and hemiplegia. In standard temporal lobectomy including mygdalohippocampectomy or tailored resection group; 2 patients transient sensory aphasia and superior temporal quadrant- anopsia.

*Outcome:* Intra-operative iECoGs were used in 34 patients 72.7% (16/22) of patients with intractable epilepsy and 89.5% (34/38) of patients with sporadic seizures achieved Engel Class I outcomes.

*Conclusions:* A lesionectomy alone can be considered a reasonable approach for those patients who exhibit sporadic seizures and have an extra-temporal or neo-temporal lesion. In patients with intractable epilepsy and/or mesial temporal lesions, a more invasive approach could achieve the better seizure outcome.

iECoG: intraoperative electrocorticography.



Study Sugano *et al.*, 2007

No. patients with epilepsy	Mean age at surgery (years)	Sex (% males)	Study design	Type of surgery	iECoG technique (No./type of electrodes/duration of ECoG before and after resection, min)	Localisation of cavernomas	Anaesthesia
8	21.7	54	Retrospective Case-control Non-randomised Non-blinded	Lesionectomy or extended lesionectomy	? ? Pre and postoperative recordings were obtained	35 temporal lobe	Induction: 5.0% sevoflurane and 95.0% oxygen without intravenous narcotic agents Maintenance: 2.5% sevoflurane with an adequate muscle relaxant

**Complications:** 1 patient with small cerebral infarction

**Outcome:** The number of 3-year postoperative seizure-free incidences for the group that underwent lesionectomy plus additional spike-positive site resection equated to 90.9%. In contrast, in the group that underwent a lesionectomy only, 76.9% were seizure-free for 3-years postoperatively. After complete removal of mass lesions, 86.4% of the residual spikes were detected over the hippocampus.

**Conclusions:** Effective surgical seizure control was achieved by carrying out additional procedures on the affected hippocampus. To detect seizure foci surrounding the lesion, especially over the hippocampus, intraoperative iECoG monitoring was shown to be an effective technique.

iECoG: intraoperative electrocorticography.

**Study Ferrier *et al.*, 2007**

No. patients with epilepsy	Mean age at surgery (years)	Sex (% males)	Study design	Type of surgery	iECoG technique (No./type of electrodes/ duration of ECoG before and after resection, min)	Localisation of cavernomas	Anaesthesia
19	36.4	73	Retrospective Case-control Non-randomised Non-blinded	Extended lesionectomy	15-30 electrodes Subdural grids and strips 54-10 min pre and postoperative recordings were obtained	17 temporal lobe 2 frontal lobe	Maintenance: propofol and sufentanyl

*Complications:* None.

*Outcome:* 17/19 patients (89%) had a minimal 1-year follow-up after ECoG guided resection of temporal CA. 12 patients (71%) were classified as Engel Class I and the remaining 5 as Engel Class II-IV. Similar outcome was observed in the neurodevelopmental lesion group.

*Conclusions:* Outcome and EcoG patterns are very similar in the groups with neurodevelopmental lesions and cavernomas.

iECoG: intraoperative electrocorticography.

Study Cho et al., 2005

No. patients with epilepsy	Mean age at surgery (years)	Sex (% males)	Study design	Type of surgery	iECoG technique (No./type of electrodes/duration of ECoG before and after resection, min)	Localisation of cavernomas	Anaesthesia
7	38.1	61	Cohort with a control group Non-randomised Non-blinded	Lesionectomy	8-16 electrodes Subdural grids and strips Pre and postoperative recordings were obtained	23 temporal lobe 23 extra temporal lobe	?

**Complications:** 4 patients 1 contralateral superior quadrant anopsia, 1 acute epidural hematoma because of placement of iECoG frame between the epidural space and skull bone. Cerebral fluid leakage led to 2 cases of mild CNS infection.

**Outcome:** Overall, 83% of the patients had satisfactory seizure control. Class A (no residual epileptic activity) of post-resection iECoG had a higher rate of seizure-free outcome (92%). Lesions at the extratemporal lobe yielded a higher rate of seizure-free outcome (78.2%, 18/23).

**Conclusions:** Application of neuronavigator and iECoG (additional cortical resection) is usually necessary for temporal lobe lesions. All patients with cavernous hemangioma were seizure-free.

Note: All the studies were ranked as JADDAD score 1.

iECoG: intraoperative electrocorticography.

with at least one year follow-up, demonstrated a very similar outcome between the groups (Engel class I: 89 vs. 71%, respectively) (Ferrier *et al.*, 2007). In another study that included 35 patients with temporal tumours, comprising 21 gangliogliomas, eight CAs, and six dysembryoplastic neuroepithelial tumours, the authors compared surgical outcome in patients in whom only lesionectomy was carried out with patients in whom additional removal of electrically-positive foci using intraoperative ECoG was performed. ECoG was performed in 23 patients (six CAs) and showed seizure reduction at 6, 12, 24, and 36 months follow-up of 100, 95.5, 90.9 and 90.9% respectively. Seizure reduction at the same follow-up time points was 92.3, 84.6, 76.9, and 76.9%, respectively, in the group undergoing only a lesionectomy, showing that the use of ECoG is associated with a better outcome. The results of this heterogeneous series reflect the effectiveness of ECoG in the treatment of CA, as well as in CNS tumours (Yeon *et al.*, 2009).

Another study (Van Gompel *et al.*, 2009) evaluated surgical results in 173 surgically treated CA patients and 102 cases had preoperative seizures; 61 with temporal CAs and 41 with extratemporal CAs. A total of 23 procedures were guided by ECoG. There were no significant differences in the long-term prognosis regarding lesionectomy versus a more extensive resection (temporal lobectomy), time of evolution, age, size of lesion, or use of ECoG. In general, and independently of lesion localisation, seizure-free outcomes were observed in 85, 87 and 88% of cases at six months, one year, and two years, respectively. The use of ECoG was related to more extensive resections and appears to improve the possibility of a seizure-free state, with an absolute increase in the seizure-free state of 12, 13 and 14% at 6, 12, and 24 months postoperatively, compared to patients in whom surgical ECoG guidance was not used (Van Gompel *et al.*, 2009).

### Patterns of epileptiform discharges in cavernomas

The interictal electroencephalographic patterns observed in ECoG recordings during CA surgery have low sensitivity and specificity, since these patterns are also encountered in ECoG recordings of other neurodevelopmental lesions (Ferrier *et al.*, 2007). Ferrier *et al.* identified the following four types of electroencephalographic patterns, using the Palmini classification (Palmini *et al.*, 1995).

- (1) Sporadic spiking: produced at irregular intervals over different sites (*figure 2*).
- (2) Continuous spiking: occurring rhythmically at regular intervals of at least 10 seconds, with a 1-second maximal inter-spike interval (frequency  $\geq 1$  Hz) (*figure 2*).

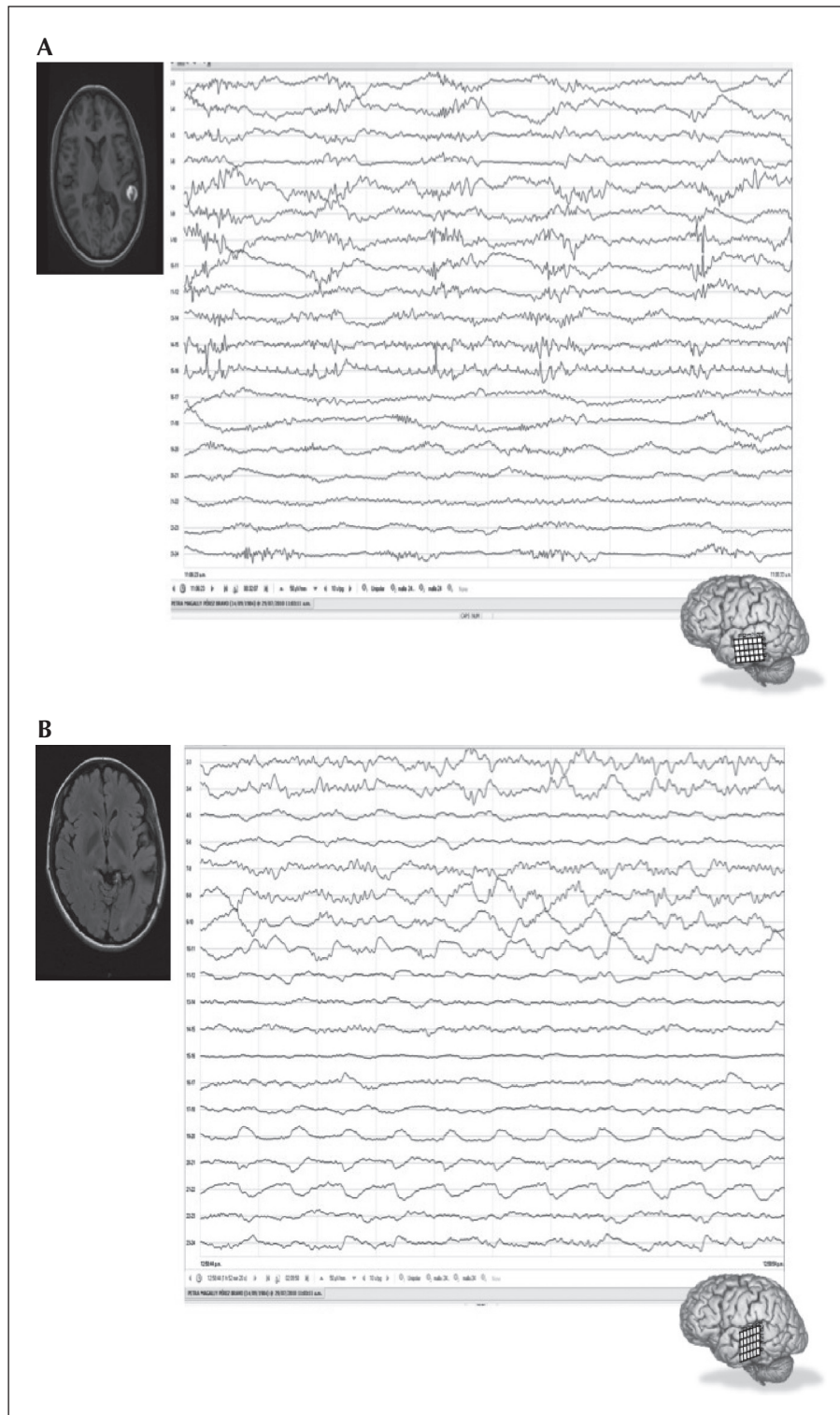
(3) Bursting discharges: sudden appearance of spikes of at least 1 second with 10 Hz or higher frequency (*figure 3*).

(4) Recruiting discharges: rhythmic activity characterised by an increase in amplitude and decrease in frequency (electrocorticographic seizures) (Ferrier *et al.*, 2007).

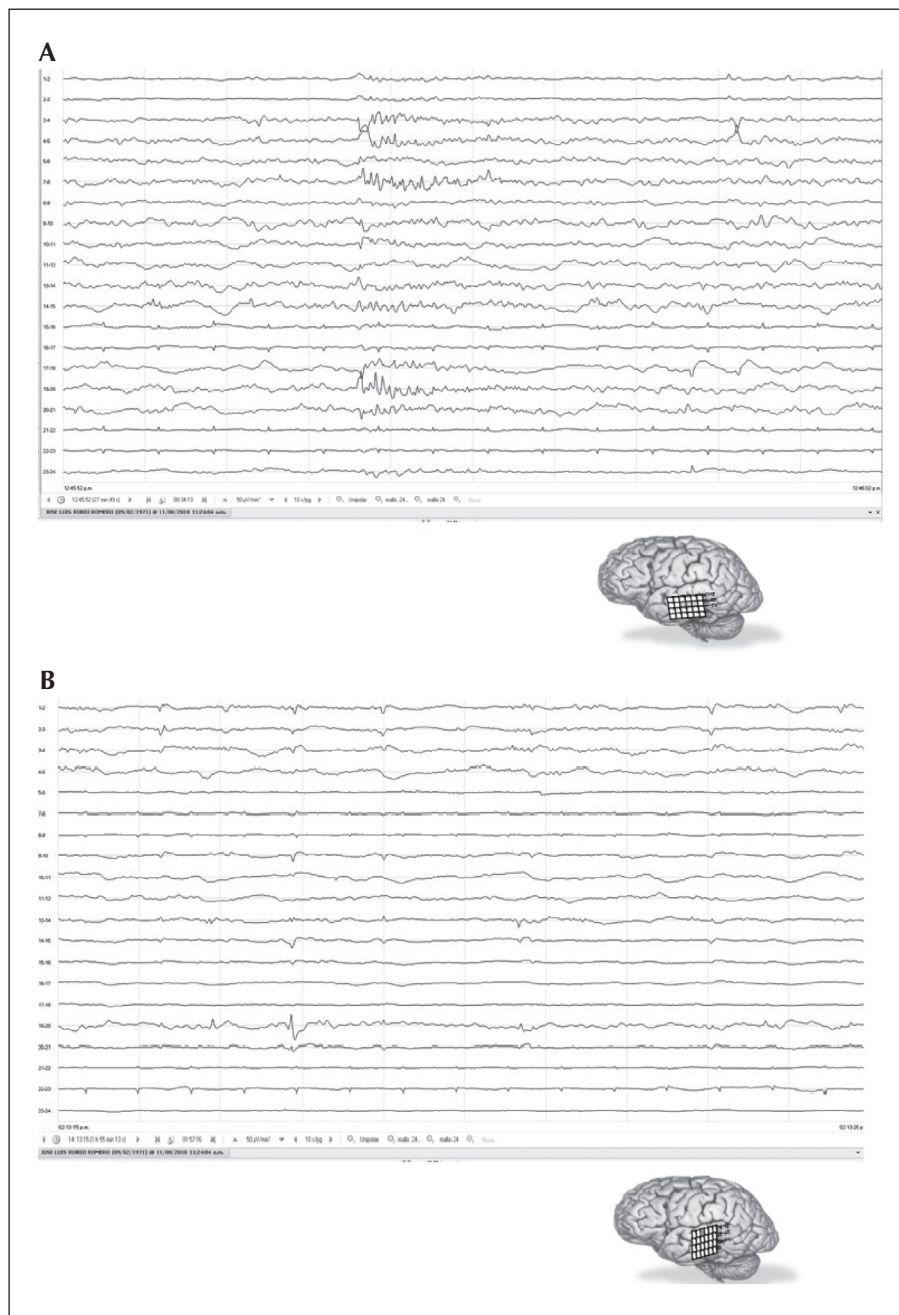
The different patterns observed in CA patients are related to the age at seizure onset, duration of epilepsy, and type and duration of lesion. The most commonly observed pattern during ECoG is sporadic spiking (Ferrier *et al.*, 2007).

Duration of epilepsy is important since a younger age at seizure onset is related to the degree of haemosiderin deposits and gliosis that surrounds the vascular lesion, and injures the CA surrounding parenchyma and results in neurological deficits (Ferrier *et al.*, 2007; Englot *et al.*, 2011). Patients with drug-resistant epilepsy secondary to CA show highly epileptiform discharge patterns on ECoG recordings, which include continuous spikes, bursts, and recruiting discharges similar to those observed in patients with neurodevelopmental lesions. This may be explained by micro-haemorrhages as an early insult in crucial stages of the developing brain resulting in functional changes, which are similar to alterations found in neurodevelopmental lesions. This indicates that the presence of continuous spikes in ECoG recordings of CA is associated with a long history of epilepsy before surgery. These findings are consistent with the poor outcome of surgical resections in patients with a long-standing history of epilepsy and emphasizes the importance of early intervention (Ferrier *et al.*, 2007). No association between the degree of haemosiderin deposits and the ECoG patterns has been reported (Baumann *et al.*, 2006). ECoG recordings during CA surgery detect additional epileptiform discharges in perilesional tissues or more remotely located areas (Kamada *et al.*, 1994), making it a very useful tool to guide the resection (Van Gompel *et al.*, 2009).

The postsurgical ECoG recordings in CA surgery can guide the careful removal of any residual epileptic foci and predict the outcome (Cho *et al.*, 2005; Sun *et al.*, 2011); however, the value of post-resection ECoG is controversial (Sugano *et al.*, 2007). Cho *et al.* (2005) showed that residual epileptic activity in post-resection ECoG is not associated with a greater seizure-free rate (92%), compared with other degrees of residual epileptic activity. While, Sugano *et al.* (2007) reported frequent residual spikes observed over the hippocampus (86.4%) and amygdala (63.6%) during surgery for temporal-lobe-mass lesions, including CA. Despite this, the seizure-free occurrence rate was 76.9%.



**Figure 2.** Case of a 35-year-old female with temporal drug-resistant epilepsy characterised by focal seizures with and without alteration of consciousness and secondarily generalised seizures, secondary to a left temporal CA. (A) Preoperative MRI (T1) showing left temporal CA, ECoG showing single spikes in channels 8-9 and 9-10, and a pattern of continuous spiking with intermixed sporadic spiking in channel 14-15. These patterns are observed in the left second temporal gyrus. (B) Postoperative MRI showing complete resection of CA and ECoG showing absence of epileptiform activity. At one year of follow-up, the patient is seizure-free. Grid: 24-contact (6×4); filters: 0.3-70 Hz; notch: 60 Hz; sensitivity 50  $\mu$ V/mm.



**Figure 3.** Case of a 37-year-old male with drug-resistant epilepsy characterised by focal seizures with and without alteration of consciousness, and secondarily generalised seizures, secondary to a left temporal CA. (A) Preoperative ECoG showing polyspike trains in channels 3-4, 4-5, 7-8, 19-20 and 20-21, localised on the lateral mesial third of the left second temporal gyrus. (B) After the resection, a single spike following deafferentation (different morphology and localisation) is observed in channel 19-20, localised in the lateral mesial third of the left first temporal gyrus. At 18 months of follow-up, the patient is seizure-free. Grid: 24-contact (6×4); filters: 0.3-70 Hz; notch: 60 Hz; sensitivity 50  $\mu$ V/mm.

## Conclusion

Small controlled studies suggest that ECoG-guided resection offers the best functional results in seizure control for subjects undergoing CA surgery, especially in the temporal lobe. Future randomised studies will be required to build upon these findings. □

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