ELSEVIER

Clinical Neurophysiology 114 (2003) 63–69

www.elsevier.com/locate/clinph

Epileptic source localization with high density EEG: how many electrodes are needed?

G. Lantz[a,b,*], R. Grave de Peralta[a], L. Spinelli[a], M. Seeck[c], C.M. Michel[a,b]

[a]*Functional Brain Mapping Laboratory, Department of Neurology, University Hospital of Geneva, 24,Rue Micheli-du-Crest, CH-1211, Geneva, Switzerland*
[b]*Plurifaculty Program of Cognitive Neuroscience, University of Geneva, Geneva, Switzerland*
[c]*Laboratory of Presurgical Epilepsy Evaluation, Functional Neurology and Neurosurgery Program of the University Hospitals Lausanne and Geneva, Switzerland*

Accepted 15 October 2002

Abstract

Objective: Electroencephalography (EEG) source reconstruction is becoming recognized as a useful technique to non-invasively localize the epileptic focus. Whereas, large array magnetoencephalography (MEG) systems are available since quite some time, application difficulties have previously prevented multichannel EEG recordings. Recently, however, EEG systems which allow for quick (10–20 min) application of, and recording from, up to 125 electrodes have become available. The purpose of the current investigation was to systematically compare the accuracy of epileptic source localization with high electrode density to that obtained with sparser electrode setups.

Methods: Interictal epileptiform activity was recorded with 123 electrodes in 14 epileptic patients undergoing presurgical evaluation. Each single epileptiform potential was down sampled to 63 and 31 electrodes, and a distributed source model (EPIFOCUS) was used to reconstruct the sources with the 3 different electrode configurations. The localization accuracy with the 3 electrode setups was then assessed, by determining the distance from the inverse solution, maximum of each single spike to the epileptogenic lesion.

Results: In 9/14 patients, the distance from the EEG source to the lesion was significantly smaller with 63 than with 31 electrodes, and increasing the number of electrodes to 123 increased this number of patients from 9 to 11. Simulations confirmed the relation between the number of electrodes and localization accuracy.

Conclusions: The results illustrate the necessity of multichannel EEG recordings for high source location accuracy in epileptic patients.

Keywords: Multichannel electroencephalograph; Source localization; Epilepsy

1. Introduction

It is now recognized that electromagnetic non-invasive source imaging may localize, precisely, primary epileptic foci with high spatial and temporal resolution. To achieve this, and to differentiate primary foci from propagated areas, a sufficient spatial sampling is needed. It has been demonstrated (Bendat and Piersol, 1986) that the sampling rate (both spatial and temporal) has to be at least 2.5 times the highest frequency component of the signal (the Nyquist frequency) in order to avoid aliasing (i.e. contamination from higher frequencies through increase of energy in lower frequency bands). As opposed to temporal sampling, spatial sampling is by definition non-continuous, which makes low pass filtering, in order to avoid aliasing, impossible (Srinivasan et al., 1998). Consequently, high spatial sampling is necessary to correctly characterize the topographical details of all frequencies as well as to avoid distortion of frequencies of interest from frequencies above the Nyquist frequency. To some extent, the problem can be diminished by the fact that the scalp acts as a spatial low pass filter, attenuating the undesired high frequency information (Nunez, 1981, Srinivasan et al., 1996). Even so, recording, for instance with the commonly used 21 electrode setup (corresponding to 6 cm inter-electrode distance), is definitely insufficient to adequately sample the spatial frequencies of around 3 cm appearing, for example, in early evoked potential components (Spitzer et al., 1989; Gevins, 1990). In a simulation study by Vanrumste et al. (2000), addressing the effect of volume conductor model errors on EEG dipole source localization, smaller localization errors were found for 53 rather than for 27 electrodes, even if this difference was quite small. Theoretical and experimental studies by Srinivasan et al. (1998) have

* Corresponding author. Tel.: + 41-22-3728339; fax: +41-22-3728333.
E-mail address: goran.lantz@medecine.unige.ch (G. Lantz).

1388-2457/02/$ - see front matter
PII: S1388-2457(02)00337-1

CLINPH 2002577

demonstrated that a minimum of 100 electrodes is needed to properly sample the electric field from the full head surface.

In epileptic patients, electromagnetic source localization procedures are becoming an important tool in presurgical epilepsy investigations of many centers. Even though, in most EEG studies, only standard electrodes setups (between 20 and 30 electrodes) have been used, the localization precision has increased, and some groups have reported accuracy down to the sublobar level (Scherg et al., 1999, Michel et al., 1999, Fuchs et al., 1999) and the possibility to differentiate between deep and superficial temporal sources (Lantz et al., 1997, 2001a). A number of investigators have used high density MEG recordings (more than 100 sensors) in epileptic patients (Paetau et al., 1999, Lamusuo et al., 1999, Scherg et al., 1999, Baumgartner et al., 2000), but only in a few studies (Herrendorf et al., 2000, Waberski et al., 2000, Gross et al., 2000) has multichannel EEG been used in epilepsy investigations, and in these cases only with 64 electrodes. To our knowledge, neither EEG source localization results obtained from data recorded with more than 100 electrodes has been previously presented, nor has the importance of dense spatial sampling for EEG source localization accuracy in epilepsy been systematically addressed.

It has been argued (Rosenow and Lüders, 2001) that large array MEG systems should be able to obtain data faster and in a more standardized way than modern EEG systems. However, recently EEG systems allowing for quick application of, and recording from, up to 125 electrodes have become available. Despite this, most epilepsy centers still base their epileptic source localizations on data recorded with standard setups of around 30 electrodes, which according to the theoretical studies should be considered as a severe subsampling. For this reason, studies comparing the results with different electrode setups are imperative. The purpose of the current investigation was to use a recently developed method for distributed source modeling (EPIFOCUS, Grave de Peralta et al., 2001, Lantz et al., 2001a) to compare the accuracy of EEG source localization results with different electrode densities, both for interictal epileptiform activity and for simulated data.

2. Patients and methods

2.1. Simulations

For the simulations 9 different electrode configurations were chosen. The 181 electrodes of the basic configuration were uniformly distributed over a spherical surface. From this basic 181-electrode configuration, 8 subsamples were constructed, comprising 166, 131, 100, 89, 68, 49, 31 and 25 electrodes, respectively. In constructing the subsamples it was attempted to, as far as possible, keep the uniformity of the electrode distribution. For each electrode configuration, the lead field matrix was computed using a 3 shell spherical head model (Ary et al., 1981, Scherg and von Cramon, 1985), with a uniform grid of 1152 points confined in a sphere of radius 86 mm. At each grid point, the 3 Cartesian components of a source were used to produce simulated surface potentials. For each electrode configuration, these simulated potentials were subsequently localized, using both EPIFOCUS and another distributed source model (weighted minimum norm, Gorodnitsky et al., 1995).

2.2. Clinical data

Fourteen patients (9 males, 5 females, age 5–53years (mean 29 years)), suffering from pharmaco resistant epilepsy were investigated. The patient group comprised all patients who were recorded with our 125-electrode system during a certain time period. In 5 of the patients magnetic resonance imaging (MRI) showed mesial sclerosis, in 4 cases, combined with temporal lobe atrophy. In 7 patients, MRI revealed other types of lesions, one mesiotemporal, two lateral-temporal, one frontal, one occipital, one frontal plus temporal, and one widespread within one hemisphere. In the two remaining cases, MRI was normal. Thirteen of the 14 patients have subsequently been subject of cortical resections and all are seizure free (Engel classification I) postoperatively. In the last patient, the phase I workup has indicated proximity of the focus to eloquent cortex, and the patient has recently been subject of a phase II investigation with intracranial electrodes, followed by a cortical resection. The follow up in this case is too short (a few weeks) to allow judgment of the outcome. In 12 of the 14 patients, the resected area corresponded to the MRI lesion, and in the two patients with normal MRI the area to resect was determined from stereo-electro-encephalography-recordings. Clinical information in all patients is given in Table 1.

Interictal epileptiform activiy was recorded at a separate session using a specially manufactured cap with 129 electrodes (Electrical Geodesics Inc, Eugene, OR, USA). The electrodes, which are mounted in 10–20 min, are arranged in a net so that they cover the head surface in a geodesic tessellation. One hundred and twenty five electrodes measure EEG activity, and 4 electrodes around the eyes are used as auxiliary channels to record eye movements. Data were recorded against a vertex electrode reference with a 500 Hz sampling rate, and filtered off line with LFF 2 Hz and HFF 30 Hz.

In each patient between 13 and 55 (mean 29) epileptiform potentials with a similar surface voltage distribution (i.e. with an inter map correlation exceeding 80%) were identified and stored as separate files. Two eccentrically located electrodes were primarily excluded, and from the remaining 123 electrodes a subsampling to 63 electrodes was performed for each individual spike. The subsampling was performed by omitting electrodes symmetrically, to the largest possible extent maintaining equidistance between the electrodes and coverage of the lower parts of the brain. A similar subsampling was subsequently performed from 63 to 31 electrodes (approximately corresponding to

Table 1
Clinical information of all patients[a]

	Patients	Sex	Age	Anatomical lesion	Defined lesion	Ictal onset	Surgery	Outcome
Mesio-temporal	1	M	37	R hippoc sclerosis + temporal atrophy		R ant temporal	Yes	Engel 1
	2	M	53	L hippoc sclerosis + temporal atrophy		L ant temporal	Yes	Engel 1
	3	M	37	R hippoc sclerosis		R ant temporal	Yes	Engel 1
	4	F	44	R hippoc sclerosis + temporal atrophy		R ant temporal	Yes	Engel 1
	5	M	35	L hippoc sclerosis + temporal atrophy		L ant temporal	Yes	Engel 1
Neocortical	6	M	28	Ganglioglioma L hippoc and amygdala		L temporal	Yes	Engel I
	7	F	20	L post temporal dysplasia		L post temporal	Yes	Few weeks follow up
	8	M	5	Cong ischemic infact L middle cerebr artery		L centro-parietal	Yes	Engel I
	9	F	15	R frontal DNET		R frontal	Yes	Engel I
	10	M	17	L occipital polymicrogyria		L occipital[b]	Yes	Engel I
	11	F	20	Glioma R sup temporal gyrus		R temporal	Yes	Engel I
	12	M	24	Tuberous sclerosis with multiple bihemispheric tubers (iricl R frontal and R temporal)		R ant temporal	Yes	Engel 1
Non-lesional	13	F	44	Normal		R mid + post temporal[b]	Yes	Engel 1
	14	M	33	Normal		L fronto-temporal[b]	Yes	Engel 1

[a] M, male; F, female; L, left; R, right; ant, anterior; post ,posterior.
[b] Based on intracranial recordings.

Fp1, Fp2, F3, F4, F7, F8, F9, F10, T7, T8, T9, T10, C3, C4, P3, P4, P7, P8, O1, O2, FC1, FC2, FC5, FC6, CP1, CP2, TP9, TP10, Fz, Cz, Pz). In this way, the same epileptiform potentials, 'recorded' with 3 different electrode configurations could be analyzed.

For each epileptiform potential source reconstructions were performed for the 123, 63 and 31 electrode setups, respectively, at the time point corresponding to the first negative maximum. The source reconstruction was performed using a linear inverse solution algorithm that optimally localizes single focal sources with a certain spatial extent. The method, called EPIFOCUS (Grave de Peralta et al., 2001, Lantz et al., 2001a) can, by its features, be considered as a hybrid of a linear distributed source model (Hämäläinen and Ilmoniemi, 1984), the single dipole model (Fender, 1987) and the MUSIC algorithm (Schmidt, 1986). The inverse solutions were calculated using an anatomically constrained spherical head model (the SMAC method, Spinelli et al., 2000) in a solution space defined by the MRI of each patient. The solution space consisted of between 1966 and 4592 solution points (inter-point distance 2 mm) equally distributed within the gray matter of the patient's MRI.

As a measure of the accuracy of the inverse solution results with the different electrode configurations, the distance from the EPIFOCUS maximum to the anatomical lesion was determined as follows: one of the coauthors of this article (M.S.), who is also the neurologist responsible for the patients in this study, was asked to review the preoperative MRI and to delineate the borders of the anatomical lesion (in the operated patients virtually equaling the resected area). In the two patients with normal MRI, the resected area itself was delineated. For each spike and each electrode configuration, the shortest distance from the EPIFOCUS maximum to the border of the delineated area was calculated. Spikes with an EPIFOCUS maximum within the delineated area were thus assigned the value 0, whereas for spikes with a maximum outside the area, the shortest distance (in millimeter) from the area was determined (Fig. 1). Finally the mean and standard deviations of the distances from inverse solution maximum to lesion were calculated, and a statistical evaluation (t test for dependent

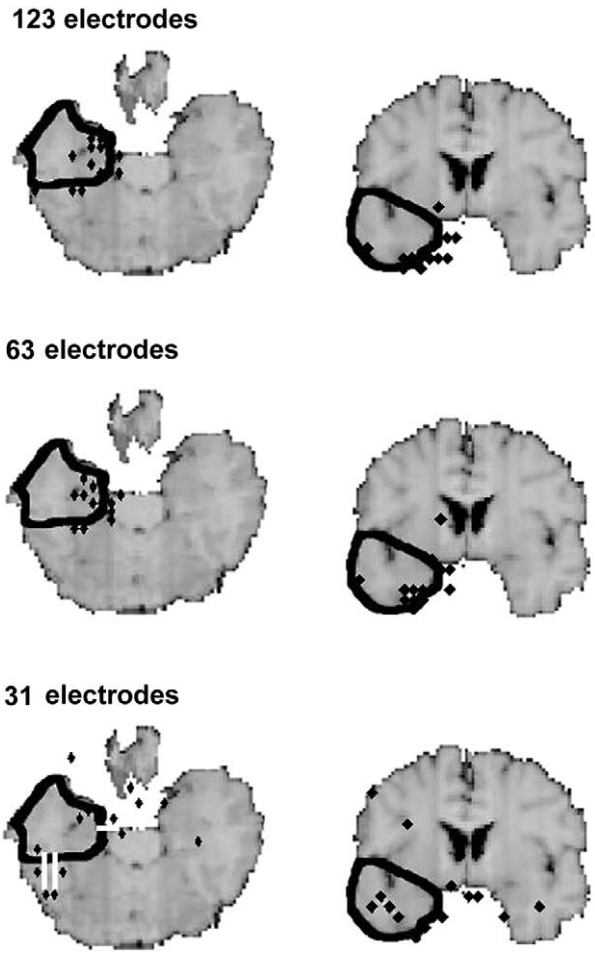

Fig. 1. The approach for determining the distance from source to lesion, and the results in one patient (pat 2). Black line shows the extension of the lesion. For each spike the shortest distance (in millimeter) from the EPIFOCUS maximum (black diamond) to the border of the lesion is calculated (white line). For spikes with an EPIFOCUS maximum within the delineated area the distance is 0. Note that all spike maxima are projected on the same horizontal and vertical slices, which make some individual spikes to appear to be located outside the brain. This is not the case, since the solution space is restricted to the patient's individual gray matter. For details see (Spinelli et al., 2000).

samples) was performed in order to reveal statistically significant differences between the different electrode configurations.

3. Results

3.1. Simulations

The results are presented in Fig. 2. With EPIFOCUS zero localization error (i.e. the source of the simulated potential is localized to exactly the same grid point it originated from) is obtained for virtually all solution points already with 68 electrodes. With the weighted minimum norm algorithm, the number of solution points with zero localization error is much lower for all electrode configurations, and the maximum number is not reached until with 166 electrodes. In order to obtain results comparable to those of EPIFOCUS, grid points with up to 3 points localization error have to be included, but it still requires 166 electrodes to reach the maximum number of correct solution points.

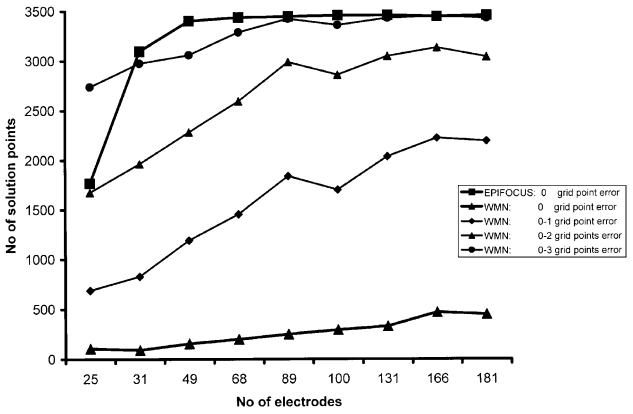

Fig. 2. Simulation results. With the EPIFOCUS algorithm zero grid point localization error is obtained for virtually all solution points already with 68 electrodes. With the weighted minimum norm algorithm the number of solution points with zero grid point localization error is much lower for all electrode configurations, and the maximum number is not reached until with 166 electrodes. In order to obtain results comparable to those of EPIFOCUS, grid points with up to 3 points localization error have to be included, but the maximum number of correct solution points is still not reached until with 166 electrodes.

3.2. Clinical data

The results for all patients are shown in Fig. 3. For all the 14 patients taken together, the mean distance from the inverse solution maximum to the lesion ranged between 2 and 46 mm (median 6) with 123 electrodes, between 0 and 50 mm (median 6) with 63 electrodes, and between 0 and 76 mm (median 22) with 31 electrodes. In the 5 patients with hippocampal sclerosis, the distances were 4–16 mm (median 4) with 123 electrodes, 0–18 mm (median 0) with 63 electrodes, and 16–44 mm (median 22) with 31 electrodes. For the patients with neocortical lesions the corresponding results were 2–46 mm (median 4) with 123 electrodes, 2–50 mm (median 22) with 63 electrodes, and 0–52 mm (median 22) with 31 electrodes. In the two non-lesional cases, finally, the distances were 8 and 34 mm with 123 electrodes, 6 and 40 mm with 63 electrodes, and 22 and 76 mm with 31 electrodes. Note that the relatively sparse distribution of solution points (inter point distance 2 mm), means that a maximum location one grid point outside the lesion already leads to a distance of 2 mm.

When comparing the results with the 123 and 31 electrode configurations, the distance from the inverse solution maximum to the lesion was significantly shorter with the denser electrode setup in 11 of the 14 patients (5/5 with hippocampal sclerosis, 4/7 with neocortical lesions, and two patients without lesion). For one case in the neocortical lesions group (pat 8) the distance was significantly shorter

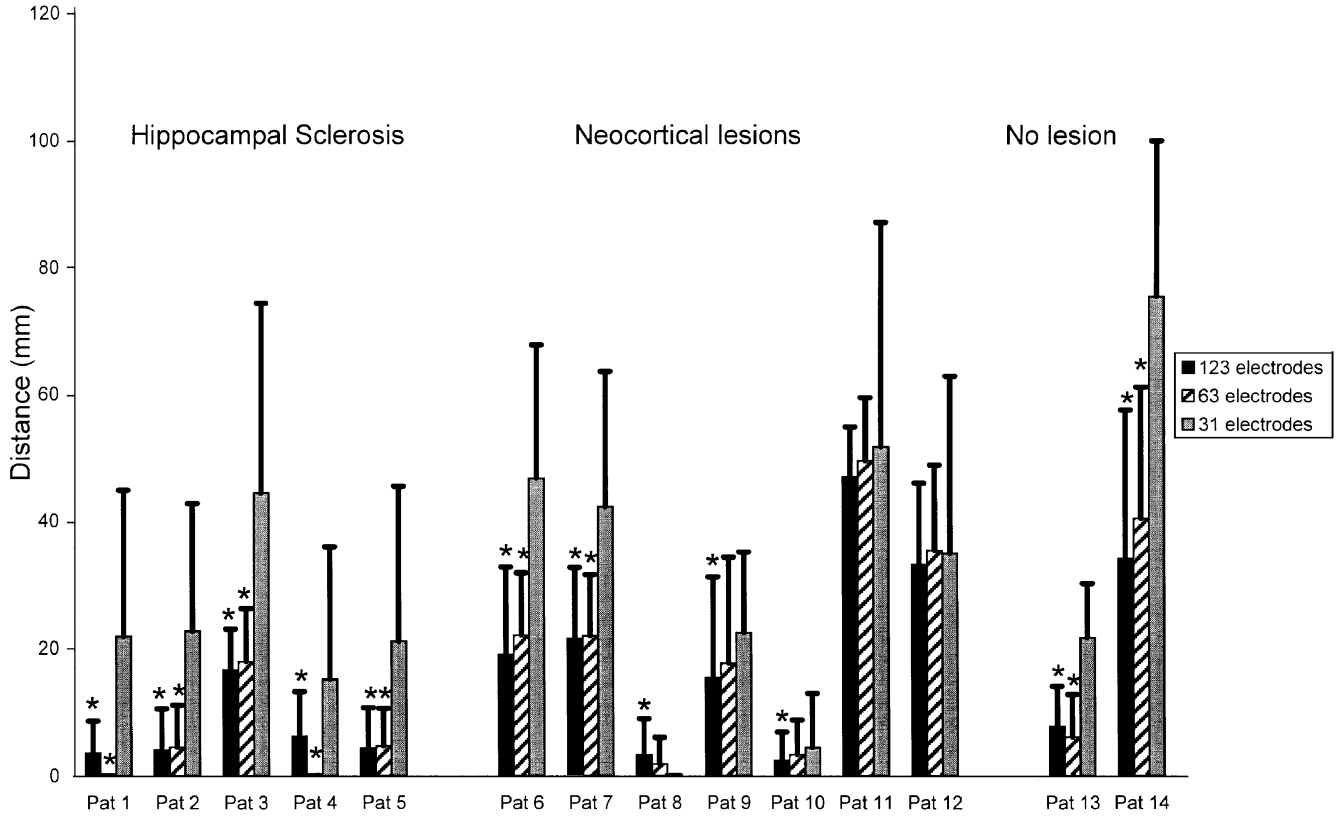

Fig. 3. Means and standard deviations of distance from source maximum to lesion for individual spikes analyzed with 123, 63 and 31 electrodes, respectively. Asterisk above black boxes (123 electrodes) and striped boxes (63 electrodes) indicate significantly shorter distances to lesion than with 31 electrodes.

with 31 than with 123 electrodes, whereas for the two remaining cases in this group there was no significant difference between the two electrode configurations.

Comparison between the 63 and 31 electrode configurations resulted in significantly shorter distances with the denser configuration in 9 of the 14 patients (5/5 with hippocampal sclerosis, 2/7 with neocortical lesions and two patients without lesion). For the remaining 5 cases in the neocortical lesions group there was no significant difference between 63 and 31 electrodes.

4. Discussion

Theoretical studies have indicated that around 100 electrodes would be necessary to sample the full surface of the head. Our study fully confirms the insufficiency of the number of electrodes normally used in clinical practice (around 30), and demonstrates the possibility of gain in localization accuracy by increasing the spatial sampling, at least with the current reconstruction models and electrode setups. Indeed, in 9 of our 14 patients the distances from the source localization maximum to the lesion were significantly shorter with 63 than with 31 electrodes. Moreover, when the number of electrodes was increased to 123, this number of patients increased from 9 to 11. Consequently, the most important step is the increase from 31 to 63 electrodes, whereas increasing from 63 to 123 electrodes only improves the results marginally. The simulations also support these results. Epileptic activity, as opposed to evoked potentials, usually involves simultaneous activation of relatively extended areas and therefore mainly contains relatively low spatial frequencies. For this reason, it is reasonable to believe that also a moderate increase in electrode density, as from 31 to 63, would constitute a significant improvement on the localization accuracy in epileptic patients. Even so, in our study there is still a tendency for better performance with the 123 electrodes setup. Furthermore, the simulations indicate that: (1) the excellent performance with 63 electrodes may be a feature of the EPIFOCUS algorithm, and (2) the performance of a weighted minimum norm solution requires well above 100 electrodes for optimal performance. Since EPIFOCUS can only be used under certain conditions (a single localized source, Grave de Peralta et al., 2001, Lantz et al., 2001a), the number of recording electrodes has to be sufficient to allow analysis, also, with other techniques. In our opinion, 123 electrode recordings are, therefore, still preferable also in epilepsy patients. However, a more detailed comparison between different source modeling algorithms is beyond the scope of this publication.

For correct source localizations, a high signal to noise

ratio (SNR) is necessary, and with EPIFOCUS, a single dominating source is also needed. Consequently, poor source reconstruction results (i.e. long distances from source to lesion) might be explained either by an unfavorable signal to noise ratio or by multiple spatially separate sources. In this study, all patients recorded with 123 electrodes during a certain time period were included, and in order to allow statistical comparisons single spikes instead of the usual averaged spikes were analyzed. This means that the data quality is necessarily quite variable between patients, and this is probably the most important reason for the distances from source to lesion in some of our patients. Since all patients with a reasonably long postoperative follow up (13/14 patients) are seizure free, the second alternative, i.e. multiple sources, is less likely, even if in at least one case (pat 12 with tuberous sclerosis and multiple tuber in both hemispheres) a more complex interictal spike focus might partly explain the long distances. It should be noted that even in cases with relatively long absolute source to lesion distances – whether due to poor SNR or to other factors – the accuracy increases with increasing number of electrodes. Only in a few cases, in which EEG source localizations are quite imprecise with all electrode setups (pat 11, pat 12, pat 14), are the advantages of denser sampling less conspicuous. In another 3 patients (pat 1, pat 4, pat 8) localization with sparser electrode configurations show shorter distances to the lesion than with 123 electrodes. In all these cases, however, the average distance to the lesion is very short with all electrode configurations (4–6 mm).

In the present investigation only interictal epileptiform activity was analyzed. In the presurgical epilepsy investigations ictal EEG recordings play an even more important role. At our department, different techniques such as frequency analysis and temporal segmentation have been used to quantitatively analyze ictal recordings (Lantz et al., 1999, Blanke et al., 2000, Lantz et al., 2001b). It is obvious that the results of these methods would also profit from increased spatial sampling. However, just like MEG and functional magnetic resonance imaging (fMRI), the present 125 electrode recording system does not permit recording for the amount of time necessary to record seizures.

In conclusion, our results illustrate the importance of high spatial sampling for source reconstruction accuracy in epileptic patients. With the inverse solution algorithm that we are using (EPIFOCUS), at least a 63 electrode setup is mandatory for optimal localization of the underlying EEG source. The simulations indicate that other inverse solution algorithms may require well above 100 electrodes for meaningful results. Recently EEG systems have become available in the market, that allow for quick application of, and recording from, up to 123 electrodes. In view of the results, it seems clear that increased spatial sampling of the interictal EEG, combined with electromagnetic source localization, may considerably increase the output of interictal EEG recordings in epilepsy patients. However, at our department these techniques are currently only used as additional tools in the presurgical workup, and in some cases as a help to guide the placement of intracranial electrodes. Further development and evaluations will be necessary before, for instance, the possibility to replace intracranial recordings can be assessed.

Acknowledgements

This study was supported by the Swiss National Research Foundation (grant No. 31-65232.01) and the Foundation Carlos and Elsie de Reuter.

References

Ary JP, Klein SA, Fender DH. Location of sources of evoked scalp potentials: corrections for skull and scalp thicknesses. IEEE Trans Biomed Eng 1981;128:447–452.

Baumgartner C, Pataraia E, Lindinger G, Deecke L. Magnetoencephalography in focal epilepsy. Epilepsia 2000;41(Suppl 3):S39–S47.

Bendat JS, Piersol A. Random data: analysis and measurement procedures, New York, NY: Wiley, 1986.

Blanke O, Lantz G, Seeck M, Spinelli L, Grave de Peralta R, Thut G, Landis T, Michel CM. Temporal and spatial determination of EEG-seizure onset in the frequency domain. Clin Neurophysiol 2000;111:763–772.

Fender DH. Source localization of brain electrical activity. In: Gevins AS, Remont A, editors. Methods of analysis of brain electrical and magnetic signals, Amsterdam: Elsevier, 1987. pp. 355–403.

Fuchs M, Wagner M, Köhler T, Wischmann HA. Linear and nonlinear current density reconstructions. J Clin Neurophysiol 1999;16:267–295.

Gevins A. Distributed neuroelectric patterns of human neocortex during simple cognitive tasks. Prog Brain Res 1990;85:337–345.

Gorodnitsky IF, George JS, Rao BD. Neuromagnetic source imaging with FOCUSS: a recursive weighted minimum norm algorithm. Electroenceph clin Neurophysiol 1995;95:231–251.

Grave de Peralta R, Gonzalez S, Lantz G, Michel CM, Landis T. Noninvasive localization of electromagnetic epileptic activity. 1. Method descriptions and simulations. Brain Topogr 2001;14:131–137.

Gross DW, Dubeau F, Quesney LF, Gotman J. EEG telemetry with closely spaced electrodes in frontal lobe epilepsy. J Clin Neurophysiol 2000;17:414–418.

Hämäläinen MS, Ilmoniemi RJ. Interpreting measured magnetic fields of the brain: estimation of current distributions Helsinki University of Technology. Technical report TKK-F-A559, 1984. p. 28.

Herrendorf G, Steinhoff BJ, Kolle R, Baudewig J, Waberski TD, Buchner H, Paulus W. Dipole-source analysis in a realistic head model in patients with focal epilepsy. Epilepsia 2000;41:71–80.

Lamusuo S, Forss N, Ruottinen HM, Bergman J, Makela JP, Mervaala E, Solin O, Rinne JK, Ruotsalainen U, Ylinen A, Vapalahti M, Hari R, Rinne JO. [18F]FDG-PET and whole-scalp MEG localization of epileptogenic cortex. Epilepsia 1999;40:921–930.

Lantz G, Michel CM, Pasqual-Marqui R, Spinelli L, Seeck M, Seri S, Landis T, Rosén I. Extracranial localisation of intracranial interictal epileptiform activity using LORETA (low resolution electromagnetic tomography). Electroenceph clin Neurophysiol 1997;102:414–422.

Lantz G, Michel CM, Seeck M, Blanke O, Landis T, Rosén I. Frequency domain EEG source localization of ictal epileptiform activity in patients with partial complex epilepsy of temporal lobe origin. Clin Neurophysiol 1999;110:176–184.

Lantz G, Grave de Peralta R, Gonzalez S, Michel CM. Noninvasive localization of electromagnetic epileptic activity. 2. Demonstration of

sublobar accuracy in patients with simultaneous surface and depth recordings. Brain Topogr 2001a;14:139–147.

Lantz G, Michel CM, Seeck M, Blanke O, Thut G, Landis T, Rosén I. Space oriented segmentation and 3-dimensional source reconstruction of ictal EEG patterns. Clin Neurophysiol 2001b;112(4):687–696.

Michel CM, Grave de Peralta R, Lantz G, Gonzalez Andino S, Spinelli L, Blanke O, Landis T, Seeck M. Spatio-temporal EEG analysis and distributed source estimation in presurgical epilepsy evaluation. J Clin Neurophysiol 1999;16:225–238.

Nunez PL. Electric fields of the brain: The nerurophysics of EEG, New York, NY: Oxford University Press, 1981.

Paetau R, Granstrom ML, Blomstedt G, Jousmaki V, Korkman M, Liukkonen E. Magnetoencephalography in presurgical evaluation of children with the Landau–Kleffner syndrome. Epilepsia 1999;40:326–335.

Rosenow F, Lüders H. Presurgical evaluation of epilepsy. Brain 2001;124:1683–1700.

Scherg M, von Cramon D. A new interpretation of the generators of BAEP waves I–V: results of a spatio-temporal dipole model. Electroenceph clin Neurophysiol 1985;62:290–299.

Scherg M, Bast T, Berg P. Multiple source analysis of interictal spikes: goals, requirements, and clinical value. J Clin Neurophysiol 1999;16:214–224.

Schmidt RO. Multiple emitter location and signal array signal processing. IEEE Trans Antennas Propagat 1986;AP-34(3):276–280.

Spinelli L, Gonzalez Andino S, Lantz G, Michel CM. Electromagnetic inverse solutions in anatomically constrained spherical head models. Brain Topogr 2000;13:115–125.

Spitzer AR, Cohen LG, Fabrikant J, Hallett M. A method for determining optimal interelectrode spacing for cerebral topographic mapping. Electroenceph clin Neurophysiol 1989;72:355–361.

Srinivasan R, Nunez PL, Tucker DM, Silberstein RB, Cadusch PJ. Spatial sampling and filtering of EEG with spline laplacians to estimate cortical potentials. Brain Topogr 1996;8:355–366.

Srinivasan R, Tucker DM, Murias M. Estimating the spatial Nyquist of the human EEG. Behav Res Methods Instrum Comput 1998;30:8–19.

Vanrumste B, Van Hoey G, Van de Walle R, D'Havé M, Lemahieu I, Boon P. Dipole location errors in electroencephalogram source ananlysis due to volume conductor model errors. Med Biol Eng Comput 2000;38:528–534.

Waberski TD, Gobbele R, Herrendorf G, Steinhoff BJ, Kolle R, Fuchs M, Paulus W, Buchner H. Source reconstruction of mesial-temporal epileptiform activity: comparison of inverse techniques. Epilepsia 2000;41:1574–1583.