Epileptic Disord 2003; 5 (Suppl 2): S 115–S 123

Focal cortical resection in malformations of cortical development

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ABSTRACT – Malformations of cortical development may be associated with drug-resistant partial epilepsy suitable for surgical therapy. From the anatomo-pathological point of view, this categorisation has been used in reference to a wide range of alterations of the cortical mantle. Focal cortical dysplasias represent the main group of malformations of cortical development, but there are also other types of alterations, such as heterotopias, double cortex or polymicrogyria. Defining candidacy for surgical therapy and tailored resection requires thorough pre-surgical evaluation so that the approach will be individualised for each patient. We present our series of 126 patients with malformation of cortical development selected from 321 consecutively operated patients. Within this group encompassing different types of malformation of cortical development, including periventricular heterotopia (nine patients), polymicrogyria (three patients), hemimegalencephaly (one patient) and subcortical band heterotopia (one patient), the largest group was 81 individuals with focal cortical dysplasia. For this last group, we propose a simplified classification defining 42 architectural dysplasias, 12 cytoarchitectural dysplasias and 27 Taylor's focal cortical dysplasias. In addition, at routine neuropathological investigation, the only morphological alteration shown by 31 patients was diffuse neuronal heterotopia. All patients underwent scalp EEG and video-EEG, and 75 patients (59.5%) also underwent stereo-EEG. Magnetic resonance imaging and stereotactic stereoscopic angiography represented the indispensable premises for further studies, in particular stereo-EEG, and for planning surgery and tailoring resection. Magnetic resonance imaging was unhelpful in 17 out of 81 patients with focal cortical dysplasia and in seven out of 31 with neuronal heterotopia, while signal alterations were present in all other cases. Common characteristics corresponding to clinical-histopathological homogeneous subgroups were found within the focal cortical dysplasia group. In patients with architectural dysplasia, the epileptogenic zone was mainly in the temporal lobe and there was a lower seizure frequency than in patients with Taylor's focal cortical dysplasia. Patients with Taylor's type had an epileptogenic zone that was mainly extra-temporal, and a distinctive interictal stereo-EEG. The best outcome was observed in patients with Taylor's type dysplasia: 69% seizure-free (Engel class Ia) after at least 1 year of follow-up, compared with 45% of cytoarchitectural dysplasia and 49% of architectural dysplasia patients.

KEY WORDS: malformation of cortical development, focal cortical dysplasia, epilepsy surgery, focal resection, SEEG

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Malformations of cortical development (MCD) may correspond to different descriptions from an anatomical point of view. Some appear as diffuse or even disseminated localisations, such as heterotopias or double cortex, while others are more or less focal, such as focal cortical dysplasias (FCD) [1].

There is no homogeneous pathological classification, even if Taylor's [2] first description of focal cortical dysplasia dates back to 1971. Different neuroimaging techniques, neuropathological and genetic advances have provided us with more information, but this seems to have increased subdivisions instead of simplifying and clarifying classification. So the term 'malformations of cortical development' indicates the broad category in which different definitions or hypotheses converge, while we wait for an exhaustive classification.

These malformations are frequently associated with medically intractable epilepsy [3].

The difficulty in categorising aetiology, morphology, histopathology or timing of the proposed aetiological insult, is considered by some authors [4] as just an 'academic dilemma', since clinical manifestations and treatment are similar. However, it is unquestionable that syndromic pictures seem to take shape with peculiar neurophysiological (surface and deep recordings) and neuropathological aspects [5] and acquire a precise individuality within MCD also in terms of outcome after surgery.

To propose focal resections in drug-resistant cases, we needed to identify the dysplasias, in the wide group of MCD, in which the focal origin of the seizures was well proven independently from the extension of the anatomical lesion.

As resective surgery relies on accurate preoperative localisation of the epileptogenic zone, the pre-surgical approach is necessary to obtain the widest and most accurate spectrum of information from clinical, anatomical and neurophysiological data, in order to perform an individualised resection for each patient.

We describe a series of MCD cases in which surgical treatment was tailored by taking into consideration electroclinical, stereo-EEG and imaging data.

Based on neurohistological properties, we subdivided the FCD cases into three groups and then examined each subgroup for common characteristics corresponding to clinically homogeneous groups.

Materials and methods

Our report is based on 126 patients selected from 321 consecutive cases of individuals that underwent surgery for intractable epilepsy, from May 1996 to December 2001, at the 'Claudio Munari' Centre for Epilepsy Surgery, Ospedale Niguarda, Milan, Italy. Some of the patients were previously presented as case reports, addressing only certain neuropathological aspects.

The patients were retrospectively selected on the basis of clinical, neuroradiological, and routine histopathological data consistent with MCD. Cases with other types of malformation or pathology were excluded, apart from hippocampal sclerosis (HS), because this condition is frequently associated with MCD (mostly with FCD) [6].

During pre-surgical investigation, all the selected patients underwent accurate collection and recording of epileptologic history to define the clinical aspects and morphology of the seizures. Several scalp EEGs and video-EEG (VEEG) were performed for all patients, with recording of at least one seizure in order to correlate ictal EEG graphic events with the clinical aspect of seizures. When electroclinical data were apparently inconsistent with magnetic resonance imaging (MRI) findings, invasive pre-surgical stereo-EEG (SEEG) was performed to precisely define the location of the epileptogenic zone.

MRI

Magnetic resonance imaging studies were performed in all patients. The following sequences were acquired: transverse double-echo spin-echo of the entire brain; T2-weighted (w) coronal turbo spin-echo (TSE); T2-w coronal TSE fluid-attenuated inversion-recovery (FLAIR); and T1-w coronal inversion recovery (IR). In most patients, 3D volume fast field echo (FFE) T1-w images were also acquired. Additional FLAIR or TSE T2-w images in the sagittal plane were obtained when necessary. In patients suspected of having temporal lobe epilepsy, transverse images were acquired parallel, and coronal images perpendicular, to the major hippocampal axis. For extra-temporal lobe epilepsies, sections were acquired parallel and perpendicular to the bicommissural line. Intravenous contrast was used in some patients but was generally not useful for diagnosis. The following features were assessed: gyration anomalies, focal thickenings of the cortex, blurring of the grey-white matter junction, abnormal signal intensity in the cortex and subcortical white matter, and focal hypoplasia. Hippocampal sclerosis was diagnosed radiologically in the presence of one or more of the following: hippocampal atrophy, increased signal on T2-w images, decreased signal on T1-w images, and loss of definition of internal structures.

Stereo-EEG recordings

In 51 patients (40.5%), preoperative SEEG was not considered necessary. In the remaining 75 (59.5%), SEEG was performed on the basis of electroclinical and imaging data. The strategy of stereo-EEG investigation was tailored to the individual anatomical and electroclinical characteristics.

Multilead [5-18] electrodes (Dixi; Besançon, France) were placed intracerebrally under general anaesthesia some weeks after stereo-arteriography, to localise blood vessels and guide electrode trajectory. This radiological proce-

dure was performed for all candidates to identify individual vascular patterns, cortical sulci and convolutions for proper planning of an electrode trajectory that would avoid blood vessels, and for surgical planning. The procedure was that described by Talairach and Bancaud (1966) [7] and later refined by Munari and Bancaud (1985) [8] and Munari *et al*. (1994) [9]. A few days after electrode implantation, 3D MRI was performed to verify electrode trajectory and location in relation to the lesion (when present) or to the suspected epileptogenic zone.

Recordings were obtained over 5-20 days under direct clinical and video control in order to detect at least one seizure. At the end of the recording period, the electrodes were removed and the final surgical strategy was tailored according to the delineation of the epileptogenic areas by SEEG monitoring and MRI findings.

The SEEG data were examined pre-operatively by at least two neurologists, and three intracerebral zones were identified: (a) the lesional zone, characterised by depression of background activity or consistent presence of slow waves; (b) the irritative zone defined by the presence of spikes and waves; and (c) the epileptogenic zone identified as the cortical area(s) that were the primary origin of the ictal discharges [7, 9, 10]. The zones thus identified were related to lesion locations when revealed by MRI.

Surgery

Surgical resections were performed for strictly therapeutic reasons to remove the cortical areas involved in the generation of seizures, despite the presence or extension of a lesion visible on MRI.

In addition to corticectomy, the anatomic lesion (when identified) was removed to the extent to which it was considered to be included in the epileptogenic zone. However, partial lesionectomy was performed when critical structures were involved.

In each case, the extent of resection was carefully planned pre-operatively, taking account of the severity of epilepsy and the risk of additional post-surgical neurological deficits. Final surgical strategy was tailored to individual patients on the basis of MRI findings coupled with VEEG or SEEG recordings in relation to the epileptogenic areas revealed by monitoring.

Transferring the limits of planned resection into the operating field requires thorough knowledge of the anatomy and vascular landmarks that were studied with the stereotactic stereoscopic angiography. This methodology permits the visualisation of the 3D vascular tree and the identification of the different convolutions in relation to vascularisation. At surgery, 'aid offered by stereoscopic angiography in the surgical planning has not been overpassed by any other method' [11]. A schema is drawn of the area to be resected, using all the information that is useful reconstructing the characteristics of that area (vascular position, electrode tracts localisation), in order to easily recognise the limits of the exeresis and to proceed with surgery *(figure 1)*.

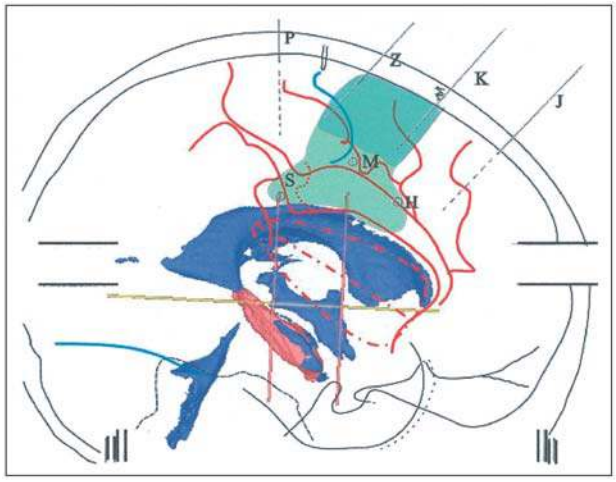

Figure 1. *Prior to surgery, the limits of excision are fixed in all three spatial planes on the antero-posterior and lateral films with respect to the exact position of the electrodes (the impact points of which will serve to guide the surgeon), and by taking into account the anatomical characteristics and vascularisation of each individual patient. In this case, the figure highlights the area of excision corresponding to I frontal convolution ant to the mesial aspect of the frontal lobe.*

In patients who underwent SEEG, electrode tracts were identified on the brain surface and represented a further landmark. Tracts present on the material removed were marked to facilitate correlation of neuropathology with the epileptogenic zone identified by SEEG, and the anatomical lesion identified by MRI.

All surgery was performed with the aid of a neuronavigation system (MKM from Zeiss) that may be of further assistance to the surgeon when landmarks are not well identified or in cases of deep seated surgery *(figure 2)*.

Seizure outcome was defined according to Engel's classification [12].

Neuropathology study

For routine neuropathology studies, surgical specimens were fixed by immersion in 10% neutral buffered formalin solution and subsequently embedded in paraffin.

Cases with types of malformations other than MCD, such as tumours, vascular lesions or post-traumatic lesions, were excluded, even in the presence of focal cortical alterations. All specimens were evaluated for:

1. *laminar cortical disruption*: disorganisation of the normal layering of the cortex observed on at least two different non-consecutive sections, at different depths of surgical specimen;

2. *undifferentiated cells*: cells of round or oval outline with a large nucleus and thin rim of cytoplasm, identified as immature neurons;

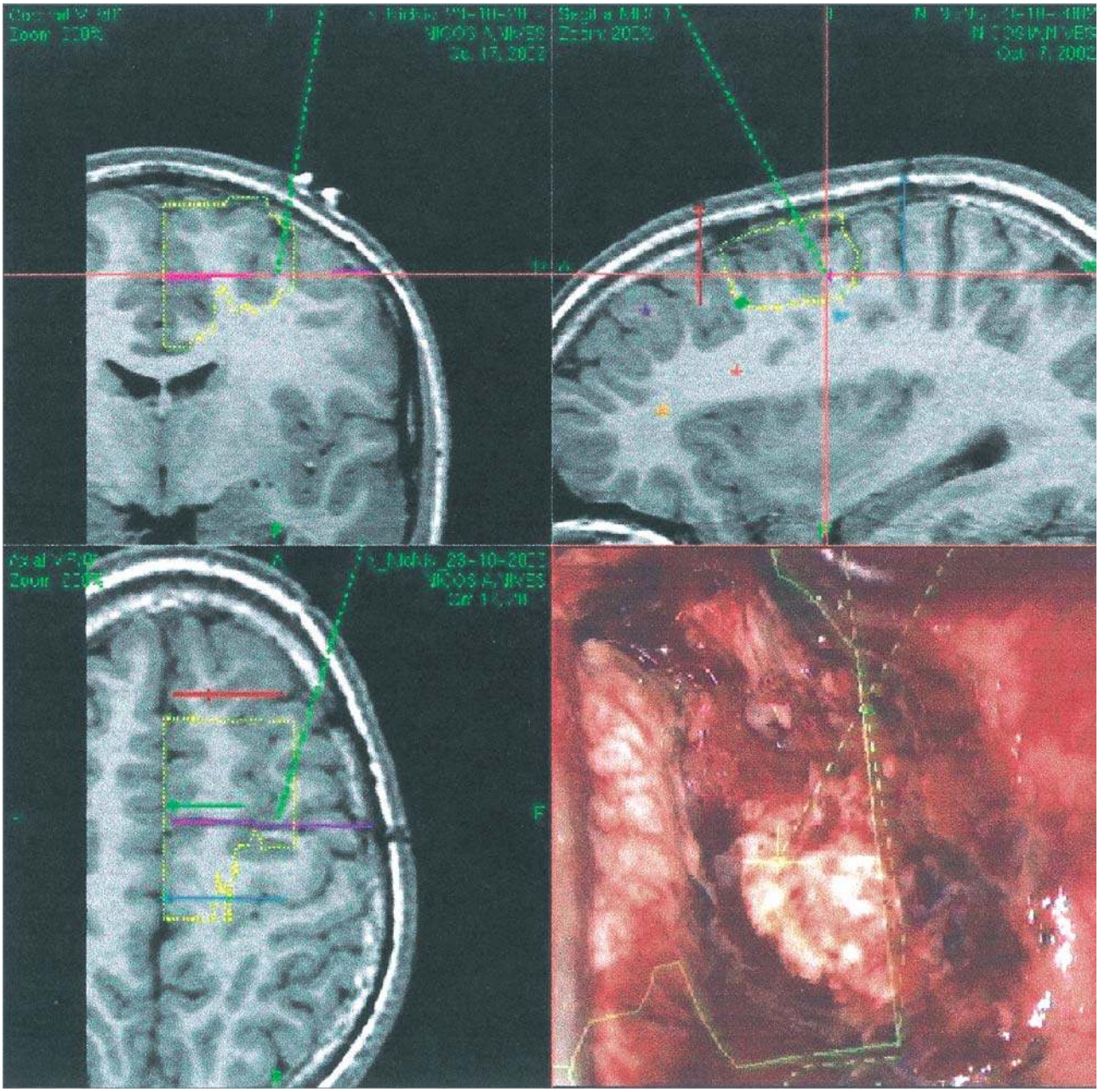

Figure 2. *Image from the neuronavigation system (MKM, Zeiss) showing multiplanar MR with electrode trajectory reconstruction and a picture from the surgical field with superimposed contours of the planned resection.*

3. *giant neurons:* abnormally large cells present in layers others than V; such cells were never present outside LV in normal cortex;

4. *dysmorphic neurons*: neurons with abnormal morphology, abnormal size or abnormal orientation and high neurofilament content [13, 14];

5. *balloon cells*: abnormal cells frequently of huge size, specifically characterised by an ill-defined cell membrane, pale eosinophilic cytoplasm and one or more eccentric nuclei.

Hippocampal sclerosis may also be present. This was diagnosed when the pyramidal cell layers in the hippocampus or dentate gyrus were disrupted, with a marked reduction in the number of neurons and the presence of extensive gliosis.

Results

Table 1 shows the main characteristics of the patients. Based on MRI and neurohistological review, the 126 cases of MCD were grouped in the categories listed in *table 2*.

Table 1. Main characteristics of the 126 patients undergoing surgery for intractable epilepsy with only MCD on surgical specimens

Age at seizure onset	Duration of epilepsy	Abnormal neurological examination	Seizure frequency (per month)	Age at surgery
6.8 yrs (SD 6.6) (range 0-33)	18.2 yrs (SD 10.2) (range 0-46)	33 patients (25.5%)	53 (SD 119) (range 1-1 000)	25 yrs (SD 11.8) (range 0-53)

Focal cortical dysplasia

With 81 patients, FCD represented the largest group, and included the following three subgroups:

1. Architectural dysplasia (AD): abnormal cortical lamination without cytoskeletal abnormalities or balloon cells and ectopic neurons frequently present in the white matter in quantities greatly exceeding those found scattered in normal tissue [15].

2. Cytoarchitectural dysplasia (CD): abnormal cortical lamination and numerous ectopic neurons in the white matter and giant neurons in cortical layers other than V.

3. Taylor-type cortical dysplasia (TFCD): abnormal cortical lamination and giant neurons, dysmorphic neurons and ectopic neurons in the white matter; balloon cells may or not be present.

Forty-two patients had AD, 12 had CD and 27 had TFCD.

Architectural dysplasia

Electroclinical findings

The 42 patients with AD consisted of 19 males (45.2%) and 23 females (54.8%). Mean age at surgery was 28 years (range 2-44, SD 9) and the mean duration of epilepsy was 21 years (range 2-39 years, SD 8). Mean age at epilepsy onset was seven years (range 0-24, SD 6) and mean seizure frequency was 57 per month (range 1-1000, SD 176). Five (12%) patients revealed an abnormal neurological examination and three (7.2%) presented mental retardation. Febrile convulsions were present in 11 (35%) patients, in nine (29%) of these, histological investigation highlighted hippocampal sclerosis homolateral to the site of the dysplasia.

Stereo-EEG was performed in 23 (55%) patients, while VEEG only (in addition to standard EEG) was performed in 18 (43%). In one patient, ictal EEG was considered sufficient to indicate surgery. Simple temporal corticectomy was performed in 28 (67%) patients, and extra-temporal or multilobar surgery in 14 (33%).

Table 2. Categories into which the 126 cases of MCD are subdivided according to neuroimaging and neurohistological data.

		n	%	*n*	%
	Periventricular heterotopia	9	2.8		
	Subcortical band heterotopia	1	0.3		
	Hemimegalencephaly	1	0.3		
	Polymicrogyria	3	0.9		
FCD	Architectural dysplasia	42	13	81	(25.3)
FCD	Cytoarchitectural dysplasia	12	3.8		
FCD	Taylor's dysplasia	27	8.5		
	Neuronal ectopy	31	9.7		

MRI findings

In 16 patients (38%), cortical lesion and hippocampal sclerosis were identified on MRI and confirmed histologically. Signal alteration only was found in the cortex of eight patients (19%), in two of these hippocampal sclerosis was demonstrated histologically. In eight other patients (19%), signal alterations suggested the presence of hippocampal sclerosis, but this condition was observed histologically in only one. In all cases, hippocampal sclerosis revealed by MRI was unilateral, and ipsilateral to the site of the dysplasia. Magnetic resonance imaging was uniformative for hippocampal sclerosis, dysplasia and other brain abnormalities in 10 patients (24%), in two of these histopathological investigation showed hippocampal sclerosis associated with architectural dysplasia.

In 23 (55%) patients, abnormalities demonstrated on MRI permitted the general diagnosis of cortical dysplasia; 17 of these patients presented focal hypoplasia. Grey-white matter blurring associated with signal hyperintensity in T2-w images, was observed in five patients.

Surgery and outcome

The temporal lobe was the intervention site in 28 (67%) patients; mesial structures were resected in all of them. Frontal areas were resected in seven patients. Two adjacent lobes were involved in six patients, in four of these a temporal lobe was also included, although mesial structures were resected in only one case. In the remaining patient, the occipital lobe was the site of intervention.

Postoperative follow-up of at least one year is available for 33 patients. Following the Engel (1987) scale for surgical outcome, 22 of these (69%) patients are in class I, of which 15 (49%) are in class Ia. No differences in outcome were observed between patients with mesial structure resections and those without.

Cytoarchitectural dysplasia

Electroclinical data

The eight males and four females in this group underwent surgery at a mean age of 27 years (SD 15, range 4-53 years); mean age at epilepsy onset was nine years (SD 9, range 0-26 years) and the mean duration of epilepsy was 18 years (SD 13, range 1-42 years). Seizure frequency was very high: 82 per month (SD 119, range 1-300). In four patients, neurological examination was abnormal and included mental retardation. Four patients underwent only VEEG. In seven patients, SEEG investigation was used to better define the surgical targets, while in the last one neither SEEG nor VEEG were considered necessary.

MRI findings

Anatomical lesions were identified in eight patients (66%), double pathology in one, HS in another one and an unremarkable MRI in the other two. Among the former, two had abnormalities similar to those observed in the TFCD patients, in the remaining case focal hypoplasia of the fronto-temporal poles was identified, without significant signal alterations.

Surgery and outcome

Surgery was performed on a temporal lobe in six patients and frontal lobe in three (25%); it was bilobar, including a temporal lobe, in two and multilobar in one. At least one year of follow-up is available for nine patients: four are in class Ia, three in class III, and two in class IV.

Taylor-type cortical dysplasia

Electroclinical data

For the fourteen males and thirteen females of this group, mean age at surgery was 22 years (SD 11, range 3-42 years), mean age at epilepsy onset was 7 years (SD 7, range 0-24 years), and the mean disease duration was 14 years (SD 8, range 2-35). Febrile convulsions were reported in two patients, however, hippocampal sclerosis was not found on histological examination. Seizure frequency was 85 per month (SD 94, range 1-400). Ten patients had abnormal neurological findings.

Nineteen patients (70%) underwent both VEEG and SEEG, four only SEEG, and four only VEEG. The interictal intralesional electrical activity recorded by intracerebral electrodes was, in most cases, characterised by a total absence of background activity and a distinctive pattern of repetitive, high amplitude, fast spikes, followed by high amplitude slow waves, interspersed by relatively flat periods. The ictal pattern, sometimes preceded by 2-3 seconds of increasing rhythmic pathological activity, was characterised by the usual low voltage fast activity.

MRI findings

Twenty-one (78%) of our TFCD patients showed focal thickening of the cortex with blurring of the grey-white matter junction, in association with increased signal intensity in subcortical white matter on T2-w images, sometimes (three cases) extending to the ventricle, and decreased signal in white matter on T1-w images. These findings are reported to be indicative of TFCD [16]. The MRI lesions in these 21 patients were always within the epileptogenic zone indicated by the electroclinical data. Another TFCD case showed focal hypoplasia with hippocampal sclerosis, associated with a slightly increased signal in T2-w FLAIR sequences, similar to the situation in AD patients. In the remaining five cases (33%), the MRI findings were unremarkable.

Surgery and outcome

Frontal corticectomy was performed in 11 patients (41%), temporal corticectomy in six (22%), and parietal corticectomy in two patients. A bilobar intervention was performed in five patients (including the temporal lobe in one), while multilobar surgery was performed in three. Sixteen patients have a follow-up of more than one year: nine (69%) are class Ia, two class III, and three class IV. In the five patients who are not seizure-free, the epileptogenic zone was not completely excised because it involved motor areas, language areas, or both.

Other types of MCD

Periventricular heterotopia

Nine (three female and six males) patients in this group underwent surgery. The duration of epilepsy was relatively high (17.3 years) and a significant percentage (44.4%) of patients revealed an abnormal neurological examination. Seven patients required SEEG exploration. In all cases, MRI revealed the lesion, and in three cases localisation was bilateral. The site of surgery was only temporal in five cases (55.5%) and bilobar or multilobar, but always included the temporal in the others. In six cases, a partial lesionectomy associated with corticectomy was performed, and seven patients are now seizure-free.

Hemimegalencephaly

In this case (an 8-month-old female), despite the presence of hemispheric alterations, we were persuaded to perform a more limited exeresis in the fronto-centro-parietal regions because of the characteristics of the ictal semiology and VEEG recordings. Due to the young age of the patient, we preferred not to use invasive recordings. Seizure outcome was not satisfactory, even if seizure frequency and intensity seemed to have improved at times. Unfortunately, even after two other interventions performed in other hospitals, this young patient is still not seizure-free.

Subcortical band heterotopia

This subgroup includes only one patient (a 20-year-old female). Magnetic resonance imaging revealed the presence of subcortical band heterotopia symmetrically extending to both hemispheres. Video-EEG monitoring per-

mitted the recording of seizures with verbal warning of visual sensation, subsequent loss of contact, late, discrete oro-alimentary and gestual automatisms. An initial flattening on the right temporo-occipital leads followed by theta rhythmic activity was also recorded. Stereo-EEG investigation was performed to study the role of the right internal heterotopic and external cortex of temporo-occipital regions and the possible spread of ictal discharge. Electrical discharge started on the mesial aspect, with subsequent propagation to the external and heterotopic cortex of temporo-occipital junction. A tailored cortectomy was performed, including II, III and IV temporal convolutions in their middle and posterior regions and posterior parahippocampus, while the mesial temporo-occipital cortex was spared for obvious functional implications. At 18 months follow-up, only subjective manifestations are present, as expected, while major seizures have disappeared.

Polymicrogyria

In this subgroup the number of patients was limited (two females and one male; age at surgery: 12.6 yrs, 7-23, ± 8.9) and too small to obtain definite indications. Still, we can note early age at onset of epilepsy (0.6 yrs) and the presence of abnormal neurological examination in two of the three patients. The alteration was clearly visible on MRI. We used invasive recording in one patient. Favourable outcome (one patient, not studied with SEEG, in class Ia) was associated with temporal localisation, and with a total lesionectomy with corticectomy. The patients with frontal and occipito-parietal localisations treated with partial lesionectomy and corticectomy are not seizure-free.

Neuronal heterotopy

In this group (31 patients: 12 females and 19 males), the main histopathological feature is the presence of heterotopic neurons in the underlying white matter exceeding the quantities present in normal tissue [15, 17].

The clinical picture is not very distinctive. Age at surgery was relatively high: 31 yrs (14-48; ± 9); six patients (19%) revealed an abnormal neurological examination, and seizure frequency was lower than in the other MCD.

About 23% of the patients had negative MR, alteration was evident in 20% and another 48% showed association with HS (double pathology). Hippocampal sclerosis alone was present in three patients (9%). Invasive recordings were considered useful in 42% of cases. In the great majority, the site of surgery was temporal (27 out of 31 patients), and outcome seemed to reflect this prevalent localisation: 73% of patients are in class I of Engel, while 19 (66%) are in class Ia.

Discussion

Several reports in the literature deal with the results of surgery in cases of MCD associated with intractable epilepsy [18-21]. The present series includes a wide variety of pathologies with different characteristics reflecting the diversity of the disease.

In 1991, Palmini *et al.* [18] reported 26 patients with « focal neuronal migration disorders ». Patients with resection of the lesion greater than 50% had better outcomes as compared to those with less than 50% resection. Moreover, resection of the epileptogenic zone defined by scalp or intracranial EEG did not correlate with surgical outcome. The conclusion was that the most important prognostic factor was extent of resection of the anatomical lesion. The prevalence of extratemporal cases in Palmini's series explains, at least in part, these conclusions.

Hirabayashi *et al.* [19] reported similar results in a series of 17 patients undergoing surgery for focal cortical dysplasia, and concluded that temporal location and focal lesions correlated with better outcome, while scalp EEG, electrocorticography or chronic invasive EEG did not correlate positively with outcome.

In the series of Bingaman & Cataltepe [20], better outcome correlated with anatomical removal of the lesion, while resection of EEG or ECoG abnormalities did not correlate with outcome.

Wyllie *et al.* [21] reported on 30 patients undergoing surgery for pathologically verified MCD: 17 extratemporal and 13 temporal cases, in the majority of which, the presence of dysplasia was not suspected preoperatively because MRI was normal. Best results (77% of patients seizure-free) were achieved in temporal lobe cases.

In more than 30% of our patients, diagnosis of MCD was also not evident on neuroimaging, but was verified pathologically. The extension of the resection was defined on the basis of clinical and neurophysiological information.

In our experience, even if surgical treatment can be conditioned by the presence of a lesion, this can not be considered the only or even the main factor in deciding where to operate. This decision is based on the recognition of the epileptogenic zone: an abstract concept concerning the cerebral zone primarily involved by epileptogenic discharges, that takes into account the anatomical characteristics of the patient along with clinical and neurophysiological data [22]. Above all, invasive recording with SEEG electrodes has a major role in extra-temporal cases when imaging is negative, or when there is a need to delineate the ictal onset zone in the presence of the diffuse lesions, or to map functional cortical areas.

Forms of MCD, such as periventricular nodular heterotopia, double cortex, polymicrogyria and schizencephaly, have been clearly defined with good correlation of clinical aspects, neuroimaging findings and neurohistological characteristics [23, 24]. This is not exactly the case for FCDs, which are variously grouped in classifications that are sometimes complex and still incomplete [?], or based on MRI findings [25-30] only.

Re-evaluation of the histological specimens allowed us to construct a classification consisting of three histopathological groups. The histological procedures we used to prepare the specimens were those available in any neuropathology department.

Seizure frequency is significantly greater in patients with TFCD than in other FCD, and SEEG showed a distinctive interictal pattern [5]. Such features were never observed in patients with AD or CD. Even when evident, the MRI characteristics of abnormal thickening of the cortex, blurring of the grey-white matter junction, and hyperintensity of subcortical white matter were rarely observed in AD patients. Our series also included cases with absolutely normal MRI, while neuropathological evaluation showed the involvement of highly circumscribed, though severely deranged, cortical areas. The good postoperative outcome of this group (69% in class Ia) suggests that although the epileptogenic zone frequently extended beyond the lesion identified on MRI, SEEG allowed precise definition of its boundaries that served to guide excision.

The electroclinical findings, imaging data and surgical outcome in AD differed from those in CD and TFCD. Seizure frequency was significantly lower in AD than TFCD, while the SEEG of AD and CD patients did not show the distinctive features observed in TFCD. The most distinctive MRI findings in AD were focal hypoplasia with reduced white matter core. Furthermore, AD was usually found in the temporal lobe, whereas in TFCD, lesions were mainly extra-temporal. In our study, the co-presence of dysplasia with HS (dual pathology), was lower than in other series [31, 32] and may be due to the fact that, in our patients, neuropathological confirmation of hippocampal sclerosis was not possible in some cases because of insufficient surgical specimens.

At surgery, it is often very difficult, with simple inspection, to be sure of the extent of the malformation in the majority of MCD. Aside from those cases in which this pathology was discovered incidentally and was not the target of surgery, in many others with well known alteration at MRI, the cortical surface seemed almost normal. Transferring data acquired by neuroimaging or pre-surgical studies exactly into the operating field is one of the major challenges for the surgeon. The unreliability of the neuronavigation systems due to accuracy errors or simply to brain shift during open surgery obliges us to consider as not yet obsolete for surgical planning, the stereotactic stereoscopic angiography, where the vascular tree furnishes the most accurate landmark for performing tailored cortectomy. In extra-temporal cases involving eloquent areas, invasive techniques with subdural or SEEG electrode seem mandatory for functional mapping. In our experience, the best results can be obtained by coupling fMRI with SEEG. In this way, information on cortical areas, both mesial and lateral and on white matter pathways, can be obtained in order to perform a more precise and safe cortical resection of the epileptogenic area.

Clinical symptomatology and neurophysiological data can direct us to a given cerebral zone and with neuroimaging we have, or can try to find, confirmation of our localisation hypothesis. Thus, in our methodology, neuroimaging represents the arrival and not the starting point. Subtle alterations of the cortical organisation (light thickening of the cortex, anomalous gyration...) can often be missed, even by an expert neuroradiologist, if not carefully searched for in a precise localisation on the basis of electroclinical indication.

For some authors [4], total lesionectomy alone seems to represent a priority for best results, while others [10] also consider complete removal of the epileptogenic zone to be a main predictor of favourable outcome. The extension of the lesion is one of the main factors to look for in presurgical evaluation. Nevertheless, in some cases, SEEG allows us to spare part of the lesion not involved in the organisation of the ictal discharge. In the group of periventricular heterotopia, for instance, seizure outcome was one of the best (77.7% of patients seizure-free), as compared to other MCD. Partial lesionectomy was considered sufficient to achieve freedom from seizures, and was based mainly on the neurophysiological indications. □

References

1. Raymond AA, Fish DR, Sisodiya SM, Alsanjari N, Stevens JM, Shorvon SD. Abnormalities of gyration, heterotopias, tuberous sclerosis, focal cortical dysplasia, microdysgenesis, dysembrioplastic neuroepithelial tumor and dysgenesis of the archicortex in epilepsy. *Brain* 1995; 118: 629-60.

2. Taylor DC, Falconer MA, Bruton CJ, Corsellis JAN. Focal dysplasia of the cerebral cortex in epilepsy. *J Neurol Neurosurg Psychiatry* 1971; 34: 369-87.

3. Palmini A, Anderman F, Olivier A, *et al.* Focal neuronal migration disorders and intractable partial epilepsy: a study of 30 patients. *Ann Neurol* 1991; 30: 741-9.

4. Bingaman WE, Cataltepe O. Epilepsy surgery for focal malformations of cortical development. In: Lüders HO, Comair YG. *Epilepsy surgery*. Philadelphia: Lippincott Williams & Wilkins, 2001: 781-91.

5. Tassi L, Colombo N, Garbelli R, *et al.* Focal cortical dysplasia: neuropathologic subtypes, EEG, neuroimaging and surgical outcome. *Brain* 2002; 125 (Pt 8): 1719-32.

6. Arai N, Oda M. Surgical neuropathology of intractable epilepsy. *Epilepsia* 1997; 38 Suppl 6: 11-6.

7. Talairach J, Bancaud J. Lesions, irritative zone and epileptogenic focus. *Confin Neurol* 1966; 27: 91-4.

8. Munari C, Bancaud J. The role of stereo-EEG in the evaluation of partial epileptic seizures. In: Morselli ML, Porter RJ, editors. *The epilepsies*. London: Butterworths, 1985: 267-306.

9. Munari C, Hoffmann D, Francione S, *et al.* Stereo-electroencephalography methodology: advantages and limits. *Acta Neurol Scand* 1994; 152 Suppl: 56-67.

10. Chassoux F, Devaux B, Landré E, *et al*. Stereoelectroencephalography in focal cortical dysplasia. A 3D approach to delineating the dysplastic cortex. *Brain* 2000; 123: 1733-51.

11. Yasarghil MG. *Microneurosurgery of CNS Tumors*. Stuttgart, New York: Georg Thieme Verlag, 1996.

12. Engel JJr. Outcome with Respect to Epileptic Seizures. In: Engel JJr, ed. *Surgical Treatment fo the Epilepsies*. New York: Raven Press, 1987: 553-71.

13. Spreafico R, Battaglia G, Arcelli P, *et al*. Cortical Dysplasia: an immunocytochemical study of three patients. *Neurology* 1998; 50: 27-36.

14. Garbelli R, Munari C, De Biasi S, *et al*. Taylor's cortical dysplasia: a confocal and ultrastructural immunohistochemical study. *Brain Pathol* 1999; 9: 445-61.

15. Hardiman O, Burke T, Phillips J, *et al*. Microdysgenesis in resected temporal neocortex: incidence and clinical significance in focal epilepsy. *Neurology* 1988; 38: 1041-7.

16. Bronen RA, Vives KP, Kim JH, Fulbright RK, Spencer SS, Spencer DD. Focal cortical dysplasia of Taylor, balloon cell subtype: MR differentiation from low-grade tumors. *Am J Neuroradiol* 1997; 18: 1141-51.

17. Meyer G, Wahle P, Castaneyra-Perdomo A, Ferres-Torres R. Morphology of neurons in the white matter of the adult human neocortex. *Exp Brain Res* 1992; 88: 204-12.

18. Palmini A, Andermann F, Olivier A, Tampieri D, Robitaille Y. Focal neuronal migration disorders and intractable partial epilepsy: results of surgical treatment. *Ann Neurol* 1991b; 30: 750-7.

19. Hirabayashi S, Binnie CD, Janota I, Polkey CE. Surgical treatment of epilepsy due to cortical dysplasia clinical and EEG findings. *J Neurol Neurosurg Psychiatry* 1993; 56: 765-70.

20. Bingaman WE, Cataltepe O. Epilepsy surgery for focal malformations of cortical development. In: Lüders HO, Comair YG. *Epilepsy surgery*. Philadelphia: Lippincott Williams & Wilkins, 2001: 781-91.

21. Wyllie E, Baumgartner C, Prayson R,*et al*. The clinical spectrum of focal cortical dysplasia and epilepsy. *J Epilepsy* 1994; 7: 303-12.

22. Bancaud J, Talairach J, Bonis A, *et al. La stéréo-électroencéphalographie dans l'épilepsie.* Paris: Masson, 1965.

23. Li LM, Dubeau F, Andermann F, *et al*. Periventricular nodular heterotopia and intractable temporal lobe epilepsy: poor outcome after temporal lobe resection. *Ann Neurol* 1997; 41: 662-8.

24. Mai R, Tassi L, Cossu M, *et al*. A neuropathological, Stereo-EEG and MRI study of subcortical band heterotopia. *Neurology* (in press).

25. Kuzniecky R, Garcia JH, Faught E, Morawetz RB. Cortical dysplasia in temporal lobe epilepsy: magnetic resonance imaging correlations. *Ann Neurol* 1991; 29: 293-8.

26. Palmini A, Gambardella A, Andermann F, *et al*. Operative strategies for patients with cortical dysplastic lesions and intractable epilepsy. *Epilepsia* 1994; 35 suppl 6: S57-S71.

27. Mischel PS, Nguyen LP, Vinters HV. Cerebral cortical dysplasia associated with pediatric epilepsy. Review of neuropathologic features and proposal for a grading system. *J Neuropathol Exp Neurol* 1995; 54: 137-53.

28. Barkovich AJ, Kuzniecky RI, Dobyns WB, Jackson GD, Becker LE, Evrard P. A classification scheme for malformations of cortical development. *Neuropediatrics* 1996; 27: 59-63.

29. Shorvon S. MRI of cortical dysgenesis. *Epilepsia* 1997; 38 Suppl 10: 13-8.

30. Barkovich AJ, Kuzniecky RI, Dobyns WB. Radiologic classification of malformations of cortical development. *Curr Opin Neurol* 2001; 14: 145-9.

31. Ho SS, Kuzniecky RI, Gilliam F, Faught E, Morawetz R. Temporal lobe developmental malformations and epilepsy. Dual Pathology and bilateral hippocampal abnormalities. *Neurology* 1998; 50: 748-54.

32. Kuzniecky R, Ho SS, Martin R, *et al*. Temporal lobe developmental malformations and hippocampal sclerosis. Epilepsy surgical outcome. *Neurology* 1999; 52: 479-84.