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Clinical Neurophysiology 110 (1999) 176–184

Frequency domain EEG source localization of ictal epileptiform activity in

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Abstract

The aim of this study was to investigate whether EEG source localization in the frequency domain, using the FFT dipole approximation (Lehmann, D. and Michel, C.M. Electroenceph. clin. Neurophysiol., 1990, 76: 271–276), would be useful for quantifying the frequency content of epileptic seizure activity. Between one and 7 extracranially recorded seizures were analyzed in each of 7 patients with mesolimbic epilepsy, who were seizure-free after temporal lobe resection. The full scalp frequency spectrum for the first 4 s after seizure onset, as well as for subsequent periods, was determined. Power peaks in the spectra were identified, and an instant dipole fit was performed for the frequencies corresponding to these peaks. Ictal frequencies, ranging between 3.5 and 8.5 Hz, showed a variable degree of stability over time in the different patients. For a particular frequency, dipole results were similar during the different phases of seizure development. In patients with more than one prominent frequency, dipole results for the different frequencies were similar. Dipole results were also similar between patients. We conclude that dipole localization of dominant frequencies, as obtained from full scalp FFT analysis, gives quite reproducible results for seizures originating in the mesial temporal area. The method may become a useful tool for the pre-surgical identification of patients with mesolimbic epilepsy.

Keywords: Epilepsy; Ictal; Source localization; Frequency analysis

1. Introduction

In patients with drug-resistant partial epilepsy, who are under consideration for epilepsy surgery, interictal and ictal EEG recorded with extracranial electrodes plays an important role in the localization of the seizure onset area. In some patients, unequivocal surface ictal patterns, together with concordant information from other non-invasive localizing methods, may provide sufficient information to delineate the epileptogenic region. In many cases, however, ictal recordings with subdural or intracerebral electrodes are necessary for the final decision on surgical strategy, and in the latter cases preceding surface ictal recordings provide important information for the planning of intracranial electrode placement.

During the past years, increasing interest has been focused on different methods for estimating the location of the intracranial source of extracranially recorded epileptiform EEG activity. So far, most methods have been aiming at localizing the source of interictally recorded epileptiform potentials. However, since the source of interictal epileptiform activity does not necessarily coincide with the seizure onset area (So et al., 1989; Hirsch et al., 1991), quantitative methods for visualizing the initiation and spread of ictal activity, could be supposed to be more accurate for determining the location and extension of the epileptogenic region.

A feature, which theoretically should be useful for the purpose of seizure analysis, is the changes in the spectral properties of the EEG activity during seizure development. Based on the frequency transformation of intra- and extracranial EEG signals, several studies could show that the spectral properties of the ictal EEG yield important information about the type and the spread of epileptic activity (Darcey and Williamson, 1985; Hilfiker and Egli, 1992; Gotman et al., 1993; Alarcon et al., 1995). However, in order to combine frequency analysis with source localization methods, the spatial distribution of the activity in a

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1388-2457/99/$ - see front matter
PII S0013-4694(98)00117-5

CLINPH 98539

certain frequency band has to be studied, rather than the spectral properties of some selected channels. Based on this spatial distribution, potential maps can be constructed for each frequency point, and these potential maps can be subsequently used for source localization algorithms. This method, called 'FFT dipole approximation' (Lehmann and Michel, 1990), is based on the approximation of a phase-corrected voltage map for each frequency point by considering the amplitude as well as the phase information of all recorded channels. Theoretical considerations (Lütkenhöhner, 1992; Valdés et al., 1992), as well as applications to normal EEG (Michel et al., 1992; Tesche and Kajola, 1993), EEG in schizophrenic patients (Michel et al., 1993), and EEG after medication (Dierks et al., 1993; Kinoshita et al., 1994; Michel et al., 1995) have shown the potential power of this method to localize specific brain activities. The aim of the present study was to investigate whether the FFT dipole approximation method could be applied to extracranial ictal recordings in patients with partial complex seizures, in order to determine the initiation and spread of seizure activity.

2. Patients and methods

All patients suffering from temporal lobe epilepsy, who over a 4-year period had been operated on in the laboratories for presurgical evaluation in Lund and Geneva, were reviewed. Two basic inclusion criteria were to be fulfilled. Firstly, the pre-surgical workup, including ictal semiology, MRI, PET and/or SPECT, neuropsychological examination, interictal and ictal EEG, and if possible ictal SPECT, should indicate mesiotemporal seizure onset. Secondly, the patients should be seizure-free after temporal lobe surgery. For the patients fulfilling these criteria, there was considered to be strong evidence of mesiotemporal focus location.

Out of all patients fulfilling the criteria, 7 cases (4 male, 3 female, age 20–46 years; mean: 35 years) with a favorable signal to noise ratio in the extracranial ictal recordings were selected. In 4 of the patients (patients 1–4), the pre-surgical

Table 1

Clinical information on all patients

	Age (years)	EEG ictal onset	MRI	PET	SPECT (CERETEC)	Neuro-psychology	First ictal symptoms/ signs	Intra-cranial verification	Pathology	Follow-up
Patient 1	44	Sp1, F7, T3, F9, T9	Normal	Not performed	Left fron-totemperal	Verbal + visual memory deficit	Staring, picking, chewing	Yes	Not performed	15 months
Patient 2	41	Sp1, F7, T3, F9, T9	Wide temporal horn left	Not performed	Left temporal	Verbal memor-y + spatial analy-sis deficit (ambi-dexter)	Epigastric aura	Yes	Hippocampal sclerosis	12 months
Patient 3	31	Sp2, F8, T4, F10, T10	Wide tem-perol horn right	Not performed	Right temporal	No distinct abnormal findings	Epigastric aura	Yes	Discrete cortical dysplasia	24 months
Patient 4	28	Sp1, F7, T3, F9, T9	Normal	Not performed	Mainly right (+left) medial temporal (lomazenil: left temporal)	Verbal + visual memory deficit	Rising pelvic sensation	Yes	Unspecific	24 months
Patient 5	20	Sp1, F7, T3	Left hippo-campal sclerosis	Left mesial temporal hypome-tabolism	Left mesial temporal hypoperfusion	Verbal memory deficit	Psychic aura	No	Hippocampal sclerosis	12 months
Patient 6	33	Sp1, F7, FT7, T3	Left hippo-campal sclerosis	Left mesial temporal hypome-tabolism	Left mesial temporal hypoperfusion	Verbal memory deficit, few naming difficulties	Olfactory and epi-gastric aura	No	Hippocampal sclerosis	23 months
Patient 7	46	Sp2, FT8, F8	Right mesio-temporal lesion, inclu-ding hippo-campus, amygdala and the adja-cent para-hippocampal gyrus	Right temporal hypome-tabolism	Right mesial temporal hypoperfusion	Discrete difficulties with visuo-spatial material	Olfactory, epigastric aura and 'déjà vu' phenomena	No	Hamartoma	15 months

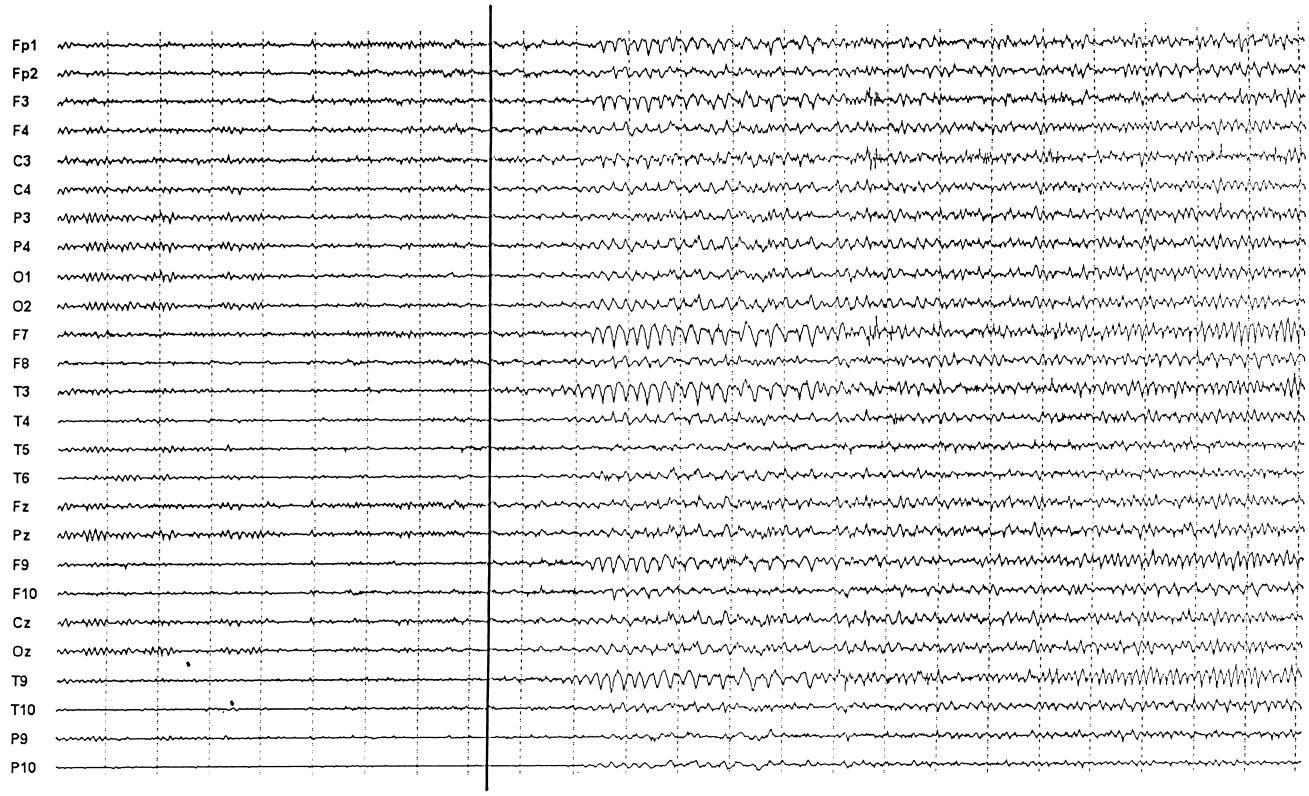

Fig. 1. Twenty-four seconds of EEG around seizure onset in one seizure of patient 1. Vertical bar indicates visually estimated seizure onset.

workup had included an intracranial investigation with subdural electrodes, which showed seizure onset at an electrode approximately located under the parahippocampal gyrus. In 3 patients (patients 5–7), concordant information from non-invasive recordings led to temporal lobe surgery without preceding intracranial recordings. All cases had been operated on with either en bloc resection of the anterior temporal lobe, including mesial temporal structures (5 cases), or with selective amygdala-hippocampectomy (2 cases). During a postoperative follow-up of 12–24 (mean 18) months, none of the patients reported seizure recurrence. Table 1 gives a detailed clinical description of the patients.

In each patient, between 1 and 7 (mean 4) seizures from a previous recording with extracranial electrodes were analyzed. The analyzed seizures were in 4 cases recorded from 26, and in 3 cases from 29 electrodes, placed according to the international 10–10 system, in some cases with special coverage of the temporal lobes. EEG was recorded using a 32 channel Nihon Kohden Neurofile equipment, with a common reference, and off-line recalculated against the average reference (Offner, 1950). In 4 cases, the sampling rate was 128 Hz, in the other cases 256 Hz. The EEG was digitally filtered with a low-frequency filter of 0.1 Hz and a high-frequency filter of 70 Hz.

For each seizure in each patient, the seizure onset (defined as the timepoint showing the first lateralized rhythmic activity (Risinger et al., 1989)), was visually estimated. In one patient (patient 5), in whom the first ictal manifestations of some seizures were repetitive lateralized 3 Hz sharp-slow wave complexes, the lateralized rhythmic activity following these sharp-slow waves was, for the purpose of this investigation, considered as seizure onset. The time period from 8 s before to 16 s after seizure onset was divided into 12 non-overlapping 2 s epochs. A few epochs with very high voltage artifacts were excluded, but otherwise the 2 s epochs were collected consecutively, without regarding eye movements or other artifacts. If throughout a seizure there was a continuous artifact in one or two electrodes, these electrodes were excluded, and the EEG was interpolated back to the original electrode configuration, using linear nearest neighbor interpolation. The EEG of two seizures in patients 1 and 4 are displayed in Figs. 1 and 2.

Each of the 2 s epochs was transformed into the frequency domain, using the fast Fourier transform (FFT). Power and phase values were obtained for each frequency between 0.5 and 32 Hz (frequency resolution 0.5 Hz), and for each electrode. The FFT dipole approximation method (Lehmann and Michel, 1990) was then used on each transformed 2 s epoch, to approximate the potential distribution of each frequency over the different recording channels, and to calculate the strength of the potential map (global field power (GFP) = the spatial standard deviation) for each frequency.

In order to determine the dominant frequency during the first period of a seizure, a grand average calculation was performed for each patient, including the first two FFT-approximated 2 s epochs after seizure onset (1–4 s after onset = TS1) over all seizures of that patient. Similar

grand averages were also calculated for the next 4 s sequence (5–8 s after onset = TS2), and for the subsequent 8 s sequence (9–16 s after onset = TS3). In addition, a grand average calculation was performed for the 8 s preceding seizure onset. Since polarity is arbitrarily chosen with the FFT approximation method, the grand averages were calculated by computing the first principal component map, i.e. the best fitting map in a global sense (Michel et al., 1995).

From the frequency spectra of these grand average calculations, different GFP peaks were identified. The dominant peak in the spectrum was always analyzed, and in cases where less prominent peaks persisted over several time periods, these peaks were also included in the analysis. The potential distributions of the different peak frequencies over the different recording channels were then used to calculate the best fitting instant dipole locations and orientations. The dipole algorithm used was based on a 3-shell spherical head model.

In order to assess the inter-seizure variability of the dipole results, an additional investigation was performed on two of the patients, one with a single and one with multiple peaks in the frequency spectrum (patients 1 and 4). In these patients, the peak frequency during each of the time periods TS1–TS3 was determined for each seizure, and the dipole solution corresponding to this frequency was calculated.

Finally, in order to compare our ictal data in the frequency domain to interictal data in the time domain, 10 interictal sharp waves were collected from the same recording as the ictal data. The average of all sharp waves was calculated, and a dipole reconstruction was performed at the negative peak of this average sharp wave. The dipole results of each patient were then compared with the ictal dipoles obtained from the different ictal grand averages of the same patient.

3. Results

In each patient, the grand average of all 2 s epochs during 8 s preceding seizure onset, and during time sequences 1–4 s (TS1), 5–8 s (TS2), and 9–16 s (TS3) after seizure onset was analyzed.

For 5 of the 7 patients, no distinct peaks were seen during the pre-onset period. Patient 1 showed a 9 Hz peak, with dipole results consistent with alpha activity (Fig. 3). In patient 5, there was a broad maximum between 1 and 8 Hz with obscure dipole results. This was the patient in whom the pre-onset period contained high voltage lateralized sharp-slow wave complexes, and the dipole results probably reflect a mixture between these waves and diffuse slow background activity.

In patient 1 (Fig. 3), a 5 Hz peak was seen during TS1, persisting as a 4.5 Hz peak during TS2. In TS3, a 7.5 Hz peak had replaced this 4.5–5 Hz peak. The dipole results for

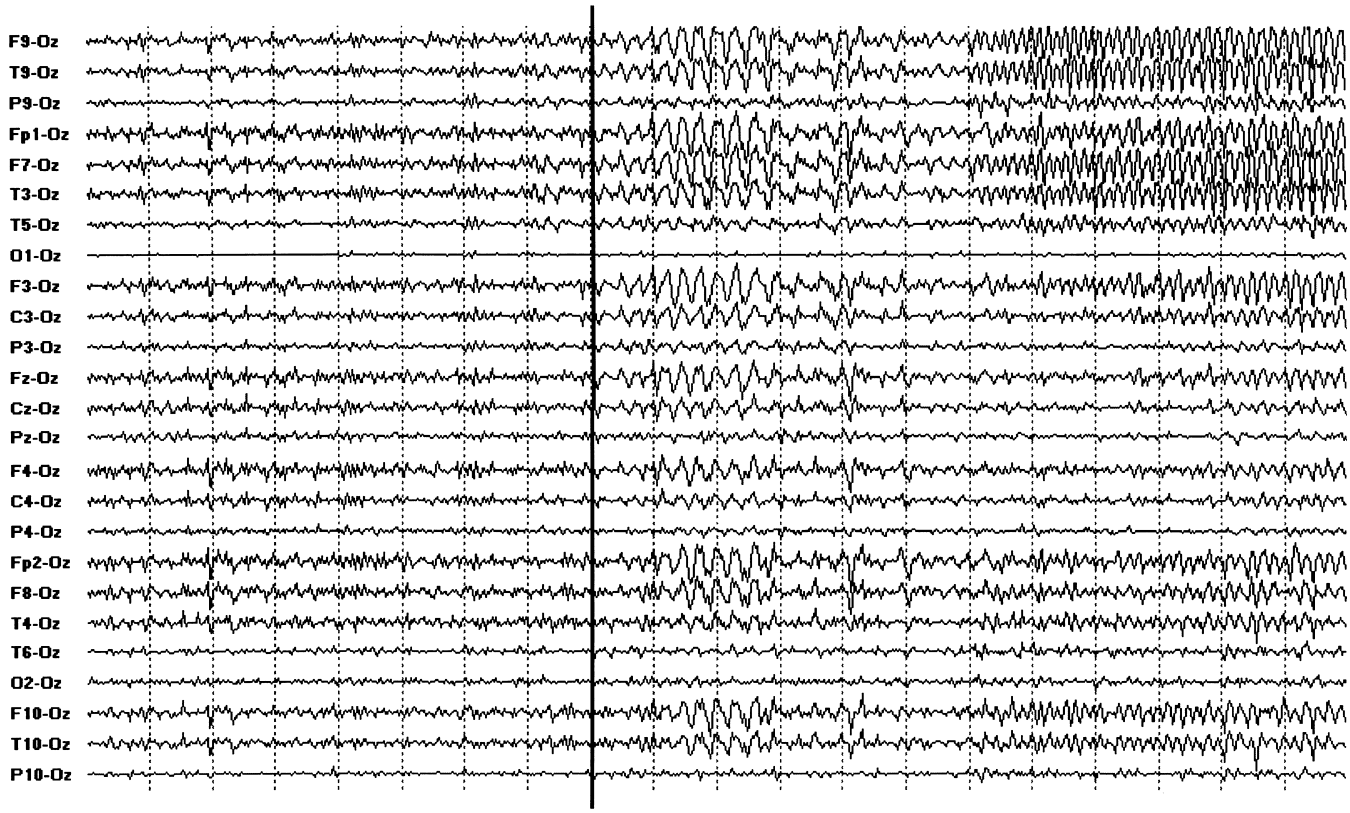

Fig. 2. Twenty seconds of EEG around seizure onset in one seizure of patient 4. Vertical bar indicates visually estimated seizure onset. Data is displayed against an Oz reference, to make it comparable to the results of Ebersole and Pacia (1996). Note slow activity during the first 2 s after seizure onset, with a slightly more frontal and central surface distribution than subsequent faster ictal rhythm.

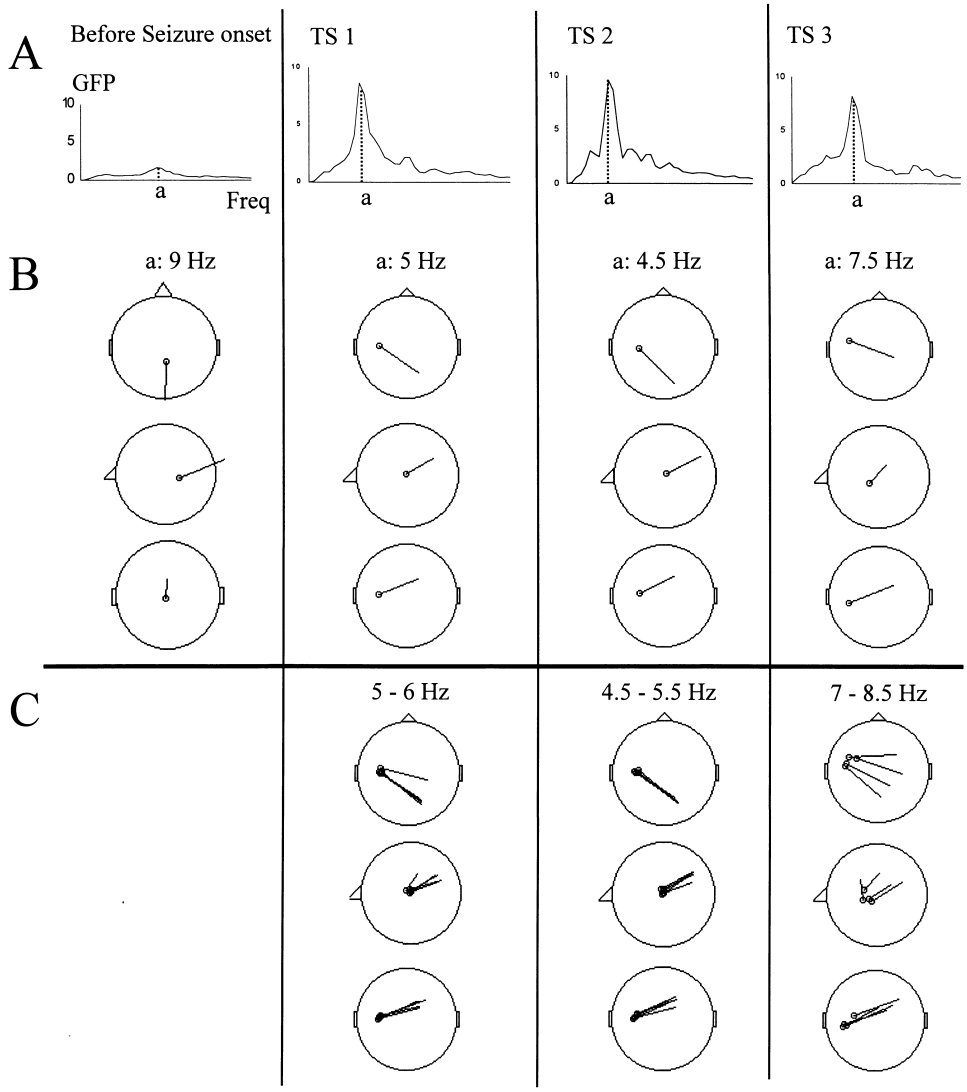

Fig. 3. Frequency profile and dipole results of prominent frequencies during different periods around seizure onset in patient 1. The analyzed time periods are: 8 s before seizure onset, 1–4 s (TS1), 5–8 s (TS2), and 9–16 s (TS3) after seizure onset. For each of these time periods the following results are displayed. The frequency spectrum in A is obtained by calculating an over seizure grand average of all FFT approximated 2 s epochs. B shows the dipole result for the dominant frequency of this spectrum. In C, individual seizures have been analyzed by averaging all 2 s epochs of a seizure during the respective time periods (2 epochs for TS1 and TS2, 4 epochs for TS3). The dipole results for the peak in the frequency spectrum of each seizure are displayed, together with the inter-seizure variability in peak frequency. Before seizure onset a 9 Hz activity peak is seen, with a posterior dipole location, which corresponds to alpha activity (Fig. 1). During TS1, a 5 Hz peak is seen, persisting as a 4.5 Hz peak during TS2. In TS3, this 4.5–5 Hz peak has disappeared, and a 7.5 Hz peak is dominating. For the 4.5–5 Hz activity dominating during TS1–TS2. the dipole results show little inter-seizure variability. The 7.5 Hz activity dominating later in seizure development shows more variable dipole results, and for some seizures a prominent 4.5–5 Hz activity persist during this time period (not shown). The dipoles for the different peaks all show the characteristic OPE pattern. The EEG of one seizure in this patient is displayed in Fig. 1.

the different peaks were quite similar, with a left temporal dipole location, and a dipole orientation that was oblique posterior in the horizontal plane, and modestly elevated in the coronal plane. This specific pattern, which we found to be quite characteristic of most seizures in this investigation, will be referred to from here on as the OPE-pattern (Oblique, Posterior, Elevated). The EEG of one seizure in this patient is displayed in Fig. 1.

In patient 3, a broad peak was seen during TS1, with its maximum at 6 Hz. During TS2, a 4 Hz activity dominated. During TS3, two peaks were seen, one at 3 Hz, and one at 7 Hz. The 6–7 Hz activity seen during TS1 and TS3 showed the typical OPE-dipole pattern. The 4 Hz activity during TS2 showed results resembling the OPE-pattern, but with a rather frontal location. The 3 Hz activity of TS3 had a dipole location suspicious of eye artifacts.

In patient 4 (Fig. 4), a broad maximum was seen during TS1, with its peak at 4.5 Hz. This peak persisted at approximately the same frequency (3.5–4 Hz), but with lower power, during TS2 and TS3. At TS2 another peak evolved at 7.5 Hz, which became broader and more prominent during TS3 (peak 6.5 Hz). The dipole corresponding to the 3.5–4.5 Hz peak dominating during TS1 had an oblique posterior elevated orientation resembling the OPE-pattern, but a

location that was rather frontal than temporal (Figs. 4 and 5). For the 6.5–7.5 Hz peak dominating during the subsequent sequences, the dipole results corresponded to the OPE pattern. The EEG of one seizure in this patient is displayed in Fig. 2.

In patients 2, 5, 6 and 7, a relatively stable peak, at 7.5 Hz, 6.5–7 Hz, 7.5–8.5 Hz and 6–8 Hz, respectively, persisted throughout the entire 16-second period (Fig. 5). The 7.5 Hz activity of patient 2 showed a rather characteristic OPE-pattern during TS1, whereas later in seizure development the orientation in the coronal plane changed from slightly elevated to more straight lateral or slightly lowered (Fig. 5). A similar change in dipole parameters was seen for patient 7 during TS2. Patients 5 and 6 both showed an OPE pattern throughout the entire seizure (Fig. 5). For patient 2, an additional 2.5 Hz peak was seen during TS1. The dipole corresponding to this peak had a basal frontal location, and probably reflects eye movements.

For two patients (patient 1 and patient 4), the dipole result corresponding to the peak frequency during TS1, TS2 and TS3, was calculated for each individual seizure. In patient 1, both dominant frequency and dipole results were quite simi-

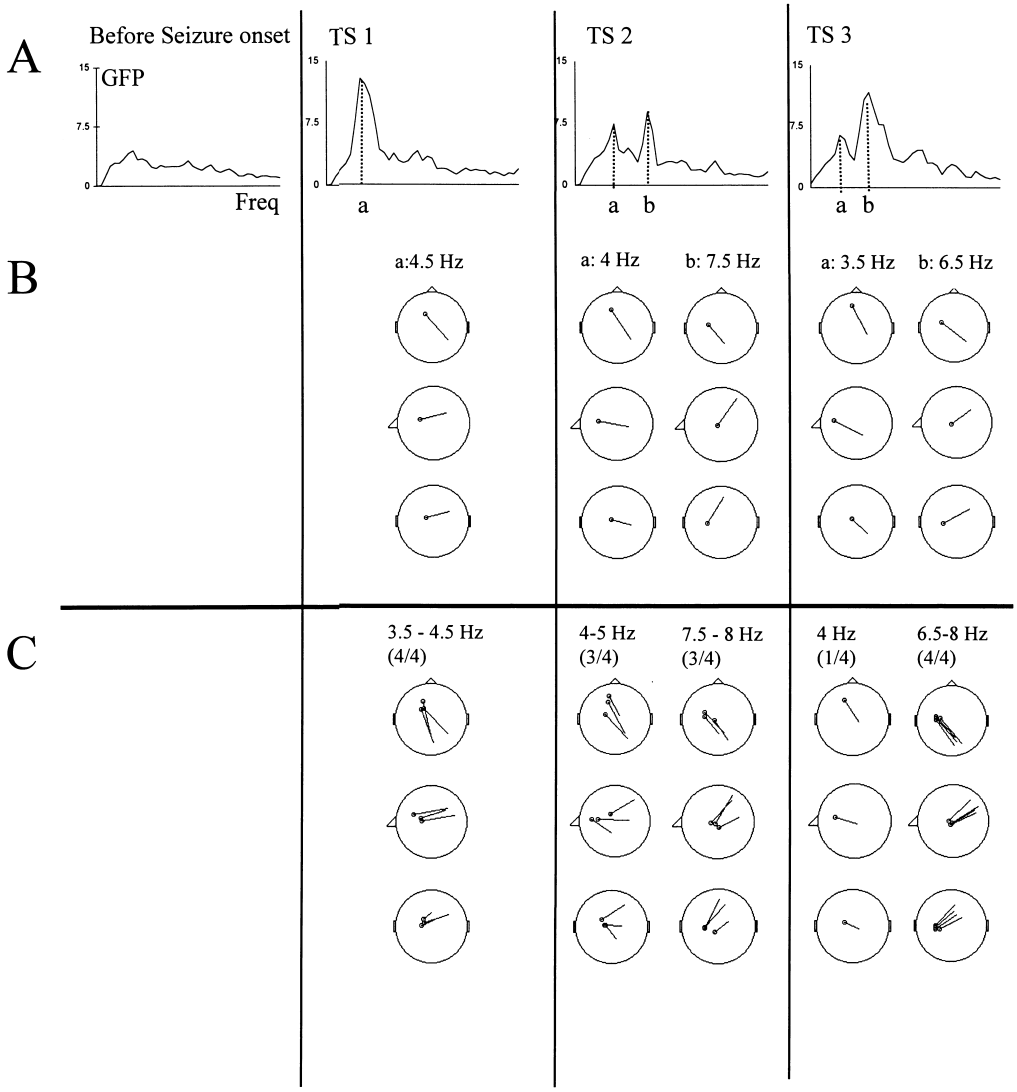

Fig. 4. Frequency profile and dipole results of prominent frequencies during different periods around seizure onset in patient 4. The analyzed time periods are: 8 s before seizure onset, 1–4 s (TS1), 5–8 s (TS2), and 9–16 s (TS3) after seizure onset. For each of these time periods the following results are displayed. The frequency spectrum in A is obtained by calculating an over seizure grand average of all FFT approximated 2 s epochs. B shows the dipole result for the dominant frequencies of this spectrum. In C, individual seizures have been analyzed by averaging all 2 s epochs of a seizure during the respective time periods (2 epochs for TS1 and TS2, 4 epochs for TS3). The dipole results for peaks in the frequency spectrum of each seizure are displayed. The inter-seizure variability in peak frequency is also indicated, as well as in how many of the seizures the respective peaks can be identified. In the pre-onset period no distinct peaks are seen. During TS1, a broad maximum appears, with its peak at 4.5 Hz. This peak persists at approximately the same frequency (3.5–4 Hz), but with a lower power, during TS2 and TS3. At TS2, another peak evolves at 7.5 Hz, and becomes broader and more prominent during TS3 (peak 6.5 Hz). The dipole corresponding to the 3.5–4.5 Hz peak dominating during TS1, has an oblique posterior elevated orientation resembling the OPE pattern, but a location that is rather frontal than temporal. For the 6.5–7.5 Hz peak dominating during the subsequent sequences, the dipole results correspond to the OPE pattern. The dipole results of the individual seizures are in good agreement with those of the averaged data. The EEG of one seizure in this patient is displayed in Fig. 2.

lar between seizures, at least during the early phases of the seizures (Fig. 3C). In patient 4, the two dominant frequencies encountered in the average calculations could be identified also in most of the individual seizures, although a few seizures showed only one of the two dominant peaks. The dipole results were rather stable between seizures, and quite similar to those of the average calculations (Fig. 4C).

Comparison of the dipole results of the FFT approximated ictal data to dipole results of interictal sharp waves, revealed quite similar results for all patients. The dipoles for both the interictal and the ictal activity showed the characteristic OPE pattern (Fig. 5).

The goodness of fit for the ictal dipoles of the different patients ranged between 93% and 98% (mean 96%) during TS1, between 95% and 98% (mean 97%) during TS2, and between 96% and 98% (mean 97%) during TS3. For the interictal dipoles, the goodness of fit ranged between 95% and 98% (mean 97%).

4. Discussion

The extracranially recorded ictal patterns in partial complex seizures of temporal lobe origin may be quite variable. One pattern, however, that is quite frequently encountered, is a gradual build-up of lateralized rhythmic activity, sometimes preceded by an initial bilateral flattening (Quesney et al., 1993). In an investigation by Risinger et al. (1989), a characteristic pattern of lateralized 5 Hz or higher frequency activity was found to be highly predictive of mesial tem-

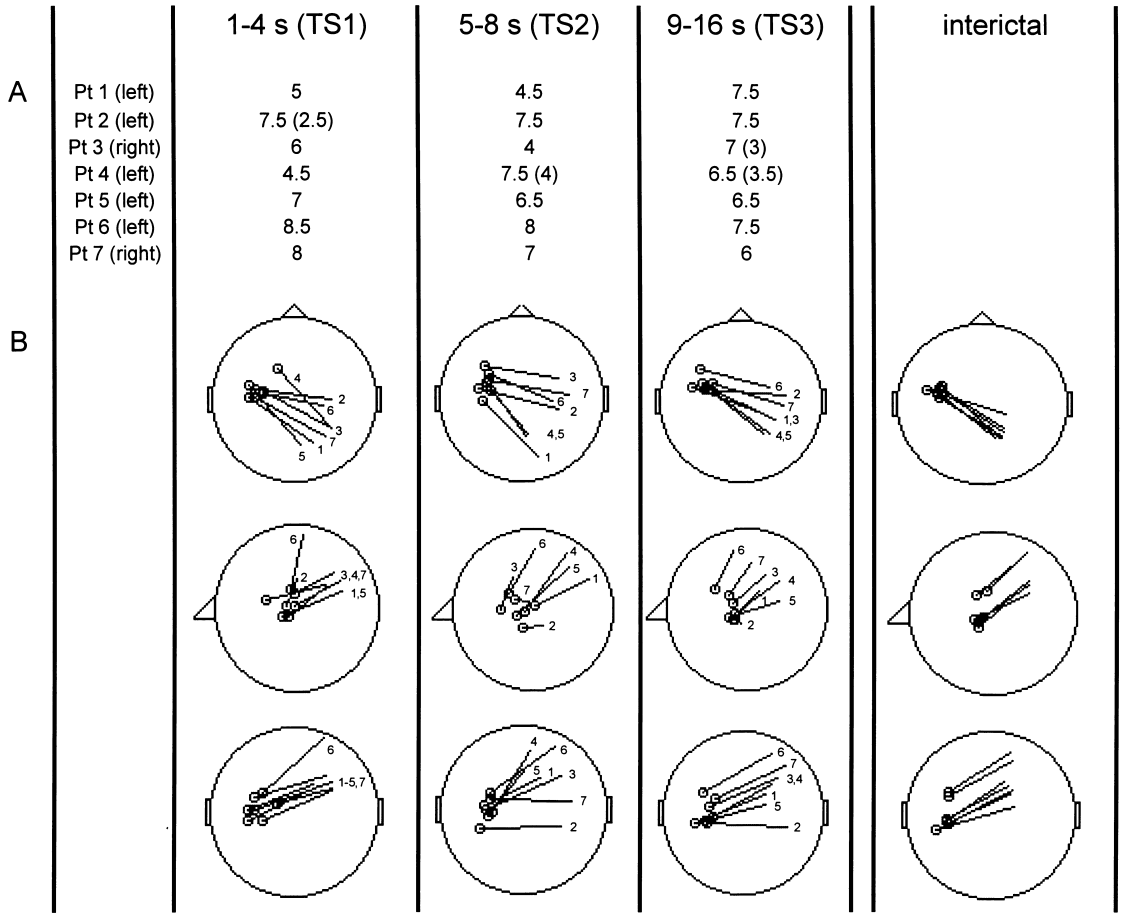

Fig. 5. Dominant frequency (A), and dipole results corresponding to this frequency (B), for all patients during the different phases of seizure development. Data is an average of all FFT approximated 2 s epochs of all seizures, during the periods 1–4 s (TS1), 5–8 s (TS2), and 9–16 s (TS3) after visually estimated seizure onset. In A, prominent spectral peaks besides the dominant ones are indicated within bracelets. In addition, the dipole corresponding to an average of 10 interictal spikes is displayed for all patients. The side of the dipoles is indicated, and right-sided dipoles are projected to homologous area left side. During TS1, a 5–8.5 Hz activity is dominating in 6 of 7 patients, and the dipoles corresponding to this activity show a more or less characteristic OPE pattern. In one patient (patient 4), a 4.5 Hz activity is dominating, and the dipole corresponding to this peak has a rather frontal location. In patient 2, an additional peak at 2.5 Hz corresponding to eye artifacts is seen (dipole not shown). During TS2, the dominant activity persists at approximately the same frequency for 5 of 7 patients. In patient 4, a new frequency peak (7.5 Hz) appears besides the 4 Hz activity, and in patient 3 the peak shifts from 6 to 4 Hz. Dipole results are relatively similar between patients. Note the deviating coronal dipole orientation of patients 2 and 7 (straight lateral rather than elevated orientation). During TS3, the dominant frequency is very similar between patients (6–7.5 Hz), and the dipole patterns show a characteristic OPE pattern for all but one case (patient 2). In patient 3, an additional peak at 3 Hz corresponding to eye artifacts is seen (dipole not shown). The dipole results of the interictal data are quite similar to those of the ictal data.

poral ictal onset, if encountered within 30 s of electrographic seizure onset. Besides this pattern, referred to as initial focal activity, a second pattern was identified, where the lateralized rhythmic activity was preceded by a diffuse electrographical change. The latter pattern, designated as delayed focal, was also found to be quite predictive of mesial temporal seizure onset. Seizures lacking the critical 5 Hz or faster activity were designated as non-focal, and showed considerably less correlation with mesiotemporal seizure onset. In recent publications, Ebersole and Pacia (1996) and Pacia and Ebersole (1997) defined extra- and intracranial electrographic seizure patterns, which they found quite specific for seizures originating in different parts of the temporal lobe. Thus, a regular persistent 5–9 Hz rhythm on extracranial recordings indicated hippocampal onset, whereas an irregular variable rhythm below 5 Hz was typical of neocortical origin. A third pattern of non-lateralizing ictal activity indicated neocortical origin.

In the present investigation, 6 of the 7 patients showed a clear 5–7.5 Hz activity peak during the first 4 s after electrographical seizure onset, and in the last patient (patient 4), a 7.5 Hz peak evolved during the subsequent 4 s period. Dipole reconstruction consistently localized this activity to the temporal lobe, with a characteristic dipole pattern (the OPE pattern). Consequently, following the definitions by Risinger et al. (1989), the seizures in these patients could be considered to be of the initial focal type. In all 7 patients, post-operative seizure freedom after temporal lobe surgery, and in 4 patients also medial subtemporal seizure onset on subsequent subdural recordings, supports the correlation between this activation pattern and mesolimbic epilepsy.

Besides the possibility of quantifying the results, an advantage of the present approach compared with visual analysis, is the information contained in the dipole location and orientation. Ebersole (1994) found the early ictal rhythms of mesiotemporal seizures to have a strong vertical dipole component, whereas lateral temporal neocortical seizures could be modeled mainly by radial dipoles. Boon et al. (1997) found similar differences between ictal dipoles in patients with temporal (mostly medial) lesions compared with patients with extratemporal neocortical lesions. In this investigation, dipole reconstruction of the ictal patterns localized the activity to one temporal lobe, with a specific oblique posterior and elevated dipole orientation (the OPE pattern) that was quite reproducible between patients. In some patients (patients 2 and 7), there was a tendency for this pattern to shift during the later part of the seizure from a distinct elevation in the coronal plane to a more straight lateral orientation. Considering the results of Ebersole (1994), this orientation shift would be consistent with a spread of seizure activity from mesial to lateral temporal regions.

In patient 4, the dipole localization during the first 4 s after seizure onset was rather frontal, whereas later in seizure development a typical OPE pattern evolved. The EEG morphology in this patient (Fig. 2) showed some resemblance to the type 1c pattern of the Ebersole and Pacia (1996) seizure classification (initial parasagittal theta rhythm followed by a lateralized 5–9 Hz rhythm), a pattern which in their investigation was also associated with mesiotemporal seizure onset. Hence, we suggest that this fronto-temporal dipole is in fact modeling the parasagittal theta rhythm characteristic of this specific seizure type.

There was also a striking similarity in dipole parameters between ictal activity, analyzed in the frequency domain, and interictal activity analyzed in the time domain. Similar dipole results for interictal epileptiform activity in patients with mesiotemporal epilepsy have been obtained in our previous investigations (Lantz et al., 1996, 1997), and the similarity between ictal and interictal dipole results has also been demonstrated by other investigators (Boon et al., 1997).

In the investigation by Risinger et al. (1989) a certain variability between seizures in the individual patient was observed, and the classification (initial focal, delayed focal, non focal), was based on the most typical seizures in the individual patient. In this investigation, we found little inter seizure variability in the two patients in whom this was systematically investigated. Even so, a certain variability is likely to exist, and the purpose of averaging the initial seizure patterns of all seizure in a patient when searching for the dominant frequencies, was to de-emphasize atypical patterns of individual seizures, thereby enhancing the common features of all seizures.

Other approaches for analyzing epileptic seizures, which are not related to frequency analysis, have been proposed. Lehnertz and Elger (1995), by computing the correlation dimension of intracranial EEG data, demonstrated decreased neuronal complexity in the seizure onset area, both during seizures and interictally. Pijn et al. (1991) found a decrease in correlation dimension during epileptic seizures recorded from the limbic cortex in the rat. Bullmore et al. (1994) demonstrated a rapid relative increase in fractal dimension over several intracranial channels at the time-point of seizure onset. Since the analysis of non-linear dynamics is not directly related to the frequency behavior of the signal (Wackerman et al., 1993), the two methods might give complementary information about the characteristics of epileptic seizures.

We conclude that dipole reconstruction of frequency analyzed ictal data, obtained from extracranially recorded epileptic seizures in patients with mesolimbic epilepsy, gives dipole results, which are quite reproducible between patients, and which are remarkably similar to the results obtained for interictal epileptiform activity. This suggests a common neuronal source for the two electrophysiological exponents of mesial temporal epileptogenesis. We think that the method may become a useful additional tool for the presurgical identification of patients with probable mesolimbic epilepsy. Future investigations will show whether the method can give useful information also in patients with epilepsy of non-mesolimbic origin.

Acknowledgements

This project was supported by Grant B95-14X-00084-31C from the Swedish Medical Research Council, by the Medical Faculty, University of Lund, by the Swedish Epilepsy Society, and by Swiss National Science Foundation Grant 4038-44081.

References

Alarcon, G., Binnie, C.D., Elwes, R.D.C. and Polkey, C.E. Power spectrum and intracranial EEG patterns at seizure onset in partial epilepsy. Electroenceph. clin. Neurophysiol., 1995, 94: 326–337.

Boon, P., D'Havé, M., Adam, C., Vonck, K., Baulac, M., Vandekerckhove, T. and De Reuck, J. Dipole modeling in epilepsy surgery candidates. Epilepsia, 1997, 38: 208–218.

Bullmore, E.T., Brammer, M.J., Bourlon, P., Alarcon, G., Polkey, C.E., Elwes, R. and Binnie, C.D. Fractal analysis of electroencephalographic signals intracerebrally recorded during 35 epileptic seizures: evaluation of a new method for synoptic visualisation of ictal events. Electroenceph. clin. Neurophysiol., 1994, 91: 337–345.

Darcey, T.M. and Williamson, P.D. Spatio-temporal EEG measures and their application human inracranially recorded epileptic seizures. Electroenceph. clin. Neurophysiol., 1985, 61: 573–587.

Dierks, T., Engelhardt, W. and Maurer, K. Equivalent dipoles of FFT data visualize drug interaction at benzodiazepine receptors. Electroenceph. clin. Neurophysiol., 1993, 86: 231–237.

Ebersole, J.S. Non-invasive localization of the epileptogenic focus by EEG dipole modeling. Acta Neurol. Scand., 1994, 152 (Suppl.): 20–28.

Ebersole, J.S. and Pacia, S.V. Localization of temporal lobe foci by ictal EEG patterns. Epilepsia, 1996, 37: 386–399.

Elger, C.E., Hoke, M., Lehnertz, K. et al. Mapping of MEG amplitude spectra: Its significance for the diagnosis of focal epilepsy. In: K. Maurer (Ed.), Topographic Brain Mapping of EEG and Evoked Potentials. Springer, Berlin, 1989, pp. 565–570.

Gotman, J., Levtova, V. and Farine, B. Graphic representation of the EEG during epileptic seizures. Electroenceph. clin. Neurophysiol., 1993, 87: 206–214.

Hilfiker, P. and Egli, M. Detection and evolution of rhythmic components in ictal EEG using short segment spectra and discriminant analysis. Electroenceph. clin. Neurophysiol., 1992, 82: 255–265.

Hirsch, L.J., Spencer, S.S., Williamson, P.D., Spencer, D.D. and Mattson, R.H. Comparison of bitemporal and unitemporal epilepsy defined by depth electroencephalography. Ann. Neurol., 1991, 30: 340–346.

Kinoshita, T., Michel, C.M., Yagyu, T., Lehmann, D. and Saito, M. Diazepam and sulpiride effects on frequency domain EEG source localisations. Neuropsychobiology, 1994, 30: 126–131.

Lantz, G., Holub, M., Ryding, E. and Rosén, I. Simultaneous intracranial and extracranial recording of interictal epileptiform activity in patients with drug resistant partial epilepsy: patterns of conduction and results from dipole reconstructions. Electroenceph. clin. Neurophysiol., 1996, 99: 69–78.

Lantz, G., Ryding, E. and Rosén, I. Dipole reconstruction as a method for identifying patients with mesolimbic epilepsy. Seizure, 1997, 6: 303–310.

Lehmann, D. and Michel, C.M. Intracerebral dipole source localization for FFT power maps. Electroenceph. clin. Neurophysiol., 1990, 76: 271–276.

Lehnertz, K. and Elger, C.E. Spatio-temporal dynamics of the primary epileptogenic area in temporal lobe epilepsy characterized by neuronal complexity loss. Electroenceph. clin. Neurophysiol., 1995, 95: 108–117.

Lütkenhöhner, B. Frequency-domain localization of intracerebral dipole sources. Electroenceph. clin. Neurophysiol., 1992, 82: 112–118.

Michel, C.M., Lehmann, D., Henggeler, B. and Brandeis, D. Localization of the sources of EEG delta, theta, alpha and beta frequency bands using the FFT dipole approximation. Electroenceph. clin. Neurophysiol., 1992, 82: 38–44.

Michel, C.M., Koukkou, M. and Lehmann, D. EEG reactivity in high and low symptomatic schizophrenics, using source modeling in the frequency domain. Brain Topogr., 1993, 5: 389–394.

Michel, C.M., Pascual-Marqui, R.D., Strik, W.K., Koenig, T. and Lehmann, D. Frequency domain source localization shows state dependent diazepam effects in 47-channel EEG. J. Neural Transm. Gen. Sect., 1995, 99: 157–171.

Offner, F.F. The EEG as potential mapping: the value of the average monopolar reference. Electroenceph. clin. Neurophysiol., 1950, 2: 215–216.

Pacia, S.V. and Ebersole, J.S. Intracranial EEG substrates of scalp ictal patterns from temporal lobe foci. Epilepsia, 1997, 38: 642–654.

Pijn, J.P., Van Neerven, J., Noest, A. and Lopes da Silva, F.H. Chaos or noise in EEG signals; dependence on state and brain site. Electroenceph. clin. Neurophysiol., 1991, 79: 371–381.

Quesney, L.F., Risinger, M.W. and Shewmon, D.A. Extracranial EEG evaluation. In: J. Engel Jr. (Ed.), Surgical Treatment of the Epilepsies. Raven, New York, 1993, pp. 173–195.

Risinger, M.W., Engel, J. Jr., Van Ness, P.C., Henry, T.R. and Crandall, P.H. Ictal localization of temporal lobe seizures with scalp/sphenoidal recordings. Neurology, 1989, 39: 1288–1293.

So, N., Gloor, P., Quesney, L.F., Jones-Gotman, M., Olivier, A. and Andermann, F. Depth electrode investigations in patients with bitemporal epileptiform abnormalities. Ann. Neurol., 1989, 25: 423–431.

Tesche, C. and Kajola, M. A comparison of the localization of spontaneous neuromagnetic activity in the frequency and time domains. Electroenceph. clin. Neurophysiol., 1993, 87: 408–416.

Wackerman, J., Lehmann, D. and Michel, C.M. Global dimensional complexity of multichannel EEG indicates change of human brain functional state after single dose of a nootropic drug. Electroenceph. clin. Neurophysiol., 1993, 86: 193–198.

Valdés, P., Bosch, J., Grave, R., Hernandez, J., Riera, J., Pasqual, R. and Biscay, R. Frequency domain models of the EEG. Brain Topogr., 1992, 4: 309–319.