Dipole Modelling and Intracranial EEG Recording: Correlation Between Dipole and Ictal Onset Zone

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Summary

This study includes 11 patients (3 males, 8 females) with mean age of 29 years (range: 15–42 years) who underwent a presurgical evaluation for refractory complex partial seizures (CPS). In all patients, neuroimaging (1.5 T optimum-MR) demonstrated intracranial structural abnormalities (space-occupying: n = 2; atrophic: n = 8; dysplastic: n = 1) and video-EEG monitoring showed CPS. Because of discrepancies in the non-invasive examinations, all underwent additional intracranial EEG monitoring. After tailored resective procedures, all but one patient became seizure free. Mean follow-up was 30 months (range: 12–52 months). Results of intracranial EEG recording were compared with spatiotemporal dipole mapping of interictal and ictal epileptic discharges. Interictal dipole modelling revealed two distinct dipole patterns. Patients with lesions located in the medial temporal lobe uniformly presented a combined dipole that consisted of a radial and a tangential component with a high degree of elevation relative to the axial plane. Patients with extrahippocampal lesions had a less stable dipole with a predominant radial component. Dipole modelling of early ictal discharges revealed a striking correspondence with the interictal findings in individual patients. Elevation of ictal dipoles was always congruent with localisation based on intracranial EEG recordings. Interictal and ictal dipole mapping of medial temporal lobe sources may limit the number of surgical candidates for refractory CPS that need intracranial EEG recording. Whether ictal dipole modelling can be equally useful in extratemporal epilepsy remains to be proven.

Keywords: Epilepsy; electroencephalography (EEG); intracranial EEG; interictal spike; ictal EEG; dipole modelling; epilepsy surgery.

Introduction

In the context of the presurgical evaluation of patients with refractory epilepsy, the main purpose of performing EEG is to identify the "epileptogenic area" (see ref. in: [2]). Intracranial EEG, recorded with subdural and/or depth electrodes, is the gold standard of presurgical localisation in epilepsy [18]. Invasive EEG procedures, however, require large resources in infrastructure and technology. They are expensive and time consuming and carry a potential risk for morbidity. Invasive recordings also have their limitations. The number of intracranial electrodes is limited because of patient safety requirements. In approximately 10–20% of patients who undergo intracranial EEG monitoring, seizures cannot be localised which leads to the decision not to perform resective surgery [20].

Several non-invasive EEG procedures have emerged that are potentially as informative and reliable in localising epileptic foci but at a lower risk to the patient. Recently, voltage topography of epileptic potentials and source (dipole) localisation are among the most investigated techniques [19]. The superiority of dipole modelling over visual inspection of scalp EEG has been demonstrated [9]. Several authors have tried to define criteria for different types of epileptic spikes in different epileptic syndromes such as medial (and lateral) temporal lobe epilepsy and benign epilepsy of childhood with centrotemporal spikes [9, 11, 13, 15, 16, 22].

In epilepsy surgery candidates with underlying structural lesions, the lesion is most likely the cause of the seizures [3, 4]. Intracranial recording in these patients is felt to be redundant in most cases. However, when discrepancies between non-invasive examinations are found, the etiologic relationship of lesion and seizures has to be further documented [4]. We have previously reported our experience with interictal and ictal dipole modelling of epileptiform abnor-

malities and compared this technique with localisation based on interictal and ictal scalp EEG findings [8]. The aim of the present paper is to compare definition of the epileptogenic area using interictal and ictal scalp EEG dipole modelling techniques with localisation based on intracranial EEG recording in epilepsy surgery candidates with epileptogenic structural lesions in the frontotemporal area.

Patients and Methods

Inclusion Criteria

Out of a series of 620 patients who were evaluated at the University Hospital of Gent Epilepsy Monitoring Unit and the Clinique Paul Castaigne at the Salpêtrière Hospital in Paris between 10/90 and 12/95, a series of 11 patients (Gent: n = 9; Paris: n = 2) were selected on the basis of the following inclusion criteria:

(a) the presence of long-standing refractory CPS documented with video-EEG monitoring; (b) the presence of a structural lesion, demonstrated with CT and/or MRI (1.5 T, optimum protocol) and confined to a limited area in the temporal or frontal lobe (1); (c) the availability of high quality interictal scalp-EEG recordings, demonstrating a unilateral epileptiform abnormality and ictal scalp-EEG recordings; (d) the availability of invasive video-EEG recordings; (e) availability of pathological examination of resected tissue and postoperative follow-up data for at least 1 year.

Methods

Invasive EEG recording was performed because of discrepancies between results of non-invasive examinations, such as non-congruency between the location of the lesion and the EEG abnormality and the clinical semiology of the habitual seizures. The absence of: a) a focal neuropsychological deficit, b) a focal glucose hypometabolism on FDG-PET, or c) a lateralised ictal scalp EEG recruitment in patients with a medial temporal lobe structural lesion were considered other possible rationales for implanting depth electrodes.

Invasive monitoring was performed using an appropriate set of depth electrodes (ADTECH, SD-12 Spencer probes®) and/or subdural strips and grids (ADTECH, T-WS-4; T-WS-8; T-WG-20; T-WG-64 Wyler subdural electrodes®) as determined for each individual patient. Semi-rigid, 12-contact depth electrodes were placed according to the occipital-temporal approach. The proximal part of the electrodes was situated in the occipital cortex; the distal part in the amygdala [2]. In some patients, a combination of different types of silicone embedded strips (4- and 8-contact) and/or a subdural grid (20- and 64-contact) were placed in the subdural space to sample EEG and to perform functional stimulation from neocortical areas near the suspected lesion [17].

For the purpose of the present study, 32-channel scalp EEG was recorded continuously for 48–72 hours at a 200 Hz sampling rate in digital-multiplexed format using a TELEFACTOR-Beehive® (Gent) or BMSI (Paris) monitoring system [2, 5]. An intracranial contact, distant from the suspected epileptogenic lesion is used as reference. Periods of active epileptiform spiking were visually located during sleep stages 1 and 2 because of a higher incidence of focal spikes during these stages. Patients with bilateral independent spikes were excluded. VHS recorded digital EEG, each containing

one manually selected epileptiform transient (sharp wave, spike, spike and wave), were sliced and converted to a TELEFACTOR-Beekeeper® format by means of a customer-designed software program (Gent) or FOCUS® (MEGIS) (Paris). Between 6–19 filtered spike files were averaged for each patient. Spatiotemporal multiple dipole modelling was performed according to the strategies that we previously described using BESA® (MEGIS, Brain Electromagnetic Source Analysis) [6]. In all patients, ictal EEG was recorded. For each seizure, a 20-second epoch was manually sampled at the onset of the first visible ictal scalp EEG changes using narrow band (2–14 Hz) digital filtering to minimise movement and muscle artefact. Each such epoch was sliced in smaller consecutive epochs of 1350 msec. These data were then read, baseline corrected and filtered in BESA®, in the same way as the interictal spike files but using a low pass filter at 14 Hz. Due to rapid frequency changes of ictal discharges, averaging was limited to too few epochs and did not significantly improve S/N ratio. Hence, original, non-averaged ictal files were further processed according to the above strategy.

Dipole modelling is a method for describing electrical activity in the brain and is based on the assumption that changes in local activity in one or a few particular brain structures result in EEG changes recorded at the scalp [18]. The dipole is generated by the electrical activities of the individual neurones within a restricted brain volume. The different neuronal currents of the individual cells that make up the little dipole for each neuron can be vectorially summed on a macroscopic scale. The summed vector or current dipole has an orthogonal orientation with respect to the cortical surface due to the columnar organisation of the cortex. At any given moment in time, an epileptic potential (spike or spike and wave) can be explained by an underlying electrical source that is represented by the dipole. The BESA® software, on which our dipole modelling methodology is based, uses a spherical, triple layered shell, head model, resulting in some inaccuracy in the *absolute location* of the dipoles. Nevertheless, important information can be retrieved from the calculation of the *orientation* of the dipole allowing characterisation of the generators of the epileptiform potentials [8, 10].

Patient Population (Table 1)

Eleven patients (3 males, 8 females) with mean age of 29 years (range: 15–42) and mean duration of seizures of 20 years (range: 8–35) were included in the study. All patients were included in a presurgical evaluation protocol after a structural lesion was detected with CT and/or MR. In 2 patients, the structural lesion appeared as space-occupying; in 8 patients an atrophic lesion was suspected; in one, a limited area of cortical dysplasia and heterotopia was present. Lesions were in the temporal lobe in 9 patients (medial temporal structures: 7 patients; medial temporal structures and a limited area of the lateral temporal neocortex: 2 patients) and in the frontal lobe in 2. Video-EEG monitoring documented CPS in all. All but one patient underwent a lesionectomy. This surgical procedure included a complete resection of the structural lesion with free margins. One patient, in whom a parasellar lesion was not resectable, underwent an ipsilateral hippocampectomy on the basis of intracranial EEG findings. Pathological diagnosis of the resected tissue in this patient revealed only mild gliosis. In 8 patients, mesial temporal sclerosis (MTS) was demonstrated. A low-grade oligodendroglioma was found in 1 patient. Focal gliosis with cortical dysplasia was demonstrated in 1 patient. According to the Engel outcome scale, postoperative seizure control was rated I in all but

Table 1. *Patient Characteristics*

No.	Patient	Sex	Age Dur.	Sz. Loc.	Lesion	Neuroimaging	Pathology	Outcome F.U.(m)
1	SL	M	33	30	LF orbital	space-occupying	oligodendroglioma gr I	Ia (52)
2	DKF	M	15	10	LT med + lat	atrophic	MTS	Ia (34)
3	DGA	F	42	35	RF parasellar	space-occupying	mild gliosis[a]	IVb (52)
4	HF	F	31	20	RT med + lat	atrophic	MTS	Ia (43)
5	DWC	M	30	29	RT medial	atrophic	MTS	Ia (18)
6	DCV	F	26	15	RT medial	atrophic	MTS	Ia (18)
7	ML	F	30	16	RT medial	atrophic	MTS	Ia (18)
8	DA	F	27	14	RT medial	atrophic	MTS	Ia (18)
9	BK	F	22	14	RT medial	atrophic	MTS	Ia (36)
10	JS	F	29	28	RT bas + med	dyspl + heterotop.	dysplasia	Ia (27)
11	MC	F	33	8	RT medial	atrophic	MTS	Ia (12)

Loc localisation; *Sz* seizure; *Dur* duration; *M* male; *F* female; *L* left; *R* right; *F* frontal; *T* temporal; *med* medial; *lat* lateral; *gr* grade; *MTS* medial temporal sclerosis; *bas* basal; *dyspl* dysplasia; *heterotop* heterotopia; *F.U.* follow-up; *Ia, IVB* refers to Engel outcome scale. [a] Hippocampal specimen in patient with an inaccessible lesion.

Table 2. *Interictal and Ictal Scalp EEG Localisation*

No.	Pat.	Loc. interictal spikes	Ictal Scalp EEG
1	SL	F7, T3	L frontotemporal recruitment
2	DKF	F7, T3, F9, T9	L > R temporal recruitment
3	DGA	T4, T10, P4	R paroxysmal activity
4	HF	F8, T4	R temporal recruitment
5	DWC	F8, F10	R temporal recruitment
6	DCV	F8, F10	R > L temporal recruitment
7	ML	F8, FT10	R temporal recruitment
8	DA	T6, O2	R temporal recruitment
9	BK	T4	Bilateral recruitment
10	JS	T4, F8, C4	R > L temporal recruitment
11	MC	F8, T10, F10	R = L paroxysmal activity

Pat patient; *Loc* localisation; *F**, *T**, *C**, *O** are electrode positions according to the 10–20 International System, odd numbers refer to positions on the left, even numbers to positions on the right side.

the one patient in whom the lesion could not be resected; average follow-up was 30 months (range: 12–52 months).

Results

Interictal and Ictal EEG (Table 2)

Prolonged interictal and ictal EEG recordings were available for review in all patients. A unilateral or predominantly (> 90% of ipsilateral discharges) unilateral spike or sharp wave focus was demonstrated in all. Ten patients had interictal spikes with amplitude maxima in anterior, mid- and/or inferior temporal electrode positions. One patient with a parasellar lesion had a spike with a mid- to posterior temporal and parietal distribution.

Ictal scalp EEG was recorded in all, but was available for dipole analysis in only 8 patients. Six patients had unique or predominant recruitment of rhythmical activity in the ipsilateral temporal scalp electrodes. In 2 patients, bilateral recruitment was recorded.

Intracranial EEG (Table 3)

In all patients, invasive EEG monitoring was performed in the presence of a known structural lesion because discrepancies, as described above, were found between results of different non-invasive tests. Two (2/11) patients had small space-occupying lesions in the frontal lobe. In one patient with a small, parasellar, space-occupying lesion, unequivocal hip-

pocampal seizure onset was demonstrated. A set of 4 frontal depth electrodes in the immediate vicinity of the lesion and frontal subdural strips recorded frontal EEG abnormalities only seconds after the initial ictal hippocampal discharge. This patient, in whom the frontal lesion was hardly accessible, underwent a hippocampectomy based on the findings of the intracranial recording. After a short seizure-free period, complex partial seizures resumed at the presurgical frequency. The other patient with a frontal orbital lesion underwent implantation of a hippocampal depth electrode and two subdural frontal strips overlying the lesion (see Case Report 2). Two (2/11) other patients had atrophic structural abnormalities involving both *medial temporal structures and lateral temporal neocortex*. In these last 2 patients, clear-cut ipsilateral hippocampal seizure onset was demonstrated. Six (6/11) patients who had *medial temporal* atrophic structural lesions also underwent implantation of bilateral hippocampal depth electrodes with/without combined subdural electrodes; in all of these, unilateral anterior to mid hippocampal seizure onset was demonstrated. Case report 1 provides a detailed account of one of these patients. Finally, one (1/11) patient with a *hippocampal* dysplastic lesion underwent invasive EEG recording and was shown to have an anterior hippocampal seizure onset.

Interictal Spike Voltage Topography and Dipole Modelling (Table 3)

Two distinct types of spike voltage field patterns and corresponding dipoles were found. All patients with structural lesions in the medial temporal lobe had a voltage field pattern with the following characteristics: ipsilateral, well delineated, negative voltage field, occupying less than 50% of the scalp with a contralateral positive voltage field that extended well beyond the midline. The negative voltage field had a steeper gradient than the positive field. The corresponding dipole had a clearly distinct radial and tangential component and an average elevation of 38.9°

Table 3. *Correlation Between Localisation of Ictal Onset Zone and Type of Interictal and Ictal Dipole*

No.	Pat.	Ictal Intracranial EEG	Type Dip.	Elev. Interictal	Elev. Ictal
1	SL	R frontobasal-ant. temp onset	2	13.9	10.7
2	DKF	L ant. hippocampal onset	1	26,8	n.a.
3	DGA	R hippocampal onset	2	6.9	2.0
4	HF	R hippocampal onset	1	24.1	n.a.
5	DWC	R ant. hippocampal onset	1	48.9	53.4
6	DCV	R mid hippocampal onset	1	58.9	47.4
7	ML	R hippocampal onset	1	34.8	22.4
8	DA	R hippocampal onset	1	31.3	56.7
9	BK	R hippocampal onset	1	29.2	76.5
10	JS	R hippocampal onset	1	62.1	69.1
11	MC	R ant. hippocampal onset	1	33.7	n.a.

n.a. not available; *R* right; *L* left; *ant* anterior; *temp* temporal; *Pat* patient; *Dip* dipole; *Elev* elevation.

(24.1°–62.1°; SD = 14.1°) relative to the axial plane (see Case Report 1 and Fig. 1). Both patients with lateral temporal structural abnormalities, associated with medial temporal lobe lesions also presented with the above spike type.

Two patients with frontal lesions presented with a quite different spike voltage field and dipole. The spike voltage field showed a less well delineated negativity with a smoother gradient towards a less pronounced positivity. The corresponding dipole had a major radial component and a minor, if any, tangential component and an average elevation relative to the axial plane of 10.4° (6.90°–13.90°; SD = 4.95°) (see Case Report 2 and Fig. 2).

Voltage Topography and Dipole Modelling of Ictal Discharges (Table 3)

In 9/11 patients, topographic voltage maps and dipoles were calculated from early epochs of ictal paroxysmal scalp EEG activity. Patients with a medial +/– lateral temporal lobe lesion were found to have an ictal dipole that consisted of a radial and tangential component with an average elevation of 54.3°

Fig. 1. (a) Inversion recovery T_1-weighted coronal image showing volume loss and loss of internal structure in the right medial temporal lobe structures. (b) Sagittal T_1-weighted MR demonstrating occipital-hippocampal multi-contact depth-electrode. (c) Intracranial EEG trace. Ictal onset with high amplitude rhythmical recruitment in channels RPT1–2, 2–3 (anterior hippocampus) at time of clinical onset (arrow), a more widespread activity in the right medial temporal lobe is noted. Electrode contacts overlying the posterior lesion in the right lateral temporo-occipital cortex (AS1–4 & PS1–4) remain silent. (d) Interictal dipole modelling. Upper part: averaged spike with maximum amplitude at F8. Lower part: calculated dipole in axial, coronal and sagittal plane. Localisation in anterior medial temporal lobe; orientation of approx. 45° relative to the axial plane with low residual variance of 4.68%: "type 1". (e) Ictal dipole modelling. Upper part: early epoch of ictal EEG, filtered (low pass) at 14 Hz. Lower part: calculated ictal dipole with "type 1" characteristics
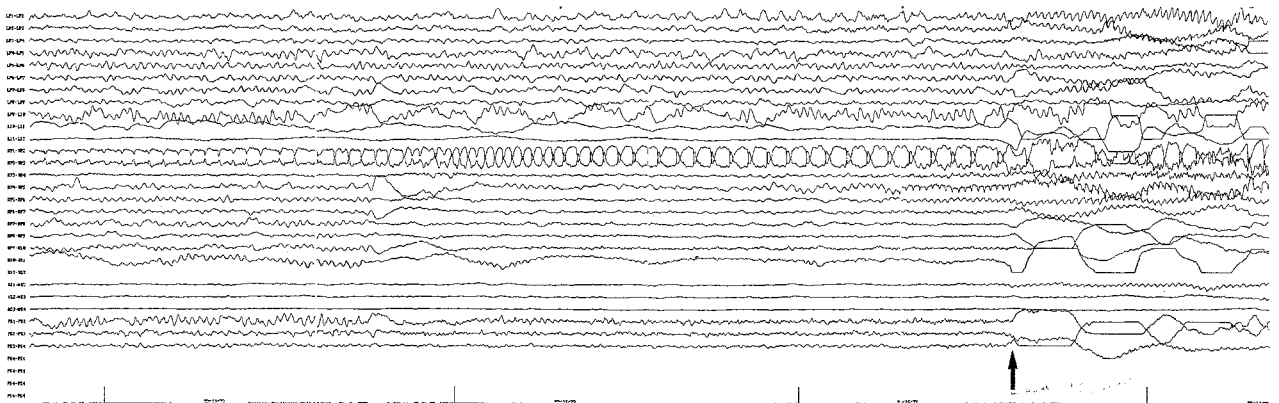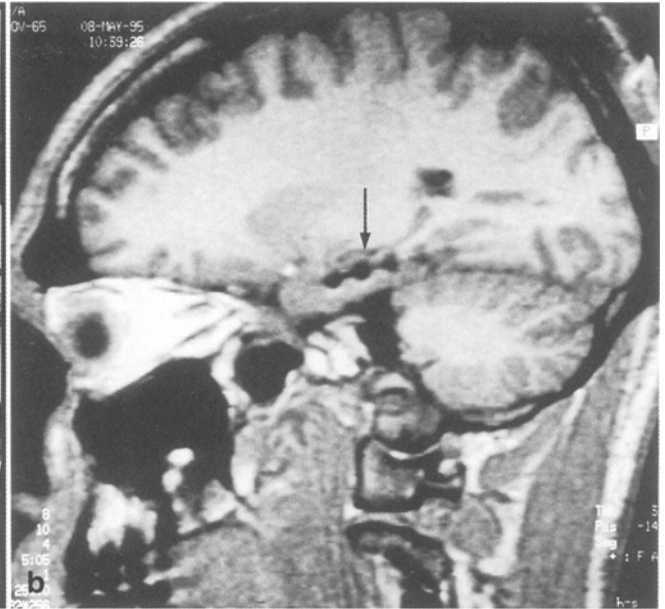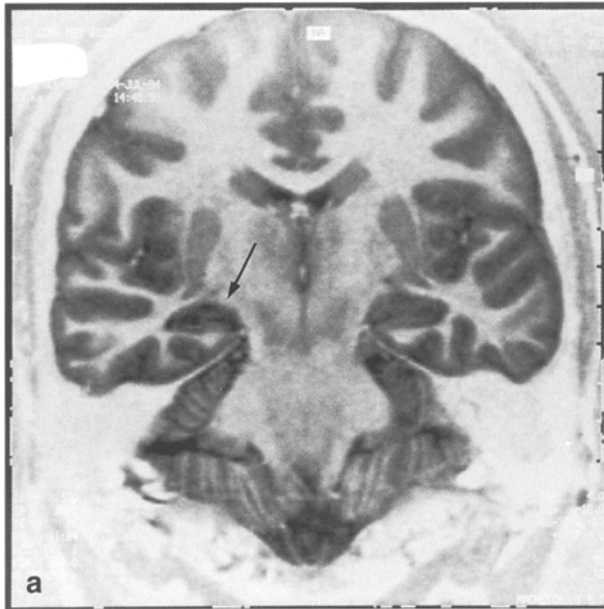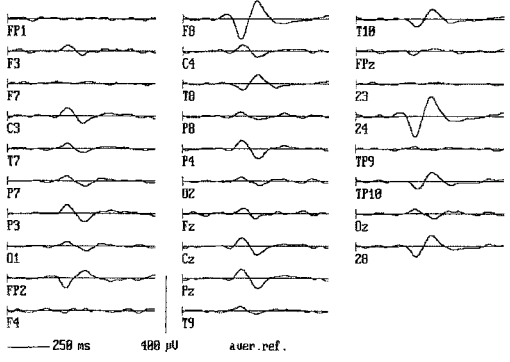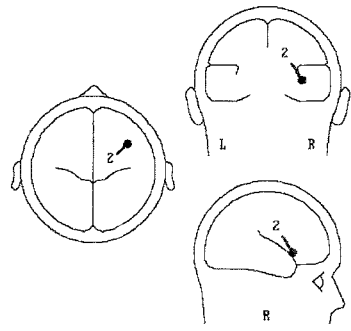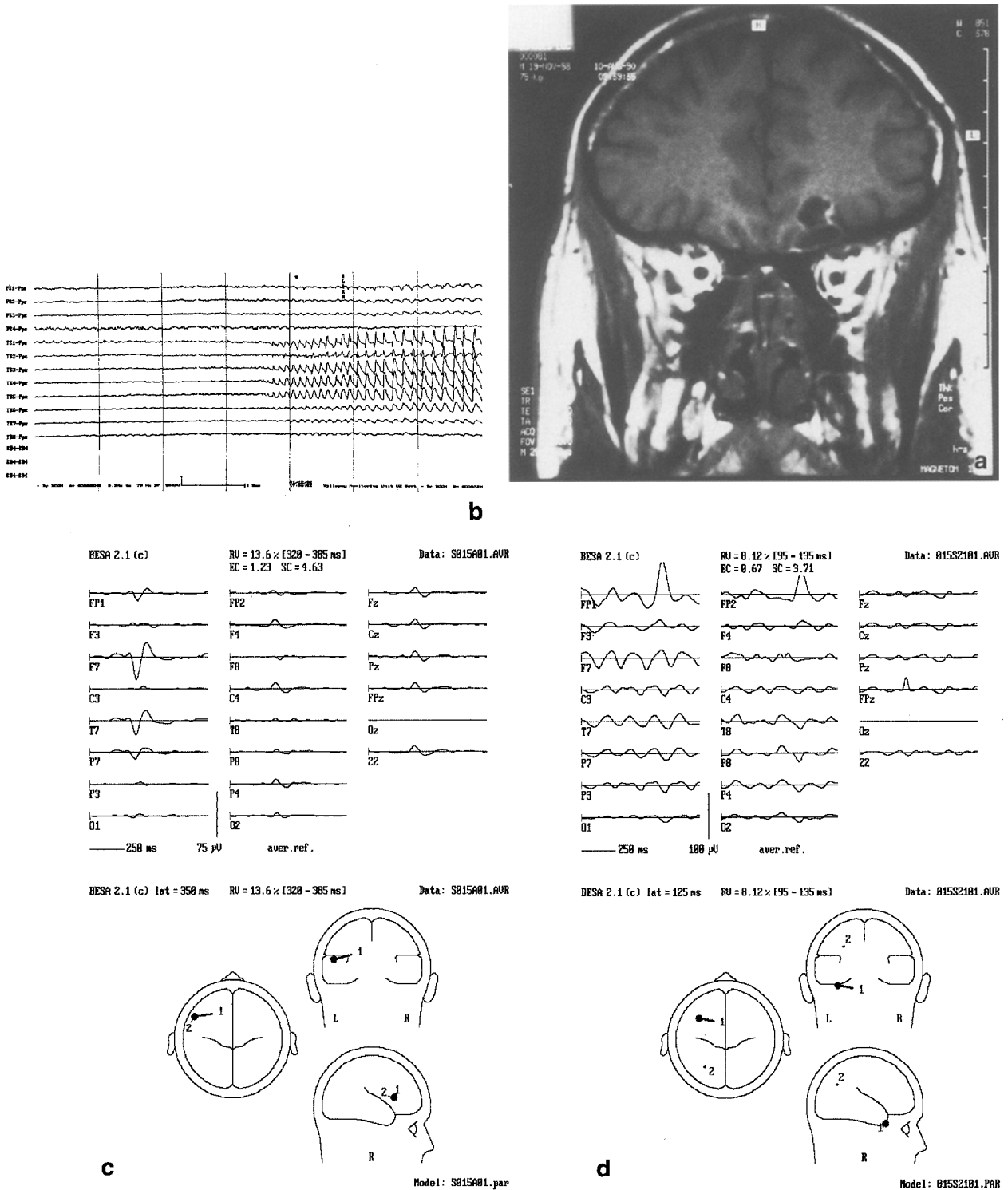
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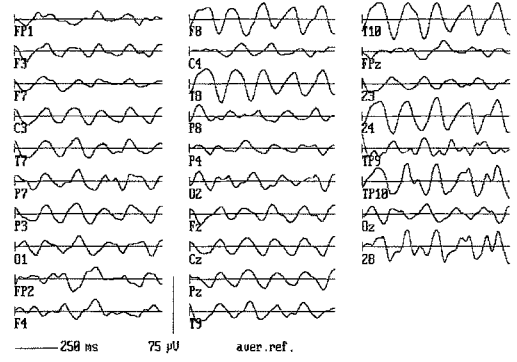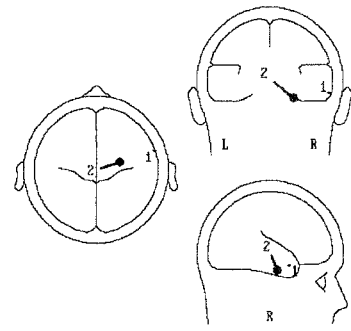
Fig. 2. (a) T_1-weighted coronal MR showing a left frontal orbital cystic space-occupying lesion. (b) Intracranial EEG trace. Electrodecremental event in electrodes of temporal subdural strip (TS1–TS4) overlying the medial basal temporal area, followed after 3 s by a high amplitude discharge of spike and wave in the electrode contacts TS1–TS6. Electrode contacts overlying the frontal orbital lesion (FS1–4) remain relatively silent. (c) Interictal dipole modelling. Upper part: averaged spike with maximum amplitude at F7. Lower part: calculated dipole with radial orientation, localisation in frontal orbital area, somewhat higher residual variance: 13.6%: "type 2". (d) Ictal dipole modelling. Upper part: early epoch of ictal EEG, filtered (low pass) at 14 Hz. Lower part: calculated ictal dipole with "type 2" characteristics

(22.4°–76.5°; SD = 18.9°) relative to the axial plane (see Case Report 1 and Fig. 1). This finding corresponded to the interictal dipole pattern found in each of these patients. The two extratemporal lesion patients presented with a different dipole pattern. The calculated ictal dipole had a predominant radial component with an elevation of 6.33° (1.95°–10.70°; SD = 6.20°), similar to this patients' interictal dipole configuration (see Case Report 2 and Fig. 2).

Case Report

Case Report 1: Patient 5 (Fig. 1)

This patient is a 30-year-old male who suffered from prolonged and repeated febrile seizures at the age of 6 months, with involvement of the left hemisoma and postictal Todd's phenomenon on the left side. Since early schoolage, the patient experienced CPS with initial fear, vocalisation, loss of contact, semipurposeful behaviour and postictal confusion and disorientation. Several trials of medical treatment with a combination of various anticonvulsant drugs revealed unsuccessful. At the time of evaluation, the patient experienced 6 seizures a month. EEG showed an anterior right temporal spike. Optimum MR showed volume loss in the right medial temporal lobe structures (Fig. 1 a) and a signal abnormality in the lateral temporal-occipital cortex on the same side. Interictal FDG-PET demonstrated a focal hypometabolism in the entire right temporal lobe and a defect of cortical activity in the temporal-occipital neocortex. Video-EEG monitoring documented CPS with clinical characteristics suggestive of medial temporal origin. An interictal spike with phase reversal on F8-F4 was recorded. Ictal EEG showed a right temporal recruitment of theta activity. Intracarotid amytal procedure demonstrated left hemisphere language dominance and intact memory function after subsequent injection of both right and left internal carotid arteries. Because of the bifocal structural abnormalities and the lack of congruency between results of non-invasive examinations, intracranial monitoring was performed. Two occipital-temporal depth electrodes (Fig. 1 b) were stereotactically implanted and two 4-contact subdural strips were placed above the suspected temporal-occipital lesion. Four habitual seizures were recorded showing clear seizure onset in the anterior hippocampal electrode contacts on the right side (Fig. 1 a–c). The neocortical strip electrodes remained silent. Subsequently, the patient underwent a modified right-sided temporal lobectomy with hippocampectomy and has remained completely seizure-free and without sequelae of 18 months postoperatively. Anatomorphological examination of the resected specimen revealed mesial temporal sclerosis. Interictal and ictal modelling revealed a "type 1" oblique dipole with a high degree of elevation relative to the axial plane (Fig. 1 d and e).

Comment: In this patient in whom non-invasive studies had revealed 2 different structural abnormalities possibly reflecting either a widespread epileptogenic zone or multiple zones, invasive monitoring demonstrated unequivocal anterior hippocampal seizure onset. The presence of a type 1 interictal and ictal dipole was suggestive of a medial-basal temporal lobe seizure origin.

Case Report 2: Patient 1 (Fig. 2)

This patient is a 33-year-old right-handed male who presented with CPS since the age of three. He had seizure-free intervals of maximum 2 years and more recently developed refractory epilepsy. Despite anticonvulsant polytherapy, there were daily episodes of short loss of awareness and automatisms followed by confusion and postictal aphasia with occasional secondary generalisation. At the age of 30, CT and MR showed a small left frontal orbital space-occupying lesion, thought to be a low grade glioma or a mucocoele (Fig. 2 a). Interictal scalp EEG during sleep showed an anterior temporal sharp wave with phase reversal over F7-T3. Video-scalp EEG monitoring classified the reported episodes as CPS of temporal lobe origin and showed a regional left frontotemporal build-up of rhythmical activity. Neuropsychological testing was normal. Interictal PET failed to show a hypometabolic zone. Intracarotid amytal testing revealed left hemisphere language and intact right-sided hippocampal function during left-sided injection. Because of the discrepancies found, invasive EEG was planned. A hippocampal depth electrode on the left side was implanted and subdural strips were placed on the fontobasal cortex overlying the lesion and on the medial and lateral temporal cortex. Widespread interictal spiking was found, involving frontobasal, lateral and basal temporal cortex. Ictal subdural EEG onset was clearly regional and involved an area posterior to the lesion in the anterior temporal neocortex and the temporal basal area (Fig. 2 b). The electrode contacts in the immediate vicinity of the lesion were relatively silent. Two years after removal of the lesion, the tip of the temporal lobe and an anterior part of the temporal basal gyrus the patient is entirely seizure-free. Pathological diagnosis of the lesion was oligodendroglioma, grade I. Interictal and ictal dipole modelling showed a "type 2" radial dipole, located near the orbital frontal area (Fig. 2 c and d).

Comment: In this patient in whom non-invasive studies had revealed discrepancies, the area of the lesion, the irritative zone and the ictal onset zone were not congruent. Complete resection of the structural lesion, only including a small part of the irritative and ictal onset zones, lead to complete seizure control. The presence of a type 2 dipole in this patient suggested that the medial temporal structures were not primarily involved.

Discussion

Electroencephalographical (EEG) recording plays an essential role in the presurgical evaluation for refractory epilepsy. In epilepsy surgery, the rationale of removing brain tissue is the resection of the "epileptogenic zone" (see ref. in: [2]). This is the area of brain tissue necessary for the generation of the habitual seizures and of which the removal is necessary to control the seizures. Unfortunately, the concept of the epileptogenic zone is a theoretical one, that cannot be measured directly. However, different EEG techniques allow direct localisation of the "irritative zone" and the "zone of ictal onset". This terminology, respectively, refers to the area of interictal spiking and the area of early EEG changes at the beginning of the clinical seizure that can be recorded with scalp and/or intracranial EEG electrodes [2, 4].

In the present study, we documented EEG abnormalities, measured at the scalp, that corresponded to a

variable degree with the location of an intracranial structural lesion. In all but one patient, invasive EEG recordings from bilateral hippocampal depth electrodes +/– subdural electrodes confirmed that the structural lesion or its immediate vicinity were in fact epileptogenic. In addition, in 10 patients in whom the lesion could be completely resected, postsurgical seizure freedom further confirmed the epileptogenicity of the structural abnormality.

Spatiotemporal multiple dipole modelling identified two different types of *interictal* spikes. All patients with lesions confined to the medial temporal structures had a negative voltage field with a steep gradient over the inferior temporal area and a stable dipole that consisted of a radial and a tangential component and had a high degree of elevation relative to the axial plane. Both patients with lesions involving medial temporal structures and parts of the lateral temporal neocortex also had this type of dipole. This may look contradictory to the findings of Ebersole who would predict a different spike pattern in these patients [9]. This is not the case, since these 2 patients were demonstrated to have a clear-cut hippocampal seizure onset with invasive EEG recording. This confirms the previous finding that medial temporal lobe foci are highly correlated with an oblique dipole that has a radial and a tangential component [9, 11]. Both patients with extratemporal (frontal) lesions had a voltage field pattern and dipole that corresponded to Ebersole's "type 2" spike. This type of interictal dipole had a predominant radial component and no or a minor tangential component. It was also less stable on spatiotemporal modelling which was reflected by a higher residual variance. We did not find dipoles of different types in a single patient.

Although interictal dipole modelling has been shown to be a reliable technique for characterising interictal spikes, application of this same technique to ictal discharges appears to be even more significant. The hypothesis that we wanted to test was whether the calculated dipole could eventually represent the ictal onset zone. Showing that this hypothesis is true could have obvious neurosurgical implications. There are few reports in the literature of *ictal* dipole modelling in epilepsy surgery candidates [8, 11]. We analysed brief epochs of ictal scalp EEG discharges. All patients with medial temporal lobe disease and both patients with combined medial and lateral temporal lobe lesions presented with a combined ictal dipole, consisting of a radial and tangential component, in perfect agreement with their interictal findings. Two

patients with an extratemporal lesion did not show this type of ictal dipole, but rather a "type 2" configuration, similar to the interictal dipole. Unlike interictal spikes that were easily recognisable and could be averaged to improve S/N ratio, ictal data were much more difficult to manage. Narrow band filtering of raw ictal data was necessary in trying to establish the earliest rhythmical changes of the scalp EEG trace. S/N ratio of ictal data was less favourable because averaging could not be performed. We have been surprised by the high level of concordance between ictal and interictal dipole calculations and feel that this is a major tribute to the methodology that we used.

In addition, we correlated elevation of the ictal dipole with localisation based on intracranial EEG findings in all our patients. Occipital-hippocampal depth electrodes and/or subdural electrodes conclusively identified the ictal onset zone in the anterior to midhippocampal structures. From the comparison of results of dipole modelling and intracranial EEG recording, the clinical implications of interictal and ictal dipole mapping seem obvious. In some epilepsy surgery candidates who have structural lesions, invasive recordings may be considered [4]. These are patients with structural abnormalities that are likely to be etiologically related to the seizures, but in whom discrepancies are found in the presurgical evaluation. Dipole mapping may provide an additional and reliable means of measuring the underlying brain source. In patients with medial temporal lesions, the finding of a type 1 interictal and ictal dipole seems to be a reliable marker of an epileptogenic zone in the hippocampus. Moreover, in patients with lesions extending to the lateral temporal neocortex, beyond the hippocampal formation, the finding of a type 1 dipole appears to be a reliable predictor for hippocampal seizure onset.

Our findings were perhaps even more interesting in 2 patients with extratemporal lesions, who consistently showed a type 2 dipole. Why in one of these patients (patient 3) a parasellar seizure onset could not be demonstrated, despite the presence of several frontal intracerebral and subdural electrodes, remains unclear. Sampling error resulting in false negative findings has been well recognised in the literature and is a major concern whenever intracranial studies are planned in the frontal and parietal lobe [20]. Another patient with a frontal orbital lesion (patient 1), who was demonstrated to have early ictal changes in the hippocampus while the area around the lesion remained relatively silent, presented with a radial

dipole suggesting extratemporal spike origin. While the surgical approach was based on the finding of a hippocampal seizure onset, seizure cure was probably achieved because the entire lesion was removed. The rationale of performing a hippocampectomy along with a frontal lesionectomy in this patient could be questioned. In these previous two patients, dipole mapping suggested that the medial temporal structures were not primarily involved. Dipole modelling of interictal and ictal epileptic discharges has important limitations [10, 11, 19]. The most important conceptional limitation is that dipole modelling is based on the assumption that a change in local activity in one or a few particular brain structures results in complex waveforms recorded at the scalp. This local activity or source is represented by a vector or dipole that can only be calculated by solving an inverse problem. However, the exact number of generators is not known and the number of terms in the equations remains an open question which leads to different possible solutions. As described in our methodology, the chosen solution is one that is anatomically and physiological as plausible as can be. Another limitation is that dipole modelling is based on a mathematical analysis that uses a three-shell spherical head model that is far from being physiological. Because of the spherical model, localisation of dipoles is less accurate than orientation. Measurement of eccentricity is least accurate. In its present form, dipole modelling does not strictly localise but rather provides information about orientation of the dipole. However, in the temporal lobe, as we have shown, changes in orientation reflect changes in localisation; an oblique dipole suggesting basal medial seizure origin versus radial dipoles suggesting ictal onset in lateral neocortical area. It is clear that dipole maps resulting from our current model should not be interpreted as surgical planning drawings. The diagnostic relevance of source localisation, especially in extratemporal regions, would be greatly enhanced when the source can be related to the anatomical structures as accurately as possible. Further research should be aimed at the development of head models that are adapted to the individual patient. This can be done by transforming the MR images of the patient's head into the coordinate system of the EEG recording. Recent studies have shown the feasibility of accurate matching of dipole data with CT, MR, and SPECT images in individual patients [7, 14, 21]. From our present study two conclusions can be drawn: a) interictal spike voltage topography and corresponding dipole mapping

provide additional and reliable localising information that is relevant in surgical candidates with refractory CPS in whom non-invasive evaluation indicates a frontal-temporal seizure origin; b) ictal dipole mapping is a promising technique that eventually may limit the number of patients in this population that need intracranial electrodes; c) whether ictal dipole modelling can be equally useful in other extratemporal epilepsies remains to be proven.

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References

1. Achten E, Boon P, De Poorter J, Calliauw L, Vandekerckhove T, De Reuck J, Kunnen M (1995) An MR protocol for presurgical evaluation of patients with complex partial seizures of the temporal lobe origin. AJNR 16: 1201–1213
2. Boon PA, Williamson PD (1989) Presurgical evaluation of patients with intractable partial seizures, indications and evaluation techniques for resective surgery. Clin Neurol Neurosurg 91: 3–11
3. Boon PA, Williamson PD, Fried I, Spencer DD, Novelly RA, Spencer SS, Mattson RH (1991) Intracranial, intraaxial, space-occupying lesions in patients with intractable partial seizures: an anatomoclinical, neuropsychological and surgical correlation. Epilepsia 32: 467–476
4. Boon PA, De Reuck J, Calliauw L, Hoksbergen I, Thiery E, Caemaert J, Decoo D, Desomer A (1994) Clinical and neurophysiological correlations in patients with refractory partial epilepsy and intracranial structural lesions. Acta Neurochir (Wien) 128: 68–83
5. Boon P, De Reuck J, Drieghe C, De Bruycker K, Aers I, Pengel J (1994) Long-term video-EEG monitoring revisited; the value of interictal and ictal video-EEG recording, a follow-up study. Eur Neurol 34: 33–39
6. Boon P, D'Havé M (1995) Interictal and ictal dipole modeling in patients with refractory partial seizures and an underlying intracranial structural lesion. Acta Neurol Scand 92: 7–18
7. Boon P, D'Havé M, Vandekerckhove T, Achten E, Adam C, Baulac M, Goossens L, De Reuck J (1996) Can dipole modeling replace intracranial EEG recording in epilepsy surgery candidates? Epilepsia 37 [Suppl 5]: 145
8. Boon P, D'Hane M, Adam S, Vonck K, Baulac M, Vandekerckhove T, De Reuck J (1997) Dipole modeling in epilepsy surgery candidates. Epilepsia 38: 208–218
9. Ebersole JS, Wade PB (1991) Spike voltage topography identifies two types of frontotemporal epileptic foci. Neurology 41: 1425–1433
10. Ebersole JS (1991) EEG dipole modeling in complex partial eplilepsy. Brain Topogr 4: 113–123
11. Ebersole JS (1992) Equivalent dipole modeling, a new EEG

method for localisation of epileptogenic foci. In: Pedley TA, Meldrum BS (eds) Recent advances in epilepsy. Churchill Livingstone, New York, pp 51–71

12. Ebner A, Hoppe M (1995) Non-invasive electroencephalography and mesial temporal sclerosis. J Clin Neurophysiol 12: 23–31

13. Gregory DL, Wong PK (1992) Clinical relevance of a dipole field in rolandic spikes. Epilepsia 33: 36–44

14. Lantz G, Ryding E, Rosen I (1994) Three-dimensional localisation of interictal epileptiform activity with dipole analysis: comparison with intracranial recordings and SPECT findings. J Epilepsy 7/2: 117–129

15. Laxer KD, Rowley AR, Novotny EJ, Gates JR, Sato S, Sutherling WW, Elger CE, Ebersole JS, Stefan H (1993) Experimental technologies. In: Engel J (ed) Surgical treatment of the epilepsies. 2nd ed. Raven, New York, pp 291–307

16. Lesser RP, Lüders HO, Moriis HH, Dinner DS, Wyllie E (1987) Extracranial EEG evaluation. In: Engel J (ed) Surgical treatment of the epilepsies. Raven, New York, pp 173–181

17. Ojemann GA, Engel J (1987) Acute and chronic intracranial recording and stimulation. In: Engel J (ed) Surgical treatment of the epilepsies. Raven, New York, pp 263–288

18. Scherg M, Picton TW (1991) Separation and identification of event-related potential components by brain electric source analysis. Event Related Brain Research. EEG [Suppl] 42: 24–37

19. Scherg M (1990) Fundamentals of dipole source potential analysis. In: Hoke M (ed) Advances in audiology. Karger, Basel, pp 40–69

20. Spencer SS, So NK, Engel J, Williamson PD, Levesque MF, Spencer DD (1993) Depth electrodes. In: Engel J (ed) Surgical treatment of the epilepsies, 2nd ed. Raven, New York, pp 359–375

21. Van Den Elsen PA, Viergever MA, Van Huffelen AC, Van Der Meij W, Wieneke GH (1991) Accurate matching of electromagnetic dipole data with CT and MR images. Brain Topogr 4: 425–432

22. Wong PK, Gregorie DL (1988) Rolandic dipole discharges in children. AM J EEG Technol 28: 243–250

Comments

This study compares the localizing value of invasive intracranial EEG monitoring with spatiotemporal dipole mapping of interictal and ictal epileptic discharges in 11 patients.

10 of the 11 patients became seizure-free. The main finding of this study is, that the authors describe a typical dipole pattern for medial temporal lobe epilepsy, in that each single patient with this lesion type showed a combined dipole consisting of a radial and tangential component with a high degree of elevation relative to the axial plane. There was also very good congruence between this type of dipole and localization based on intracranial EEG recordings. Based on this finding in 9 patients the authors optimistically conclude that interictal dipole modelling may reduce the number of patients evaluated for pharmacoresistant epilepsy that would need intracranial invasive EEG recording.

It seems very important to remind the neurosurgical reader who will not be familiar with the basic implications and weaknesses that can be misleading when working with dipole source modelling. The authors themselves have pointed out that the applied model bares some important conceptual limitations, namely the inappropriate head model. The dipole technique does not localize the dipole vector, it only provides information about the orientation of the vector. This is a very important limitation that the reader should keep in mind. Dipole modelling therefore does not allow to exactly differentiate between medial temporal lobe epilepsy because the dipole will be placed or localized into the medial temporal lobe, but because the dipole vector shows a different orientation in space if it has been generated in the medial temporal lobe. The localizing value is therefore an indirect one and based on the fact of the different orientation in space. Since these are only 11 cases, it is not totally unthinkable that there might be cases of medial temporal lobe epilepsy associated with some lesion or cysts in which the orientation of the dipole vector could be different and therefore misleading. This is a careful study, and the clear differentiation of 2 types of dipoles could be a helpful finding if it will be confirmed in further studies with a larger number of patients. It is still a very long way of careful comparisons before dipole modelling can actually replace invasive recording. The head models and source models have as yet important conceptual limitations and despite the very nice work the authors performed for this study these limitations, for which the authors are not responsible, remain.

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