Childs Nerv Syst (2011) 27:381–390
DOI 10.1007/s00381-010-1279-7

ORIGINAL PAPER

Electrocorticography and seizure outcomes in children with lesional epilepsy

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Received: 23 August 2010 / Accepted: 7 September 2010 / Published online: 21 September 2010

Abstract
Purpose The use of electrocorticographically (ECoG)-guided cortical resection in children with lesional epilepsy is controversial. Given the important developmental issues associated with recurrent childhood seizures, sustained seizure control is a key therapeutic goal. We therefore evaluated the effect of the decision to perform lesionectomy or ECoG-guided cortical resection on seizure outcome and surgical morbidity in the pediatric population.
Methods We retrospectively analyzed seizure outcomes in 67 patients between the ages of 3 months and 16 years who underwent surgery for lesional epilepsy at British Columbia Children's Hospital. Thirty-four patients underwent ECoG, and 33 patients had lesionectomy without ECoG.
Results One year post-operatively, 80% of patients who had ECoG-guided cortical resection or lesionectomy were seizure free. However, there was a trend toward improved seizure freedom in patients who had ECoG at most recent follow-up (79% patients with ECoG seizure free, vs. 61% with lesionectomy only; mean follow-up time 5.8 year, P= 0.078). There was no increase in neurological morbidity in patients who had ECoG-guided cortical resection, and these patients were less likely to experience repeat epilepsy surgery.
Conclusions Overall, using ECoG to guide additional cortical resection may lead to more robust seizure freedom in children with lesional epilepsy without increasing their risk of surgical morbidity.

Keywords Brain tumors · Child · Electroencephalography · Epilepsies, partial/diagnosis/*surgery · Post-operative complications · Treatment outcome

Introduction

Epilepsy is a common condition potentially associated with a wide range of developmental, cognitive, behavioral, and psychiatric issues in children [10, 17]. For seizures arising secondary to a focal cortical lesion, surgical resection is effective in improving seizure control and developmental outcomes [20, 22, 56]. In the presence of discrete cortical lesions, including vascular malformations and low-grade tumors, significant debate exists as to the involvement of perilesional tissue in the origin of epileptogenicity [4, 13, 55]. Consequently, the extent of surgical resection required to attain optimal seizure outcomes is also unclear. Simple lesionectomy achieves short-term seizure freedom rates of 61% to 87% in the pediatric population [11, 23, 33, 35, 40]. However, there is mounting evidence to suggest that patients may experience a better seizure outcome when electrocorticography (ECoG) is used to guide additional resection of epileptically active perilesional tissue [14, 25, 31, 35, 37, 44, 50].

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Surgical morbidity and seizure recurrence also affect the post-operative clinical course of these patients. The initial decision to perform ECoG-guided cortical resection or simple lesionectomy may substantially influence these elements of the clinical course. Whereas some authors advocate for initial lesionectomy, with subsequent ECoG-guided cortical resection only if seizures are not adequately controlled, others endeavor to minimize the number of surgeries by performing ECoG-guided cortical resection with the first epilepsy surgery [7, 12, 21, 33, 34, 50]. Few studies have specifically addressed these issues in children.

The aim of the current study was to evaluate the seizure outcome of pediatric patients following lesionectomy, with or without ECoG-guided cortical resection, as the initial treatment for poorly controlled lesional epilepsy. We specifically examine durability of post-operative seizure freedom and surgical morbidity to provide information that could guide clinical and operative decision-making in this patient population.

Methods

We retrospectively reviewed the medical records of pediatric patients who underwent surgery for lesional epilepsy between 1984 and 2008 at British Columbia Children's Hospital (BCCH), Vancouver, Canada. Ethical approval for this research was obtained from the University of British Columbia/Children and Women's Health Centre of British Columbia Research Ethics Board. Patients were included in the study if they had recurrent seizures attributable to a discrete lesion on neuroimaging (computed tomography (CT) or magnetic resonance imaging (MRI)), had tried at least one antiepileptic medication prior to surgery, and had surgical lesionectomy with or without ECoG-guided cortical resection. Patients with a single seizure secondary to a lesion were not included. All patients had a follow-up of at least 1 year. Patients were excluded if their epilepsy was caused by mesial temporal lobe sclerosis, diffuse hemispheric disorders, or malformations of cortical development. However, patients who had elements of focal cortical dysplasia on neuropathological examination in addition to a tumor were not excluded from this study.

Pre-operative evaluation

During the study period, patients with epileptogenic lesions potentially amenable to surgical resection were identified by an epileptologist or one of several pediatric neurosurgeons. Surgical candidacy was determined after detailed assessment coordinated through the Epilepsy Clinic at BCCH. Patients underwent history and neurologic exam, neuroimaging, electrophysiologic recordings, and neuropsychological evaluation. The decision to use ECoG in any individual patient was multifactorial and was influenced by practice patterns of the epileptologist and/or neurosurgeon involved. No consistent clinical factors guided the decision to use ECoG, as subsequently demonstrated by the equivalency of clinical characteristics between patients who underwent lesionectomy and those who underwent ECoG-guided cortical resection. Furthermore, recruitment to the lesionectomy and ECoG-guided cortical resection groups was similar over the entire study period.

In patients where the lesion was located adjacent to eloquent cortex, functional MRI was performed in the more recent years of the study period to assess language and motor function.

Surgical procedure

All surgeries were performed under general anesthesia. Patients were divided into surgical groups based on whether ECoG was performed during the operative procedure. If ECoG was not used, the operative procedure consisted of a simple lesionectomy. When ECoG was used, the operative procedure consisted of simple lesionectomy with or without additional cortical resection beyond the lesion based on ECoG findings and proximity to eloquent cortex. When appropriate, functional mapping was used to localize eloquent cortex.

Subdural grids or strips were placed depending on the operative exposure and recording was performed for a maximum of 20 min. ECoG was considered positive if interictal spikes or electrical seizures were recorded in proximity to the lesion. Rare spikes (generally less than one spike in 5 min) or background slowing were not used as indication for further resection. Post-resection ECoG was not performed if the pre-resection ECoG was quiescent. All resection specimens were examined by a neuropathologist to establish histopathologic diagnosis.

Post-operative evaluation

Post-operatively, patients underwent neuroimaging (MRI) to examine the extent of surgical resection and were followed regularly in the Epilepsy Clinic. Patients who had not been seen in clinic for longer than 1 year were contacted by their epileptologist or nurse clinician to ascertain the most recent seizure outcome. Seizure outcome was assessed by an epileptologist based on the Engel classification system and reported at 1 year post-operatively and at most recent follow-up for each patient. In this study, we recorded seizure freedom rates; all Engel classification ratings except for class Ia or Ib were considered treatment failures.

Data recording and statistical analysis

Data collected from medical records included patient gender, age at onset of epilepsy, age at surgery, duration and type of seizures, location of lesion (based on neuroimaging), histopathologic diagnosis, surgical complications, ECoG findings, and seizure outcome.

A comparative table was created to examine baseline patient characteristics. Outcome measures of seizure freedom were statistically analyzed using one-sided Fisher's exact tests. A Kaplan–Meier survival analysis of seizure outcome with log rank (Mantel–Cox) testing was also performed. Correlation of pre-operative patient characteristics with seizure outcome was investigated using logistic regression. Statistical significance was considered to be $P<0.05$.

Results

Patient population

Data from 67 pediatric patients with poorly controlled lesional epilepsy was analyzed. Thirty-three patients underwent lesionectomy and 34 patients had ECoG-guided cortical resection as the initial operative intervention. Characteristics of the patient population are detailed in Table 1. Importantly, there were no substantial differences between patients in the lesionectomy or ECoG-guided cortical resection groups based on age at seizure onset, duration of epilepsy prior to surgery, lesion location (temporal or extratemporal), lesion type (tumor or vascular malformation), seizure type, and seizure frequency. Results of logistic regression modeling demonstrated that patient clinical characteristics did not significantly predict seizure outcome at either 1 year or most recent follow-up. This analysis suggests that patients in the lesionectomy and ECoG-guided cortical resection groups were clinically comparable, and key baseline clinical characteristics did not significantly contribute to outcome.

Patients ranged in age from 3 months to 16 years. The vast majority of patients in each group had tumors: 28 in the ECoG group and 26 in the lesionectomy group. Four patients in each group were found to have elements of cortical dysplasia in addition to their primary lesion on histopathologic examination of the resection specimen. All patients except for two had complete lesion resection confirmed by neuroimaging (CT, MRI, or both as appropriate). In these two cases, partial resection was performed due to proximity to eloquent cortex. When ECoG was performed, additional resection of epileptically active cortex occurred in 60% of surgeries. Reasons for lack of additional cortical resection despite use of ECoG included lack of interictal spikes/electrical seizures or proximity to eloquent cortex. Post-resection ECoG was negative in 15 out of 17 surgeries in which it was performed.

Seizure outcome and recurrence

We examined seizure outcome at 1 year after the initial epilepsy surgery and also at most recent follow-up, prior to any additional operative intervention, for each patient. Of the 34 patients who underwent ECoG-guided cortical resection, 27 were seizure free 1 year post-operatively (79%), compared with 25 out of 33 (76%) who underwent simple lesionectomy. Statistical testing revealed no significant difference in seizure freedom between groups at this time point (odds ratio (OR)=1.2; confidence interval (CI)= 0.39–3.9; $P=0.47$). However, there was a trend toward a higher rate of seizure freedom in patients who had ECoG-guided cortical resection at the most recent follow-up prior to additional operative intervention (Fig. 1; 79% seizure free in the ECoG-guided cortical resection group compared with 61% in the simple lesionectomy group; OR=2.5; CI= 0.85–7.4; $P=0.078$).

To further investigate this increased rate of seizure freedom over time in patients with initial ECoG-guided cortical resection compared to those with simple lesionectomy, we performed a Kaplan–Meier survival analysis. A trend toward increased durability of seizure freedom was demonstrated for the patients with initial ECoG-guided cortical resection, although this was not statistically significant (Fig. 2a; $P=0.089$). Specifically, 24% ($n=8$) of patients who had lesionectomy as the initial surgery experienced seizure recurrence, compared with 9% ($n=3$) in those who underwent ECoG-guided cortical resection (Fig. 2b). Nine percent of patients in both groups never attained seizure freedom at any time, potentially reflecting a component of our overall patient population with difficult to control seizures despite attempts at pharmacologic and surgical management.

Thirteen patients out of our total patient population went on to have further operative interventions, primarily due to seizure recurrence. Two patients with initial lesionectomy underwent a second surgery for tumor recurrence and one patient with initial ECoG-guided cortical resection underwent a second surgery for both tumor and seizure recurrence. We decided to investigate the seizure outcomes at most recent follow-up including these additional surgeries. The three patients in the ECoG group who went on to have second surgeries had repeat ECoG-guided cortical resection. Of the patients in the lesionectomy group who had second surgeries, six had ECoG with this subsequent operative intervention and four had repeat lesionectomy (Fig. 3a). Patients were analyzed in groups according to their initial operative intervention. The seizure freedom rate in the patients with initial ECoG-guided cortical resection

Table 1 Characteristics of children undergoing surgery for lesional epilepsy

	ECoG	Lesionectomy
Number of patients	34	33
Males	21	18
Age at surgery (years)	Mean, 9.53; med, 10.71	Mean, 8.75; med, 7.92
Duration of epilepsy (years)	Mean, 3.50; med, 2.42	Mean, 1.91; med, 0.753
Post-op follow-up (years)	Mean, 5.64; med, 4.75	Mean, 6.96; med, 5.00
Location		
Temporal	22	17
Frontal	8	11
Occipital	2	2
Parietal	2	3
Lesion type		
Ganglioglioma	18	15
Astrocytoma	1	6
Cavernoma	2	5
DNET	7	4
AVM	1	1
Hamartoma	1	1
Meningiomatosis	1	0
Oligodendroglioma	0	1
Cysticercosis	1	0
Neurocytoma	1	0
Dysplastic cyst	1	0
Elements of CD	4	4
Seizure type		
Partial	25	22
Secondary generalization	9	11
Seizure frequency		
>/= 1/day	22	18
<1/day	12	15
Focal neurological signs	9	4

DNET dysembryoplastic neuroepithelial tumor, *AVM* arteriovenous malformation, *CD* cortical dysplasia

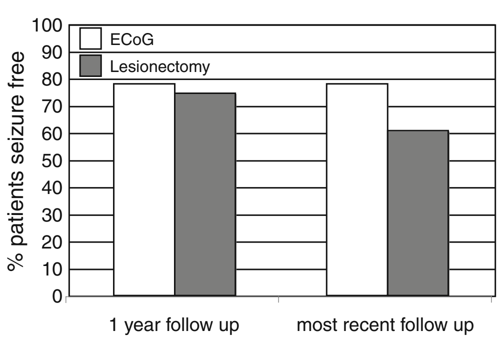

Fig. 1 Percentage of patients who are seizure free at 1 year post-operative follow-up and most recent follow-up after ECoG-guided cortical resection or lesionectomy (prior to any repeat surgeries). There is a trend toward a greater percentage of seizure freedom in patients with ECoG-guided cortical resection (P=0.078)

was 82%, compared with 73% in patients with initial lesionectomy (Fig. 3b; OR=1.75; CI=0.54–5.6; P=0.26; mean follow-up time 6.3 years including repeat surgeries).

Patients who were seizure free 1 year post-operatively were encouraged to attempt taper of antiepileptic medications, with the exception of children in whom focal cortical dysplasia was demonstrated on pathological examination, or children who had repeat epilepsy surgery. At the time of last follow-up, after all operative interventions, a similar proportion of patients with initial ECoG-guided cortical resection or initial lesionectomy remained on antiepileptic drugs (32% in the ECoG-guided cortical resection group vs. 36% in the lesionectomy group). Furthermore, 9% of patients in the ECoG-guided cortical resection group and 12% of patients in the lesionectomy group remained on more than one antiepileptic drug. The majority of patients were therefore able to discontinue antiepileptic therapy post-operatively, although not all patients who were seizure free attempted wean of antiepileptic drugs.

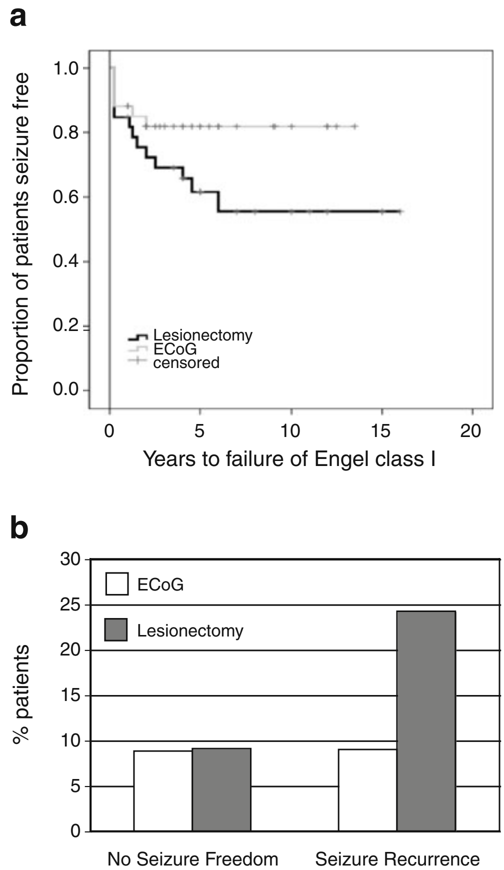

Fig. 2 Durability of seizure freedom and seizure recurrence in patients with initial ECoG-guided cortical resection or lesionectomy. **a** Kaplan–Meier plot showing seizure-free status with respect to time in years. Time to failure of Engel class I was reported as the first seizure recurrence for each patient. Patients who never achieved seizure freedom were reported as Engel class I failure at 3 months after the initial surgical intervention. There is a trend toward greater sustainability of seizure freedom in patients with initial ECoG-guided cortical resection. **b** Similar proportions of patients with initial ECoG-guided cortical resection or lesionectomy never experience seizure freedom. A greater percentage of patients who had initial lesionectomy experience seizure recurrence compared to those with initial ECoG-guided cortical resection

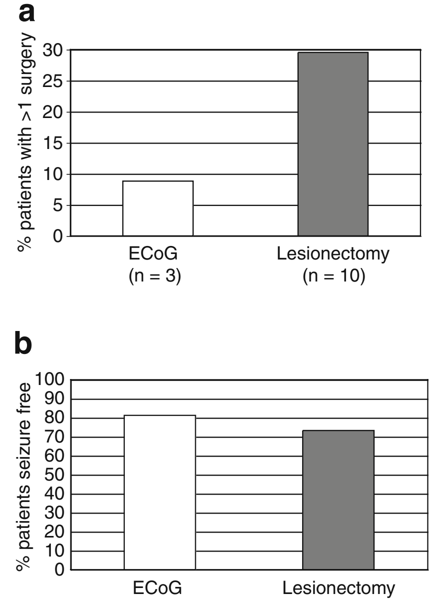

Fig. 3 Seizure freedom and multiple surgeries. **a** Patients with initial lesionectomy experienced more repeat surgeries compared to those with initial ECoG-guided cortical resection. **b** Percentage of patients who are seizure free at most recent follow-up after initial ECoG-guided cortical resection or lesionectomy (including repeat surgeries). There is no significant difference in seizure outcome identified between the groups

Surgical morbidity

In order to compare the morbidity associated with lesionectomy and ECoG-guided cortical resection, we reviewed all surgical complications resulting from the total 80 surgeries performed on our patient population (Table 2). Surgical complications occurred in six surgeries (14%) when ECoG was performed, and in seven surgeries (19%) when lesionectomy was performed. One of each type of operative procedure resulted in more than one complication as a result of a single surgery, in both cases consisting of a transient speech apraxia combined with extremity or facial weakness.

The type of surgical complications experienced in each patient group was similar. Whereas visual field defects were generally permanent, weakness (facial or extremity) was either transient or resulted in mild functional impairment. Speech apraxia was also transient. Two patients who underwent ECoG-guided cortical resection had aseptic meningitis that was successfully treated with steroids. One patient who had lesionectomy experienced a CSF leak that did not require operative intervention. Overall, 7% of patients experienced permanent post-operative deficits.

We also examined the number of surgeries and surgical morbidity each patient underwent based on their initial operative intervention. The rate of second surgery in patients who had lesionectomy as the first operative intervention was approximately three times higher compared with those who had initial ECoG-guided cortical resection (Fig. 3a: 9% in the ECoG group vs. 30% in the lesionectomy group). Of the patients who had surgical complications resulting from the initial surgery, none experienced additional morbidity if they went on to have further operative intervention.

Pre-operative variables

We performed a logistic regression analysis to identify whether several pre-operative variables affected seizure outcome in our population (Table 3). None of these

Table 2 Surgical complications related to ECoG-guided cortical resection and lesionectomy

	ECoG	Lesionectomy
Total number of surgeries with complications	6	7
% surgeries with complications	14	19
Complication type		
Single extremity weakness	1	1
Hemiparesis	2	1
Facial weakness	0	1
Speech apraxia	1	1
Visual field defect	1	2
CSF leak	0	1
Aseptic meningitis	2	0
Intraoperative burn	0	1
>1 complication/surgery	1	1

variables (including duration of epilepsy before surgery, lesion location, and seizure type) were found to statistically predict to seizure outcome at 1 year or most recent follow-up (correlation coefficient=0.032 at 1 year, 0.049 at most recent follow-up). The levels of each variable are stated as (first vs. second), so the odds ratio of the binary variables can be interpreted as the odds of seizure freedom of the first level to the second level.

Discussion

Despite their association, the pathophysiology of epilepsy secondary to focal cortical lesions is multifactorial and not well understood. Perilesional alterations in cortical physiology could predispose to seizure activity [26, 57], suggesting that optimal surgical outcome may be obtained if both the lesion and surrounding pathologic tissue are resected. ECoG-guided cortical resection provides a way to identify cortical tissue that has abnormal electric activity, although the precise relationship of this activity to epileptic potential continues to be unclear [1–3]. Correspondingly, the use of ECoG to guide additional cortical resection in pediatric patients undergoing surgery for excision of radiographically well-defined lesions is controversial. Although studies indicate relatively good seizure freedom rates after both lesionectomy and ECoG-guided cortical resection, very little data exists about how the decision to perform either of these procedures as the initial operative intervention affects the extended clinical course. Our results demonstrate that there is a trend toward not only better seizure outcome in patients who undergo initial ECoG-guided cortical resection, but that these patients experience less chance of seizure recurrence and fewer epilepsy surgeries without any additional surgical morbidity.

Patient demographics

Low-grade tumors (particularly ganglioglioma and astrocytoma) were more common than vascular malformations in our patient population, in agreement with other studies of lesional epilepsy in children [39, 54]. Although we excluded patients with lesions due to primary cortical dysplasia, eight out of 67 resections were found to contain elements of cortical dysplasia on histopathologic examination. Cortical dysplasia is frequently associated with dysembryoplastic neuroepithelial tumors and ganglioglioma [9, 45, 51], and in this study all patient with elements of cortical dysplasia had a pathologic diagnosis of ganglioglioma. Due to the relatively low incidence of cortical dysplasia in our population, it is not possible to determine in this study whether the presence of cortical dysplasia predicts seizure outcome.

Seizure outcome

The decision to pursue ECoG at our institution was multifactorial during the study period, and no specific clinical guidelines were employed to determine which patients received initial lesionectomy or ECoG-guided cortical resection. Although it is not possible to ensure complete equivalency of patients between the two groups in a retrospective study design, patients did not differ in regard to key seizure, lesion, and clinical characteristics. At 1 year post-operatively, a similar proportion of patients in both groups (~80%) were seizure free, suggesting that lesionectomy removes sufficient epileptogenic tissue to initially sustain seizure freedom in most patients. This rate of seizure freedom at 1 year is in agreement with previous studies including pediatric and adult patients [11, 16, 53]. However, at the time of most recent follow-up prior to any repeat operative intervention in the current study (average,

Table 3 Logistic regression of pre-operative variables

Variable	Odds ratio	Lower 95% CI	Upper 95% CI	*p*
1 year outcome				
ECoG vs. lesionectomy	0.714	0.21	2.428	0.589
Duration of pre-operative epilepsy	0.941	0.794	1.117	0.488
Lesion location (temporal vs. extratemporal)	1.596	0.46	5.53	0.461
Seizure type (generalized vs. partial)	1.859	0.548	6.301	0.319
Most recent outcome				
ECoG vs. lesionectomy	0.436	0.142	1.339	0.147
Duration of pre-operative epilepsy	1.048	0.867	1.226	0.628
Lesion location (temporal vs. extratemporal)	0.967	0.324	2.888	0.952
Seizure type (generalized vs. partial)	1.309	0.415	4.129	0.646

5.8 year), 61% of patients with initial lesionectomy were seizure free. There is substantial variability in seizure freedom rates in pediatric studies of lesionectomy alone for lesional epilepsy, ranging from 61–87% [11, 23, 33, 35, 40]. Comparative interpretation of these studies is difficult due to differences in cortical pathologies included, sample size, pre-operative epilepsy severity, and follow-up time. Overall, it is generally agreed that the majority of children treated with lesionectomy will become seizure free. Some authors therefore argue that lesionectomy without ECoG is the appropriate initial management for lesional epilepsy [34, 35, 40].

However, our results indicate that there is a trend toward a higher seizure freedom rate in patients with initial ECoG-guided cortical resection (79%) at an average follow-up time of 5.8 years. This result is not significant, possibly reflecting some limitations in sample size and/or relatively small effect size. The use of complete seizure freedom rather than gradations of improvement in seizure control may also have led to decreased sensitivity in detecting differences between lesionectomy and ECoG-guided cortical resection. There are very few studies consisting of exclusively pediatric patients that compare the effectiveness of ECoG-guided cortical resection with simple lesionectomy [33, 35]. Several studies of combined pediatric and adult patients report improved seizure outcomes with the use of ECoG compared with simple lesionectomy, especially in the temporal lobe [31, 50, 53]. Our data suggest that improved seizure outcomes can be achieved with ECoG in pediatric patients regardless of lesion location.

Seizure recurrence

Seizure outcome at 1 year post-operatively has been used as a predictor of long-term seizure outcome in adults [8, 18, 19]. In children, some studies indicate that seizure outcome seems to be similarly stable after 2 years post-operatively [27, 36, 47]. Significantly, these studies involved a combination of surgical interventions, including ECoG-guided cortical resection, lesionectomy, lobectomy, and hemispherectomy. On the other hand, some studies indicate that there continues to be a measurable risk of seizure recurrence up to 10 years post-operatively [6, 48]. Kaplan–Meier analysis in the current study, though not statistically significant, suggested that patients who underwent simple lesionectomy continued to be at risk for seizure recurrence up to 6 years post-operatively. On the other hand, patients who underwent ECoG-guided cortical resection had a decreased incidence of seizure recurrence overall, and were unlikely to experience seizure recurrence after 2 years post-operatively, in agreement with the above-mentioned pediatric long-term outcome studies [27, 36]. The delayed seizure recurrence associated with initial lesionectomy may be secondary to perilesional epileptogenic foci that are not resected and subsequently develop the ability to precipitate seizures [32]. Because recurrent seizures are associated with cognitive impairment and behavioral difficulties [17, 29, 30, 43, 52], the increased sustainability of seizure freedom associated with ECoG-guided cortical resection may provide benefit to the developing brain [38, 47, 59].

Morbidity

One argument for performing lesionectomy alone is that resection of additional cortex guided by ECoG may increase post-operative morbidity. In this study, surgical morbidity was similar in frequency and type when comparing patients who underwent lesionectomy to those who had ECoG-guided cortical resection. Nineteen percent of patients overall experienced surgical morbidity, and 7% of the post-operative deficits were permanent. These morbidity rates are similar to those observed in previous pediatric studies [6, 46, 47]. In the current study, we did not evaluate cognitive outcomes, but there is some evidence to suggest that cognition is not negatively impacted by ECoG-guided cortical resection [38, 42]. Our results provide further evidence supporting the idea that ECoG-guided cortical resection is safe in children, and does not lead to an increased frequency or severity of surgical morbidity or neurologic complications relative to simple lesionectomy.

Overall clinical course

Due to the relatively good seizure outcome after lesionectomy in the majority of patients with lesional epilepsy, some authors have recommended ECoG-guided cortical resection only if initial lesionectomy fails [12, 33–35]. We therefore examined our patient group who underwent multiple surgeries to identify how the initial decision to pursue lesionectomy or ECoG-guided cortical resection affected their extended clinical course. Overall, we found that there was a trend toward better seizure outcome in patients with initial ECoG-guided cortical resection (82% seizure free), compared with those with initial lesionectomy (73%). It could be argued that relatively similar rates of seizure freedom are eventually obtained in either group. There is also a similar proportion of patients who continue to take antiepileptic medications in each group. Because not all patients who are seizure free post-operatively even attempt wean of antiepileptic medications due to social and psychological factors, this is not an accurate measure of surgical efficacy. Indeed, a prolonged interval of seizure freedom prior to wean of antiepileptic drugs may also predict better outcome, necessitating an extended time of post-operative follow-up to determine whether antiepileptic drug discontinuation is successful [28]. However, patients who underwent initial lesionectomy more frequently experienced repeat epilepsy surgery, and these patients therefore had a prolonged time to seizure freedom compared with patients with initial ECoG-guided cortical resection. Because shorter duration of epilepsy, earlier age at surgery and seizure freedom correlate with better developmental and behavioral outcomes [5, 38, 49], the time to seizure freedom may be relevant to the decision of whether to pursue lesionectomy or ECoG-guided cortical resection in pediatric patients. Furthermore, each additional operative intervention is associated with a small but measurable risk of surgical morbidity. We suggest that the decision to undertake lesionectomy rather than ECoG-guided cortical resection as the first operative intervention balance the benefit of not resecting potentially functional brain tissue with the disadvantages of increased risk of seizure recurrence, repeat surgery, and the associated surgical morbidity.

Pre-operative variables

We examined several pre-operative variables to determine whether specific patient characteristics predicted seizure outcome. None of the factors were found to significantly affect seizure freedom, including duration of pre-operative epilepsy, lesion location, or seizure type. Some studies have shown that short pre-operative seizure duration leads to increased chance of seizure freedom [11, 12, 15]. Interestingly, patients in these studies underwent lesionectomy alone in all cases. In our population, duration of pre-operative epilepsy did not contribute to seizure outcome, perhaps because perilesional epileptogenic foci were resected in a greater proportion of our patients due to use of ECoG-guided cortical resection.

There is also a suggestion that seizure outcome for patients with temporal lobe lesions may improve with ECoG-guided cortical resection [25, 31]. Although we did not observe a specific benefit of ECoG-guided cortical resection in the subgroup of patients with temporal lobe lesions, we did not specifically examine patients with mesiotemporal lesions, for whom the most benefit from ECoG-guided cortical resection seems to be demonstrated [24, 25].

In general, the most important factor in predicting post-operative seizure control has been found to be completeness of lesion resection [33, 41, 58]. The generally favorable seizure outcome in our patient group, nearly all of who had complete lesion resection (65 out of 67 patients), supports this assertion.

Conclusions

Our results suggest ECoG-guided cortical resection may provide a higher and more sustainable rate of seizure freedom for children with lesional epilepsy. In addition, the risk of surgical morbidity is not increased with ECoG-guided cortical resection, and patients with initial ECoG-guided cortical resection experience fewer repeat surgeries. Given the vulnerability of the developing brain to recurrent seizure activity, ECoG-guided cortical resection should be considered as a possible initial operative intervention for the general population of pediatric patients with lesional epilepsy.

Acknowledgements We would like to acknowledge Dr. Ash Singhal and Dr. Doug Cochrane for their valuable input, as well as Mr. Boris Kuzeljevic for guidance in regards to statistical methodology. Mr. Andrew Battison received funding from the Office for Pediatric Surgical Evaluation and Innovation (OPSEI).

Conflicts of interest The authors declare that they have no conflict of interest.

References

1. Alarcon G, Guy CN, Binnie CD, Walker SR, Elwes RD, Polkey CE (1994) Intracerebral propagation of interictal activity in partial epilepsy: implications for source localisation. J Neurol Neurosurg Psychiatry 57:435–449
2. Asano E, Benedek K, Shah A, Juhasz C, Shah J, Chugani DC, Muzik O, Sood S, Chugani HT (2004) Is intraoperative electrocorticography reliable in children with intractable neocortical epilepsy? Epilepsia 45:1091–1099

3. Asano E, Juhasz C, Shah A, Muzik O, Chugani DC, Shah J, Sood S, Chugani HT (2005) Origin and propagation of epileptic spasms delineated on electrocorticography. Epilepsia 46:1086–1097
4. Awad IA, Rosenfeld J, Ahl J, Hahn JF, Luders H (1991) Intractable epilepsy and structural lesions of the brain: mapping, resection strategies, and seizure outcome. Epilepsia 32:179–186
5. Basheer SN, Connolly MB, Lautzenhiser A, Sherman EM, Hendson G, Steinbok P (2007) Hemispheric surgery in children with refractory epilepsy: seizure outcome, complications, and adaptive function. Epilepsia 48:133–140
6. Benifla M, Rutka JT, Otsubo H, Lamberti-Pasculli M, Elliott I, Sell E, RamachandranNair R, Ochi A, Weiss SK, Snead OC 3rd, Donner EJ (2008) Long-term seizure and social outcomes following temporal lobe surgery for intractable epilepsy during childhood. Epilepsy Res 82:133–138
7. Berger MS, Ghatan S, Haglund MM, Dobbins J, Ojemann GA (1993) Low-grade gliomas associated with intractable epilepsy: seizure outcome utilizing electrocorticography during tumor resection. J Neurosurg 79:62–69
8. Berkovic SF, McIntosh AM, Kalnins RM, Jackson GD, Fabinyi GC, Brazenor GA, Bladin PF, Hopper JL (1995) Preoperative MRI predicts outcome of temporal lobectomy: an actuarial analysis. Neurology 45:1358–1363
9. Blumcke I, Wiestler OD (2002) Gangliogliomas: an intriguing tumor entity associated with focal epilepsies. J Neuropathol Exp Neurol 61:575–584
10. Boel MJ (2004) Behavioural and neuropsychological problems in refractory paediatric epilepsies. Eur J Paediatr Neurol 8:291–297
11. Bourgeois M, Sainte-Rose C, Lellouch-Tubiana A, Malucci C, Brunelle F, Maixner W, Cinalli G, Pierre-Kahn A, Renier D, Zerah M, Hirsch JF, Goutieres F, Aicardi J (1999) Surgery of epilepsy associated with focal lesions in childhood. J Neurosurg 90:833–842
12. Cappabianca P, Alfieri A, Maiuri F, Mariniello G, Cirillo S, de Divitiis E (1997) Supratentorial cavernous malformations and epilepsy: seizure outcome after lesionectomy on a series of 35 patients. Clin Neurol Neurosurg 99:179–183
13. Cascino GD, Kelly PJ, Sharbrough FW, Hulihan JF, Hirschorn KA, Trenerry MR (1992) Long-term follow-up of stereotactic lesionectomy in partial epilepsy: predictive factors and electroencephalographic results. Epilepsia 33:639–644
14. Chang EF, Christie C, Sullivan JE, Garcia PA, Tihan T, Gupta N, Berger MS, Barbaro NM (2010) Seizure control outcomes after resection of dysembryoplastic neuroepithelial tumor in 50 patients. J Neurosurg Pediatr 5:123–130
15. Cohen DS, Zubay GP, Goodman RR (1995) Seizure outcome after lesionectomy for cavernous malformations. J Neurosurg 83:237–242
16. Cohen-Gadol AA, Wilhelmi BG, Collignon F, White JB, Britton JW, Cambier DM, Christianson TJ, Marsh WR, Meyer FB, Cascino GD (2006) Long-term outcome of epilepsy surgery among 399 patients with nonlesional seizure foci including mesial temporal lobe sclerosis. J Neurosurg 104:513–524
17. Elger CE, Helmstaedter C, Kurthen M (2004) Chronic epilepsy and cognition. Lancet Neurol 3:663–672
18. Eliashiv SD, Dewar S, Wainwright I, Engel J Jr, Fried I (1997) Long-term follow-up after temporal lobe resection for lesions associated with chronic seizures. Neurology 48:621–626
19. Elwes RD, Dunn G, Binnie CD, Polkey CE (1991) Outcome following resective surgery for temporal lobe epilepsy: a prospective follow up study of 102 consecutive cases. J Neurol Neurosurg Psychiatry 54:949–952
20. Engel J Jr (1996) Surgery for seizures. N Engl J Med 334:647–652
21. Ferroli P, Casazza M, Marras C, Mendola C, Franzini A, Broggi G (2006) Cerebral cavernomas and seizures: a retrospective study on 163 patients who underwent pure lesionectomy. Neurol Sci 26:390–394
22. Freitag H, Tuxhorn I (2005) Cognitive function in preschool children after epilepsy surgery: rationale for early intervention. Epilepsia 46:561–567
23. Giulioni M, Galassi E, Zucchelli M, Volpi L (2005) Seizure outcome of lesionectomy in glioneuronal tumors associated with epilepsy in children. J Neurosurg 102:288–293
24. Giulioni M, Gardella E, Rubboli G, Roncaroli F, Zucchelli M, Bernardi B, Tassinari CA, Calbucci F (2006) Lesionectomy in epileptogenic gangliogliomas: seizure outcome and surgical results. J Clin Neurosci 13:529–535
25. Giulioni M, Rubboli G, Marucci G, Martinoni M, Volpi L, Michelucci R, Marliani AF, Bisulli F, Tinuper P, Castana L, Sartori I, Calbucci F (2009) Seizure outcome of epilepsy surgery in focal epilepsies associated with temporomesial glioneuronal tumors: lesionectomy compared with tailored resection. J Neurosurg 111:1275–1282
26. Haglund MM, Berger MS, Kunkel DD, Franck JE, Ghatan S, Ojemann GA (1992) Changes in gamma-aminobutyric acid and somatostatin in epileptic cortex associated with low-grade gliomas. J Neurosurg 77:209–216
27. Hamiwka L, Jayakar P, Resnick T, Morrison G, Ragheb J, Dean P, Dunoyer C, Duchowny M (2005) Surgery for epilepsy due to cortical malformations: ten-year follow-up. Epilepsia 46:556–560
28. Hemb M, Velasco TR, Parnes MS, Wu JY, Lerner JT, Matsumoto JH, Yudovin S, Shields WD, Sankar R, Salamon N, Vinters HV, Mathern GW (2010) Improved outcomes in pediatric epilepsy surgery: the UCLA experience, 1986–2008. Neurology 74:1768–1775
29. Hermann BP, Seidenberg M, Bell B (2002) The neurodevelopmental impact of childhood onset temporal lobe epilepsy on brain structure and function and the risk of progressive cognitive effects. Prog Brain Res 135:429–438
30. Holmes GL, Chevassus-Au-Lois N, Sarkisian MR, Ben-Ari Y (1997) Consequences of recurrent seizures during development. Rev Neurol 25:749–753
31. Jooma R, Yeh HS, Privitera MD, Gartner M (1995) Lesionectomy versus electrophysiologically guided resection for temporal lobe tumors manifesting with complex partial seizures. J Neurosurg 83:231–236
32. Juhasz C, Chugani DC, Muzik O, Watson C, Shah J, Shah A, Chugani HT (2000) Electroclinical correlates of flumazenil and fluorodeoxyglucose PET abnormalities in lesional epilepsy. Neurology 55:825–835
33. Khajavi K, Comair YG, Wyllie E, Palmer J, Morris HH, Hahn JF (1999) Surgical management of pediatric tumor-associated epilepsy. J Child Neurol 14:15–25
34. Khan RB, Boop FA, Onar A, Sanford RA (2006) Seizures in children with low-grade tumors: outcome after tumor resection and risk factors for uncontrolled seizures. J Neurosurg 104:377–382
35. Kim SK, Wang KC, Hwang YS, Kim KJ, Cho BK (2001) Intractable epilepsy associated with brain tumors in children: surgical modality and outcome. Childs Nerv Syst 17:445–452
36. Kloss S, Pieper T, Pannek H, Holthausen H, Tuxhorn I (2002) Epilepsy surgery in children with focal cortical dysplasia (FCD): results of long-term seizure outcome. Neuropediatrics 33:21–26
37. Kuruvilla A, Flink R (2003) Intraoperative electrocorticography in epilepsy surgery: useful or not? Seizure 12:577–584
38. Loddenkemper T, Holland KD, Stanford LD, Kotagal P, Bingaman W, Wyllie E (2007) Developmental outcome after epilepsy surgery in infancy. Pediatrics 119:930–935
39. Montes JL, Rosenblatt B, Farmer JP, O'Gorman AM, Andermann F, Watters GV, Meagher-Villemure K (1995) Lesionectomy of MRI detected lesions in children with epilepsy. Pediatr Neurosurg 22:167–173

40. Packer RJ, Sutton LN, Patel KM, Duhaime AC, Schiff S, Weinstein SR, Gaillard WD, Conry JA, Schut L (1994) Seizure control following tumor surgery for childhood cortical low-grade gliomas. J Neurosurg 80:998–1003
41. Paolicchi JM, Jayakar P, Dean P, Yaylali I, Morrison G, Prats A, Resnik T, Alvarez L, Duchowny M (2000) Predictors of outcome in pediatric epilepsy surgery. Neurology 54:642–647
42. Pilcher WH, Silbergeld DL, Berger MS, Ojemann GA (1993) Intraoperative electrocorticography during tumor resection: impact on seizure outcome in patients with gangliogliomas. J Neurosurg 78:891–902
43. Plioplys S, Dunn DW, Caplan R (2007) 10-year research update review: psychiatric problems in children with epilepsy. J Am Acad Child Adolesc Psychiatry 46:1389–1402
44. Rassi-Neto A, Ferraz FP, Campos CR, Braga FM (1999) Patients with epileptic seizures and cerebral lesions who underwent lesionectomy restricted to or associated with the adjacent irritative area. Epilepsia 40:856–864
45. Sakuta R, Otsubo H, Nolan MA, Weiss SK, Hawkins C, Rutka JT, Chuang NA, Chuang SH, Snead OC 3rd (2005) Recurrent intractable seizures in children with cortical dysplasia adjacent to dysembryoplastic neuroepithelial tumor. J Child Neurol 20:377–384
46. Sinclair DB, Aronyk KE, Snyder TJ, Wheatley BM, McKean JD, Bhargava R, Hoskinson M, Hao C, Colmers WF, Berg M, Mak W (2003) Pediatric epilepsy surgery at the University of Alberta: 1988–2000. Pediatr Neurol 29:302–311
47. Spencer S, Huh L (2008) Outcomes of epilepsy surgery in adults and children. Lancet Neurol 7:525–537
48. Sperling MR, Nei M, Zangaladze A, Sharan AD, Mintzer SE, Skidmore C, Evans JG, Schilling CA, Asadi-Pooya AA (2008) Prognosis after late relapse following epilepsy surgery. Epilepsy Res 78:77–81
49. Steinbok P, Gan PY, Connolly MB, Carmant L, Barry Sinclair D, Rutka J, Griebel R, Aronyk K, Hader W, Ventureyra E, Atkinson J (2009) Epilepsy surgery in the first 3 years of life: a Canadian survey. Epilepsia 50:1442–1449
50. Sugano H, Shimizu H, Sunaga S (2007) Efficacy of intraoperative electrocorticography for assessing seizure outcomes in intractable epilepsy patients with temporal-lobe-mass lesions. Seizure 16:120–127
51. Takahashi A, Hong SC, Seo DW, Hong SB, Lee M, Suh YL (2005) Frequent association of cortical dysplasia in dysembryoplastic neuroepithelial tumor treated by epilepsy surgery. Surg Neurol 64:419–427
52. Tromp SC, Weber JW, Aldenkamp AP, Arends J, vander Linden I, Diepman L (2003) Relative influence of epileptic seizures and of epilepsy syndrome on cognitive function. J Child Neurol 18:407–412
53. Van Gompel JJ, Rubio J, Cascino GD, Worrell GA, Meyer FB (2009) Electrocorticography-guided resection of temporal cavernoma: is electrocorticography warranted and does it alter the surgical approach? J Neurosurg 110:1179–1185
54. Van Oijen M, De Waal H, Van Rijen PC, Jennekens-Schinkel A, van Huffelen AC, Van Nieuwenhuizen O (2006) Resective epilepsy surgery in childhood: the Dutch experience 1992–2002. Eur J Paediatr Neurol 10:114–123
55. Wennberg R, Quesney LF, Lozano A, Olivier A, Rasmussen T (1999) Role of electrocorticography at surgery for lesion-related frontal lobe epilepsy. Can J Neurol Sci 26:33–39
56. Wiebe S, Blume WT, Girvin JP, Eliasziw M (2001) A randomized, controlled trial of surgery for temporal-lobe epilepsy. N Engl J Med 345:311–318
57. Wolf HK, Roos D, Blumcke I, Pietsch T, Wiestler OD (1996) Perilesional neurochemical changes in focal epilepsies. Acta Neuropathol 91:376–384
58. Zaatreh MM, Firlik KS, Spencer DD, Spencer SS (2003) Temporal lobe tumoral epilepsy: characteristics and predictors of surgical outcome. Neurology 61:636–641
59. Zupanc ML, Rubio EJ, Werner RR, Schwabe MJ, Mueller WM, Lew SM, Marcuccilli CJ, O'Connor SE, Chico MS, Eggener KA, Hecox KE (2010) Epilepsy surgery outcomes: quality of life and seizure control. Pediatr Neurol 42:12–20