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Invasive EEG-electrodes in presurgical evaluation of epilepsies: Systematic analysis of implantation-, video-EEG-monitoring- and explantation-related complications, and review of literature

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ABSTRACT

Introduction: Stereoelectroencephalography (sEEG) is a diagnostic procedure for patients with refractory focal epilepsies that is performed to localize and define the epileptogenic zone. In contrast to grid electrodes, sEEG electrodes are implanted using minimal invasive operation techniques without large craniotomies. Previous studies provided good evidence that sEEG implantation is a safe and effective procedure; however, complications in asymptomatic patients after explantation may be underreported. The aim of this analysis was to systematically analyze clinical and imaging data following implantation and explantation.

Results: We analyzed 18 consecutive patients (mean age: 30.5 years, range: 12–46; 61% female) undergoing invasive presurgical video-EEG monitoring via sEEG electrodes (n = 167 implanted electrodes) over a period of 2.5 years with robot-assisted implantation. There were no neurological deficits reported after implantation or explantation in any of the enrolled patients. Postimplantation imaging showed a minimal subclinical subarachnoid hemorrhage in one patient and further workup revealed a previously unknown factor VII deficiency. No injuries or status epilepticus occurred during video-EEG monitoring. In one patient, a seizure-related asymptomatic cross break of two fixation screws was found and led to revision surgery. Unspecific symptoms like headaches or low-grade fever were present in 10 of 18 (56%) patients during the first days of video-EEG monitoring and were transient. Postexplantation imaging showed asymptomatic and small bleedings close to four electrodes (2.8%).

Conclusion: Overall, sEEG is a safe and well-tolerated procedure. Systematic imaging after implantation and explantation helps to identify clinically silent complications of sEEG. In the literature, complication rates of up to 4.4% in sEEG and in 49.9% of subdural EEG are reported; however, systematic imaging after explantation was not performed throughout the studies, which may have led to underreporting of associated complications.

1. Introduction

Epilepsy affects more than 50 million people worldwide and is characterized by repeated seizures [1]. People with epilepsy have a significantly increased mortality and morbidity rate and suffer from social stigma [2, 3]. Recurring seizures impose a high burden on patients, caregivers, and healthcare systems [4–7]. Despite optimal anticonvulsant therapy, approximately 30% of patients with epilepsy have seizures that do not respond to antiepileptic drugs (AEDs) and are categorized as drug refractory [8, 9]. These patients have a poor chance for seizure freedom due to AEDs of approximately 5% to 15% with every new AED [9–11], but may profit from epilepsy surgery. During the last five decades, epilepsy surgery rapidly improved and became a readily available and cost-effective option for drug-refractory epilepsies in developed countries [12, 13]. Invasive EEG recording techniques are now widely used to locate the epileptogenic zone by defining the irritative and

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seizure onset zones [12, 14]. Regarding invasive EEG recordings, three different approaches are available: (1) grid electrodes, (2) stereoelectroencephalography (sEEG) electrodes, or (3) a combination of both systems — each with their own advantages and disadvantages [12, 14]. Grid electrodes can cover large cortical areas of the brain convexity with high local resolution, but have the disadvantage of a poor sampling of deep cortical areas. Moreover, they require large craniotomies, which are often burdensome for the patients. [14]. A combination of both techniques seems to be the best option in regard of depth and local resolution, but can be challenging due to methodical reasons like brain shift [15]. Because of better tolerability with shorter implantation and explantation times, less wound surface, and shorter inpatient stay, sEEG electrodes are increasingly employed for presurgical EEG evaluation [12].

Regarding complications of sEEG, a large meta-analysis from Mullin et al. [16] analyzed 57 publications with 2624 patients from 1983 to 2015 and a total of 22,085 implanted electrodes. The most common complications were hemorrhagic with subdural hematoma (0.4%; SDH), epidural hematoma (0.3%; EDH), or intracerebral hemorrhage (0.7%; ICH) totaling in a pooled prevalence of 1.0% per electrode. In total, 11 (11/24, 45.8%) of these hemorrhages led to surgical evacuation, and three people died from ICHs (3/2624; 0.1%). Infections were reported with a pooled prevalence of 0.8%, and cerebral abscesses were the most common focus. In 1.4% of patients, superficial wound infections were reported. Only four of 2624 cases developed meningitis after implantation (pooled prevalence: 0.15%). Hardware-related complications were reported in several patients and were mostly due to malpositioning (14/2624; pooled prevalence: 0.6%) or implant malfunction (11/2624; 0.4%). A total of 0.6% (11/2624, pooled prevalence) of the patients had permanent or transient neurological deficits after implantation. Other complications (thrombosis, pulmonary embolism, urinary tract infection, allergic reactions, and psychiatric changes) occurred in 1.1% (pooled prevalence). In total, 121 surgical complications related to sEEG insertion, and monitoring were reported, which equals to a pooled prevalence of 1.3% [16]. The design and periprocedural settings (duration and method of implantation, antibiotics) differed substantially among the included studies. Systematic reporting regarding the impact of electrode explantation on complications is rarely provided in the literature [16–27].

The aim of this study was to analyze complications in patients undergoing invasive video-EEG monitoring with robot-assisted implanted sEEG electrodes in patients undergoing postexplantation computed tomography (CT) scans.

2. Methods

2.1. Patient identification, data acquisition, and ethics

Patients were identified retrospectively via a hospital database search for the B13Z DRG coding for invasive epilepsy diagnostics between 9/2014 and 01/2018. Data regarding patients' characteristics, medical history, epilepsy syndrome, anticonvulsant treatment, surgical procedures, implanted electrodes, complications, and radiological diagnostics were systematically obtained and transferred to datasheets. All consecutive patients with solely implanted sEEG electrodes were included into the analysis. Patients with additional subdural grid electrodes were excluded. This study was approved by the local ethics committee.

2.2. Rating of adverse events and complications

Identified complications were categorized as infection, hemorrhage, intracerebral edema, neurological deficit, material failure, and others. Unspecific and conventional side effects after electrode implantation or removal (mild meningeal syndrome, low-grade fever, sporadic headache, noncerebral infections, discreet branch channel bleedings after sEEG removal) were considered as expected mild functional disturbances and not as complications. Complications were categorized according to two established grading systems for periprocedural complications during invasive Video-EEG monitoring [28, 29] allowing comparison with previous studies [30]. Hamer et al. used a four-step scale grading system. Grade 1 described a transient complication without requirement of treatment; grade 2, a transient complication that required treatment, but resolved completely; grade 3, a complication leading to a permanent neurological deficit despite treatment; and grade 4, death related to the invasive diagnostic procedure. In our cohort, patients without complications were categorized as grade 0, as described previously [28, 30].

A second grading system used by Wellmer et al. separates into minor and major complications [28]. Major complications were defined as complications leading to medical or surgical treatment or a new onset neurological deficit. All other complications were categorized as minor.

2.3. Procedural aspects

2.3.1. sEEG implantation and explantation

All patients underwent a CT and/or magnetic resonance imaging (MRI) scan as base for neuronavigation. Number of electrodes and placement were determined by a consensus between an expert board of neurosurgeons and epileptologists. Trajectories for electrode placement were planned using a special navigation software for robotic surgery assistance (Brain Robotic Surgery Asistant (ROSA), formerly MedTech, Montpellier, France, now Zimmer Biomet, Warsaw, IN, USA), and a fusion of preoperative CT and MRI scans was performed to achieve a representative recording of the potential epileptogenic zone in consideration of anatomical limitations (i.e., blood vessels, ventricular system). All patients received a single shot of 2-g ceftriaxone i.v. before operation to prevent periprocedural infections; sEEG electrodes (Ad-Tech Medical Instrument Corporation, Oak Creek, WI, USA) were implanted using ROSA device in general anesthesia by experienced neurosurgeons. It was recently shown that ROSA-assisted electrode placement is a highly precise and reliable method for sEEG implantation [31–33]. Patients were operated in supine position, the head fixed in a clamp (DORO, Prodemics, Freiburg, Germany). The head was mapped using a robotic laser scan of the skin surface and referenced to the preoperative CT and MRI scan. Thereafter the skin surface of the planned electrodes was marked, shaved, disinfected, and sterile draped. The depth of the borehole was measured on the planning CT or MRI along the trajectory. The robot positioned a cannulated platform forward in the depth of the calculated borehole distance, which held back the twist drill, and the borehole (2.1 mm) was manually performed with a twist drill (Salcman Twist Drill, Elekta, Stockholm, Sweden). The dura, the arachnoidea, and the cortex surface were coagulated with monopolar coagulation (Force FX Electrosurgical Generator, Valleylab, Colorado, USA). An anchor bolt was placed. A blunt stylet (0.85 mm) was inserted, followed by the implantation of the electrodes. The premeasured electrode (Spencer Probe Depth Electrodes, 1.1-mm diameter, Ad-Tech Medical, Wisconsin, USA) was implanted, and fixed with the adjacent screw to the anchor bolt. All implantation steps were completed before heading for the next electrode to avoid cerebrospinal fluid (CSF) loss. After surgery, the final position of electrodes was identified on a postoperative CT scan, which was merged with the preoperative MRI scan for further analysis. A routine CT scan after electrode explantation was established after the introduction of an internal procedure protocol. CSF leaks were not observed, however would have been evident on dressing change every two days.

2.3.2. Video-EEG monitoring

Continuous video-EEG from both sEEG and scalp electrodes was recorded at 2048 Hz with a Micromed system (Micromed S.p.A., Mogliano Veneto, Treviso, Italy). Patients were under continuous 24-h surveillance by medical technical assistants and regularly visited by epileptologists at least once daily, according to guideline recommendations [34]. All patients received 2.000- to 4.000-IE low molecular weight heparin (LMWH, enoxaparin) to avoid deep venous thrombosis. As backup medication in case of prolonged or frequent seizures, midazolam nasal spray,

or intravenous lorazepam was used [35]. After video-EEG monitoring and stimulation, patients' sEEG electrodes were explanted. Epilepsy surgery was performed no earlier than 30 days after explantation to allow time for an interdisciplinary case discussion and informed consent into the resection.

2.3.3. Data entry and statistical analysis

Data entry and analysis were performed using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). A double-entry procedure was employed to assure a high level of data accuracy. Statistical analyses were performed using IBM SPSS Statistics 22 (IBM Corporation, Armonk, NY, USA) and BiAS for Windows Version 10.01 (epsilon-Verlag, Frankfurt/Main, Germany). Data are presented as mean ± standard deviation (SD), minimum and maximum, or percentages where appropriate. Comparisons between groups were performed using the appropriate parametric and nonparametric tests. Figures were made using GraphPad PRISM (GraphPad Software Inc., La Jolla, CA, USA) and Pixelmator (Pixelmator Team, Vilnius, Lithuania).

3. Results

3.1. Characteristics of the sEEG cohort

A total number of 18 patients (61% female) were included in this retrospective analysis. Mean age was 30.5 years (SD: 9.4; range: 12–46) and the mean disease duration was 16.6 years (SD: 8.3; range: 1–28). All patients failed at least 2 AEDs (mean: 2.3, SD: 0.5; range: 2–8) in adequate doses and fulfilled the International League Against Epilepsy (ILAE) criteria for pharmacoresistant epilepsy [9]. When admitted for sEEG monitoring all patients were on an anticonvulsant polytherapy, 67% on two and 33% on three AEDs. The most common AEDs were lamotrigine (53%), levetiracetam (53%), zonisamide (39%), oxcarbazepine (22%), and brivaracetam (22%). Only one patient took carbamazepine (6%) and one valproate (6%). Except for one patient (6%), who had a combined idiopathic generalized and focal epilepsy (FE), all patients had FE (94%). An equal number of seven subjects had a right or left hemispheric epilepsy (38.9%), in four cases bilateral epilepsy was reported (22%). For a detailed list of sociodemographic and clinical characteristics please refer to Table 1. Five patients of the cohort (27.8%) were admitted for epilepsy surgery and additional three (16.7%) are planned for surgery, one for minimal invasive thermal ablation of a periventricular heterotopia [36]. Long-term follow-up was available in four patients over at least 12 months, three patients are seizure-free (Engel I), and one patient reported ongoing seizures (Engel IVb). Neuropsychological follow-up revealed stable cognitive functions in all patients that underwent surgery without any new postoperative deficits. The remaining nine patients were not suitable for resective epilepsy surgery. In three of them a vagal nerve stimulator (VNS) was implanted, another is planned for. In the subgroup, which did not qualify for epilepsy surgery, no delayed manifestation of sEEG-related long-term adverse effects was reported. The mean follow-up time in this subgroup was 8.7 months (±7.1, range: 3–23).

3.2. Characteristics of sEEG implantations

We analyzed a total number of 167 electrodes with a mean number of 9.3 electrodes per patient (SD: 2.5, range: 6–13). Most subjects

Table 1
Sociodemographic and clinical characteristics of the cohort.

	Total n = 18
Age in years[a]	30.5 ± 9.4 range: 12–46
Disease duration (years)[a]	14.6 ± 8.3 range: 1–28
Sex	% (n)
Male	38.9 (7)
Female	61.1 (11)
Antiepileptic drugs (AEDs)	
Mean number[a]	2.3 ± 0.5 range: 2–3
2 AEDs	66.7 (12)
3 AEDs	33.3 (6)
Previously failed AEDs[a]	4.8 ± 1.7 range: 2–8
Prescribed AEDs	% (n)
Lamotrigine	52.6 (10)
Levetiracetam	52.6 (10)
Zonisamide	38.9 (7)
Oxcarbazepine	22.2 (4)
Brivaracetam	22.2 (4)
Lacosamide	5.6 (1)
Carbamazepine	5.6 (1)
Valproate	5.6 (1)
Epilepsy syndrome	% (n)
Focal	94.4 (17)
Focal + generalized	5.6 (1)
Hemisphere	
Right	38.9 (7)
Left	38.9 (7)
Bilateral	22.2 (4)
Lobe	
Temporal	50.0 (9)
Left-hemispheric	22.2 (4)
Right-hemispheric	11.1 (2)
Bilateral	16.7 (3)
Frontal	16.7 (3)
Occipital	5.6 (1)
Parietal	5.6 (1)
Multilobar	22.2 (4)

AED = antiepileptic drug.
[a] Mean ± standard deviation.

Table 2
Characteristics of sEEG-implantation within the cohort.

Electrodes and contacts	
Total no. of sEEG electrodes	167
Total no. of sEEG contacts	1602
Mean no. of electrodes/patient[a]	9.3 ± 2.5 range: 6–13
Mean no. of contacts/electrode[a]	9.6 ± 2.2 range: 4–14
Mean no. of contacts/patient[a]	89.0 ± 24.4 range: 43–123
Mean duration of implantation in days[a]	9.6 ± 1.6 range: 3–11
Mode of implantation	**% (n)**
Unilateral	55.6 (10)
Bilateral	44.4 (8)
Electrode location/patient	(Total n = 18)
Frontal lobe	44.4 (8)
Temporal lobe	38.9 (7)
Temporal and other lobes	16.6 (3)
Electrode location/electrodes	(Total n = 167)
Frontal lobe	31.7 (53)
Temporal lobe	65.2 (109)
Seizures and semiology	
Total	248
Mean no./patient[a]	13.8 ± 16.5 range: 3–61
SPS/CPS	235
Patients with SPS/CPS only	11
Mean no./patient[a]	13.1 ± 16.8 range: 1–61
GTCS	13
Mean no./patient[a]	0.7 ± 1.2 range: 0–5
Patients with GCTS and SPS/CPS	7

sEEG = stereoelectroencephalography, SPS = simple partial seizure, CPS = complex partial seizure, GTCS = generalized tonic–clonic seizure.
[a] Mean ± standard deviation.

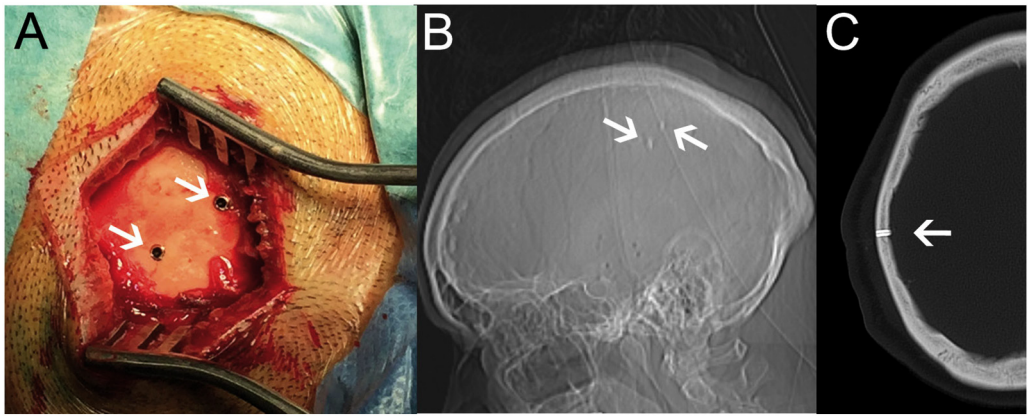

Fig. 1. Illustration of two broken fixation screws in an asymptomatic patient after GTCS with forced head hyperextension. Fragments of the screws are marked with a white arrow at surgical site during a second operation (A), CT after explantation of sEEG electrodes showing the fragments in a sagittal CT localizer (B), and (C) axial scan. All screw fragments were completely removed in a second operation without transient or persisting neurological deficits.

received a unilateral (56%) implantation to evaluate structures within the temporal (39%) or frontal lobe (44%). The 167 implanted electrodes comprised 1602 contacts with a mean number of 9.6 contacts per electrode (SD: 2.2, range: 4–14) and a mean number of 89 contacts per patient (SD: 24.4; range: 43–123). The mean duration of implantation was 9.6 days (SD: 1.6; range: 3–11). During monitoring, a mean number of 13.8 seizures (SD: 16.5; range: 3–61) was observed, mostly simple partial or complex partial seizures (94.8%). Overall, 13 generalized tonic–clonic seizures (GTCS) were reported (13/248, 5.2%). Seven patients (38.9%) had GTCS and simple partial (SPS) and/or complex partial seizures (CPS) during the monitoring. No patient presented isolated GTCS. All remaining patients (n = 11, 61.1%) had only SPS and/or CPS. For more details on characteristics of sEEG implantation, monitoring, and seizures, see Table 2.

3.3. Periprocedural complications after sEEG implantation

There were no neurological deficits reported after implantation or explantation in any of the enrolled patients. Therefore, all documented periprocedural complications have to be classified as incidental findings.

One patient with negative patient history for hemorrhages or major bleedings showed a considerably increased bleeding propensity during implantation. Imaging after implantation showed a clinically silent subarachnoid hemorrhage (SAH) and a decrease in prothrombin time (PT; initially 71%, minimum: 48%) that could be explained by an isolated previously unknown factor VII deficiency. Before explantation, prothrombin complex concentrate (PCC) was substituted without any further bleeding complications. Additional CT scans showed a timely

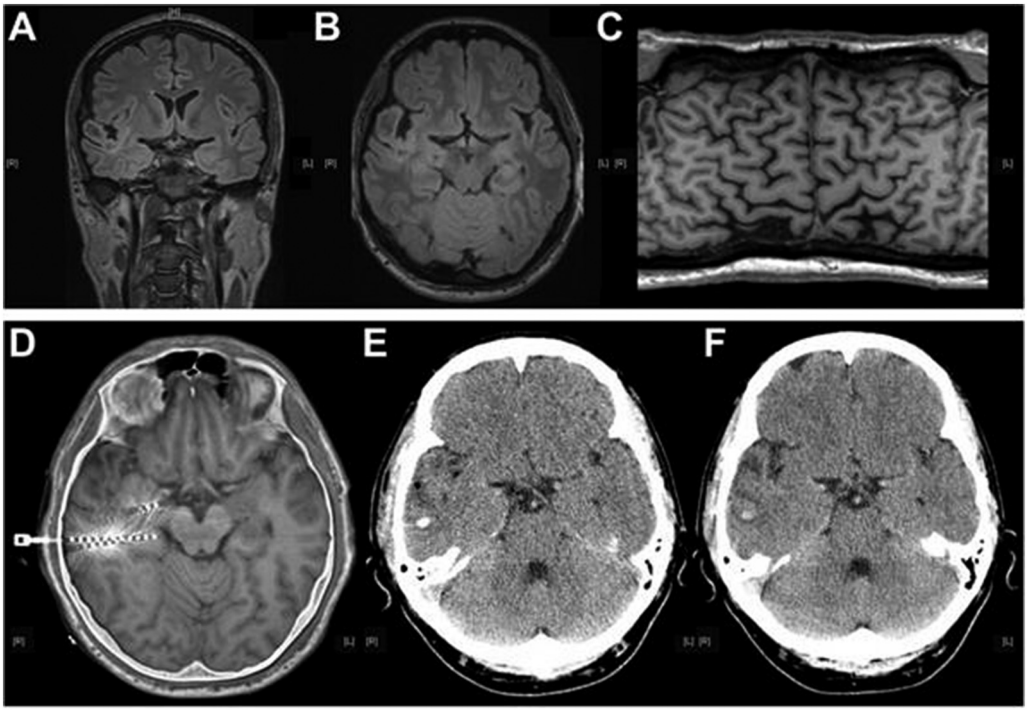

Fig. 2. Illustrative case of a 45-year-old patient with cystic malformation of the right superior and middle temporal gyrus and refractory structural temporal lobe epilepsy (A: coronal, B: transversal, C: Mercator map); surface-EEG recordings revealed a right temporolateral irritative and seizure onset zone within the structural lesion; sEEG was performed using seven electrodes ahead of respective surgery to evaluate the involvement of mesiotemporal structures (D: transversal fusion of MRI and postimplantation CT scan). Postexplantation CT revealed an asymptomatic limited bleeding localized close to the branch channel of one electrode (volume: 0.15 ml, E), which was in timely resorption 4 days after explantation (F). The patient is currently planned for lesionectomy.

resorption of the SAH. The patient reported sporadic unspecific headache responding well to nonsteroidal anti-infalmmatory drugs (NSAIDs). No other major or minor complications were registered after sEEG implantation.

3.4. Complications during video-EEG monitoring

Two parietal fixation screws consisting of titanium broke, probably during a GTCS with repetitive head knocking against the padded bed safety guard. The patient did not show any symptoms or deficits except sporadic unspecific headache responding well to NSAID. During explantation, both fractured screws were discovered as broken on the calvaria level and could not be instantaneously removed. While all unaffected electrodes were explanted without any difficulty, the remaining fragments were removed in a second operation (Fig. 2).

In line with other publications, we found a C-reactive protein (CRP) peak (mean: 1.5 mg/dl [15 g/l] ± 1.6; range: 0.0–5.3; reference: <0.5 mg/dl) 2–3 days after surgery (maximum at mean of 2.0 days ± 0.7; range: 1–3). There were no reported cases of meningitis, abscess or local wound infection. A relevant leukocytosis was observed in three patients (max: 13.1/nl, reference: <11.4/nl, see Fig. 1). A total number of 16 unspecific side effects was reported in 10 patients during video-EEG-monitoring. Sporadic headache was the most common symptom (n = 10; 55.6%), followed by branch channel bleedings (n = 4; 22.2%), transient low-grade fever (n = 1; 5.6%; >38.0 °C in only one measurement), and noncerebral infections (n = 1; 5.6%). All headache syndromes were uncharacteristic and transient and responded well to NSAIDs. One patient developed mild pneumonia after extubation, which was sufficiently treated with antibiotics.

3.5. Periprocedural complications after sEEG explantation

In 16 of all patients, a CT scan was performed after explantation and showed asymptomatic limited bleeding close to branch channels in four of 141 (2.8%) electrodes, with a mean volume of 2.3 ml (SD: 1.0, range: 0.9–3.8) and associated locally limited intracerebral edema. Additional CT scans showed a timely resorption in all cases. In two patients, an isolated, asymptomatic intracerebral edema close to a branch channel was found after explantation. All unspecific and specific complications after sEEG implantation and explantation, as well as during video-EEG monitoring, are displayed in detail in Table 3.

Using the established grading systems for sEEG according to Wellmer and Hamer [28, 30], minor complications (Hamer grade 1) were observed in 4.2% and major complications (Hamer grade 2) in 1.4% per electrode. The only major complication occurring during video monitoring was the fracture of two fixation screws during a GTCS. Most of the minor complications (5/6) occurred after explantation. Overall, 95.8% of the 167 sEEG electrodes were implanted and explanted without any complications (see Table 4). There were no grade 3 or 4 complications according to Hamer et al., and no patient died during sEEG monitoring.

Table 3
Rate of complications during sEEG monitoring per patient and electrode.

Unspecific[a]	Total % (n)	Implantation % (n[b])	Monitoring % (n[b])	Explantation % (n[c])
Patients reporting any complications[c]	55.6 (10)	0.0 (0)	55.6 (10)	16.7 (3)
Total	88.9 (16)	0.0 (0)	50.0 (9)	38.9 (7)
Low-grade fever	5.6 (1)	0.0 (0)	5.6 (1)	0.0 (0)
Sporadic headache	55.6 (10)	0.0 (0)	38.9 (7)	16.7 (3)
Noncerebral infections	5.6 (1)	0.0 (0)	5.6 (1)	0.0 (0)
Branch channel bleedings	22.2 (4)	0.0 (0)	0.0 (0)	25.0 (4)[d]

sEEG-related/electrode	Total % (n)	Implantation % (n[b])	Monitoring % (n[d])	Explantation % (n[c,d])
Intracerebral bleedings[b,d]				
Total	3.0 (5)	0.6 (1)	0.0 (0)	2.8 (4)
Subarachnoid	0.6 (1)	0.6 (1)	0.0 (0)	0.0 (0)
Subdural	0.0 (0)	0.0 (0)	0.0 (0)	0.0 (0)
Intracerebral	2.4 (4)	0.0 (0)	0.0 (0)	2.8 (4)
Edema[b,d]				
With bleeding	1.8 (3)	0.0 (0)	0.0 (0)	2.1 (3)
Without bleeding	1.2 (2)	0.0 (0)	0.0 (0)	1.4 (2)
Material failure[b]				
Per electrode	1.2 (2)	0.0 (0)	1.4 (2)	0.0 (0)

[a] Mild meningeal syndrome, low-grade fever (>38.0 °C in only one measurement), sporadic headache, noncerebral infections, discreet branch channel bleedings after removal of stereoelectroencephalography electrodes (sEEG).
[b] Per 167 implanted electrodes.
[c] Patients with unspecific complications after implantation and explantation were only mentioned once.
[d] Postexplantation CT scan available in 16 of 18 patients.

4. Discussion

Invasive EEG monitoring is an important diagnostic method in patients with pharmacoresistant focal epilepsies, and the use of sEEG electrodes represents a well-established, minimally invasive, and safe method from both patient and professional view.

In our cohort of 18 consecutive patients, we calculated a risk of 1.2% per electrode (or 6% per patient) for major complications with clinical consequence. These findings are in line with a recent publication showing a risk of 0.8% per electrode for major and total complications [37] (calculated after published data according to Wellmer et al. [28]). The risk for minor complications without clinical consequences in our cohort was estimated to 4.2% per electrode. Focusing on major complications with immediate consequences for the patient, our results are in line with previous studies reporting major complications in up to 4.3% per electrode [30, 38–41]. In line with other publications, hemorrhagic complications were the most common in our cohort with 3.0% per electrode. Fortunately, we did not observe any case of sEEG-related severe infection or anesthesia shock, as previously described [30]. The only major complication was a case of material failure in which two fixation screws broke on the calvaria level, equal to a risk of 1.2% per electrode. Due to the immediate observation of a lost turning resistance and missing parts of the screw during explantation, both screws probably broke during a GCTS with repetitive head contact to the padded bed barrier. The electrodes attached to these screws were fixed on the right parietal region of the scalp, the most exposed ones in this patient during the seizure. However, periprocedural complications due to material failure are occasionally reported and usually result in a second or enlarged surgery [30, 42]. To avoid fractures of material

Table 4
Grading of sEEG-related complications per electrode.

Classification after Wellmer et al. [28]	Total % (n[c])	Implantation % (n[c])	Monitoring % (n[d])	Explantation % (n[d])
Minor	4.2 (7)	0.6 (1)	0.0 (0)	4.2 (6)
Major	1.2 (2)	0.0 (0)	1.4 (2)	0.0 (0)

Classification after Hamer et al. [29]	Total % (n[c])	Implantation % (n[c])		Explantation % (n[c])
- 1 -	4.2 (7)	0.6 (1)	0.0 (0)	4.2 (6)
- 2 -	1.2 (2)	0.0 (0)	1.4 (2)	0.0 (0)
- 3 -	0.0 (0)	0.0 (0)	0.0 (0)	0.0 (0)
- 4 -	0.0 (0)	0.0 (0)	0.0 (0)	0.0 (0)

[c] Per 167 implanted electrodes.
[d] Data available for 141 electrodes.

Table 5
Review of literature on sEEG complications.

Study			Cohort			Electrodes				Prophylaxis		Imaging
Authors	Year	Design	n	Male/female ratio	Mean age (y)	Total number	Mean number per patient	Robot-assisted implantation	Mean duration (d)	Intraoperative antibiotics	Thrombosis	Regular postimplantation
Blauwbomme et al. [50]	2013	r	17	0.7	32.6	223	13	Yes	–	–	–	MRI
Cardinale et al. [21]	2013	r	500	–	–	6496	13.0	Yes	–	–	–	CT
Vadera et al. [51]	2013	r	14	1.0	39.7	–	–	–	–	–	–	CT
Dylgjeri et al. [52]	2014	r	10	1.0	6.6	115	11.5	Yes	–	–	–	CT
Dorfmüller et al. [53]	2014	r	19	–	3.7	–	11.6	Yes	5.4	–	–	–
Gonzales-Martinez et al. [23]	2014	p	122	1.1	33.0	1586	13.0	No	7.0	–	–	CT
Gonzales-Martinez et al. [54]	2014	r	30	1.5	14.9	402	13.4	No	9.7	–	–	CT
Nowell et al. [55]	2014	r	22	1.8	32.6	187	8.5	Yes	–	–	–	CT
Serletis et al. [33]	2014	p	200	0.9	32.0	2663	13.3	Yes	9.0	–	–	–
Taussig et al. [56]	2014	p	65	–	8.2	748	5.4	No	5.4	–	–	–
Munyon et al. [27]	2015	r	20	0.8	28.6	254	12.7	Yes	8.8	–	–	CT/MRI
Mathon et al. [30] (sEEG only)	2015	r	128	1.1	32.4	1201	9.4	No	15.6	Yes	–	CT
Gonzales-Martinez et al. [59]	2016	p	101	1.4	33.2	1245	12.5	Yes	8.0	–	–	–
Salado et al. [57]	2017	r	99	1.3	30.0	1292	13.1	No	–	–	–	CT
Minkin et al. [58]	2017	r	36	1.3	24.0	369	10.0	No	–	–	–	CT/MRI
Ollivier et al. [37]	2017	r	66	1.6	28.0	901	13.7	Yes	11.0	Yes	–	CT

All relevant original publications since 2010 on periprocedural complications during sEEG monitoring in epilepsy with ≥10 enrolled patients were mentioned in this table. Studies with both sEEG and grid electrodes at the same time were excluded. For a review on earlier publications on this topic see, Mullin et al. [16]. r = retrospective, p = prospective, d = days, y = years, n = number.

during seizures, we would recommend the mandatory use of padded bedrails, a 24/7 surveillance by specifically trained nurses or technicians, and to create patients awareness of possible harms associated with in-bed objects or inadequate behavior.

Another patient with negative patient history for hemorrhages or major bleedings developed a clinically silent SAH after implantation, which was detected via routine postimplantation CT scan. During implantation, a considerably increased bleeding propensity was already observed by the surgeon. During video-EEG monitoring, prothrombin time (PT) significantly decreased (initially 71%, min: 48%), and an isolated, previously unknown factor VII deficiency was detected, so that we emanate a coherence between SAH and coagulopathy. Factor VII deficiencies are a rare disease, which often have their first manifestation with sudden unexpected hemorrhagic complications [43]. There was one case of mild inhospital pneumonia postextubation in one patient, which was considered a nonspecific complication, due to endotracheal intubation and volatile anesthesia. Unspecific postoperative transient inflammation with low-grade fever and increased CRP (max: 1.5 g/dl or 15 g/l) has been repeatedly reported after neurosurgical operations [44]. Moreover, mild leukocytosis (max: 13.1/nl) was shown to be a nonspecific response to surgery [45]. During video-EEG monitoring, CRP and leukocyte count normalized in all analyzed patients until explantation. These findings underline that a sole increase in CRP and postoperative leukocytosis without relevant fever is not a mandatory indication for antibiotic treatment. However, indication for antibiotic therapy should be discussed individually in close consideration of each clinical course to increase safety and avoid complications due to delayed antibiotic therapy.

As an important finding, our study demonstrates the significance of a postexplantation CT scan to detect subclinical periprocedural complications. Such findings may be underreported in the literature; as in most studies, a standardized brain imaging was performed only once after implantation of the electrodes [20, 21, 23, 26, 33, 42, 46, 47]. For comparison, a detailed review of relevant literature on sEEG complications is given in Table 5. Additional scans after explantation were executed only in cases of suspected complications [28, 37]. To our knowledge, only one previous study systematically applied postexplantation CT scans to exclude bleeding complications [30]. These authors found an overall complication rate of 4.9% per patient in a total of 163 procedures with sEEG or combined evaluation with subdural grid electrodes. After explantation, pneumocephalus (87.2%), and pneumoventricle (9.3%) leading to headache, and frequently unspecific infectious symptoms up to afebrile meningeal syndromes were described. In six of all patients (3.7%), hemorrhages occurred, but none after explantation. In one case, an intracerebral abscess was detected 22 days after the end of invasive recording and initial unsuspicious CT scan.

In our study, an asymptomatic limited bleeding close to branch channels occurred in four out of 141 electrodes (2.8%) after explantation. This was a higher rate than after implantation, but the difference was not statistically significant ($p = 0.13$), possibly due to the low number of patients. Complications after explantation may be associated with long duration of video-EEG monitoring. Ingrowth of electrodes as described in cerebral shunt placement [48] or a prolonged periprocedural

Imaging	Complications per patient/electrode										
Regular postexplantation	Total % (n)	Minor n % (n)	Major % (n)	Hemorrhagic	Infectious	Material failure	Transient deficits	Permanent deficits	Others	Surgical complication	Periprocedural mortality/death
–	5.9 (1) 0.4 (1)	0.0 (0) 0.0 (0)	5.9 (1) 0.5 (1)	0	1	0	0	0	0	0	0
–	4.4 (22) 0.3 (22)	2.2 (11) 0.2 (11)	2.2 (11) 0.2 (11)	14	2	1	1	2	0	1	1
–	14.3 (2) - (2)	7.1 (1) - (1)	7.1 (1) - (1)	1	1	0	0	0	0	0	0
–	0.0 (0) 0.0 (0)	0.0 (0) 0.0 (0)	0.0 (0) 0.0 (0)	0	0	0	0	0	0	0	0
–	0.0 (0) 0.0 (0)	0.0 (0) 0.0 (0)	0.0 (0) 0.0 (0)	0	0	0	0	0	0	0	0
–	2.5 (3) 0.19 (3)	2.5 (3) 0.19 (3)	0.0 (0) 0.0 (0)	3	0	0	0	0	0	0	0
–	5.0 (1) 0.2 (1)	5.0 (1) 0.2 (1)	0.0 (0) 0.0 (0)	1	0	0	0	0	0	0	0
–	4.5 (1) 0.5 (1)	4.5 (1) 0.5 (1)	0.0 (0) 0.0 (0)	1	0	0	0	0	0	0	0
–	2.5 (5) 0.2 (5)	1.5 (3) 0.1 (3)	1.0 (2) <0.1 (2)	2	2	0	1	0	0	0	1
–	0.0 (0) 0.0 (0)	0.0 (0) 0.0 (0)	0.0 (0) 0.0 (0)	0	0	0	0	0	0	0	0
–	10.0 (2) 0.8 (2)	10.0 (2) 0.8 (2)	0.0 (0) 0.0 (0)	0	0	0	2	0	0	0	0
CT	5.5 (7) 0.5 (7)	- -	- -	5	2	0	0	0	0	0	0
–	3.9 (4) 0.3 (4)	3.0 (3) 0.2 (3)	1.0 (1) <0.1 (1)	4	0	0	0	0	0	0	0
–	0.0 (0) 0.0 (0)	0.0 (0) 0.0 (0)	0.0 (0) 0.0 (0)	0	0	0	0	0	0	0	0
–	0.0 (0) 0.0 (0)	0.0 (0) 0.0 (0)	0.0 (0) 0.0 (0)	0	0	0	0	0	0	0	0
–	22.7 (15) 1.7 (15)	13.6 (9) 1.0 (9)	9.1 (6) 0.7 (6)	9	0	2	2	0	0	2	0

application of LMWH as thrombosis prophylaxis [49] may represent relevant factors putting patient outcome at risk.

5. Conclusion

We systematically analyzed complication rates associated with sEEG in patients with pharmacoresistant focal epilepsies. Use of this method involves an acceptable risk, and the rate of complications with transient or persisting neurological deficits is relatively low compared to grid implantations. This study suffers from the limitation of a small number of patients, but the use of two established grading systems for complications and adverse events allows a comparison with previous investigations.

We highlighted the clinical significance of CT scan after electrode explantation. Systematic imaging after implantation and explantation helped to identify clinically silent but relevant complications of sEEG electrodes and should be implemented in clinical routine.

Conflicts of interest (COI)

K.M. Klein reports personal fees from UCB, Eisai, Novartis, and GW Pharmaceuticals outside the submitted work.

S. Schubert-Bast reports personal fees from UCB, Eisai, Desitin Pharma, and Shire outside the submitted work.

F. Rosenow reports personal fees from Eisai, grants and personal fees from UCB, grants and personal fees from Desitin Pharma, personal fees and other from Novartis, personal fees from Medronic, personal fees from Cerbomed, personal fees from ViroPharma and Shire, grants from European Union, and grants from Deutsche Forschungsgemeinschaft, outside the submitted work.

A. Strzelczyk reports personal fees and grants from Desitin Arzneimittel, Eisai, LivaNova, Sage Therapeutics, UCB Pharma, and Zogenix, outside the submitted work.

None of the other authors report conflicts of interest.

We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

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References

[1] World Health Organization. Epilepsy: Fact Sheet; 2018.
[2] Jacoby A. Stigma, epilepsy, and quality of life. Epilepsy Behav 2002;3:10–20.
[3] Strzelczyk A, Griebel C, Lux W, Rosenow F, Reese JP. The burden of severely drug-refractory epilepsy: a comparative longitudinal evaluation of mortality, morbidity, resource use, and cost using German health insurance data. Front Neurol 2017;8:712.
[4] Strzelczyk A, Bergmann A, Biermann V, Braune S, Dieterle L, Forth B, et al. Neurologist adherence to clinical practice guidelines and costs in patients with newly diagnosed and chronic epilepsy in Germany. Epilepsy Behav 2016;64:75–82.

[5] Thomas SV, Sarma PS, Alexander M, Pandit L, Shekhar L, Trivedi C, et al. Economic burden of epilepsy in India. Epilepsia 2001;42:1052–60.
[6] Hong Z, Qu B, Wu XT, Yang TH, Zhang Q, Zhou D. Economic burden of epilepsy in a developing country: a retrospective cost analysis in China. Epilepsia 2009;50:2192–8.
[7] Willems LM, Richter S, Watermann N, Bauer S, Klein KM, Reese JP, et al. Trends in resource utilization and prescription of anticonvulsants for patients with active epilepsy in Germany from 2003 to 2013 — a ten-year overview. Epilepsy Behav 2018;83:28–35.
[8] Kwan P, Brodie MJ. Early identification of refractory epilepsy. N Engl J Med 2000;342:314–9.
[9] Kwan P, Arzimanoglou A, Berg AT, Brodie MJ, Allen Hauser W, Mathern G, et al. Definition of drug resistant epilepsy: consensus proposal by the ad hoc Task Force of the ILAE Commission on Therapeutic Strategies. Epilepsia 2010;51:1069–77.
[10] Luciano AL, Shorvon SD. Results of treatment changes in patients with apparently drug-resistant chronic epilepsy. Ann Neurol 2007;62:375–81.
[11] Callaghan BC, Anand K, Hesdorffer D, Hauser WA, French JA. Likelihood of seizure remission in an adult population with refractory epilepsy. Ann Neurol 2007;62:382–9.
[12] Reif PS, Strzelczyk A, Rosenow F. The history of invasive EEG evaluation in epilepsy patients. Seizure 2016;41:191–5.
[13] Picot MC, Jaussent A, Neveu D, Kahane P, Crespel A, Gelisse P, et al. Cost-effectiveness analysis of epilepsy surgery in a controlled cohort of adult patients with intractable partial epilepsy: a 5-year follow-up study. Epilepsia 2016;57:1669–79.
[14] Rosenow F, Luders H. Presurgical evaluation of epilepsy. Brain 2001;124:1683–700.
[15] Munyon CN, Koubeissi MZ, Syed TU, Luders HO, Miller JP. Accuracy of frame-based stereotactic depth electrode implantation during craniotomy for subdural grid placement. Stereotact Funct Neurosurg 2013;91:399–403.
[16] Mullin JP, Shriver M, Alomar S, Najm I, Bulacio J, Chauvel P, et al. Is SEEG safe? A systematic review and meta-analysis of stereo-electroencephalography-related complications. Epilepsia 2016;57:386–401.
[17] Maxwell RE, Gates JR, Fiol ME, Johnson MJ, Yap JC, Leppik IE, et al. Clinical evaluation of a depth electroencephalography electrode. Neurosurgery 1983;12:561–4.
[18] Kratimenos GP, Thomas DG, Shorvon SD, Fish DR. Stereotactic insertion of intracerebral electrodes in the investigation of epilepsy. Br J Neurosurg 1993;7:45–52.
[19] Cossu M, Cardinale F, Castana L, Citterio A, Francione S, Tassi L, et al. Stereoelectroencephalography in the presurgical evaluation of focal epilepsy: a retrospective analysis of 215 procedures. Neurosurgery 2005;57:706–18 [discussion 706-18].
[20] Mcgonigal A, Bartolomei F, Regis J, Guye M, Gavaret M, Trebuchon-Da Fonseca A, et al. Stereoelectroencephalography in presurgical assessment of MRI-negative epilepsy. Brain 2007;130:3169–83.
[21] Cardinale F, Cossu M, Castana L, Casaceli G, Schiariti MP, Miserocchi A, et al. Stereoelectroencephalography: surgical methodology, safety, and stereotactic application accuracy in 500 procedures. Neurosurgery 2013;72:353–66 [discussion 366].
[22] Balanescu B, Franklin R, Ciurea J, Mindruta I, Rasina A, Bobulescu RC, et al. A personalized stereotactic fixture for implantation of depth electrodes in stereoelectroencephalography. Stereotact Funct Neurosurg 2014;92:117–25.
[23] Gonzalez-Martinez J, Mullin J, Vadera S, Bulacio J, Hughes G, Jones S, et al. Stereotactic placement of depth electrodes in medically intractable epilepsy. J Neurosurg 2014;120:639–44.
[24] Gonzalez-Martinez J, Bulacio J, Alexopoulos A, Jehi L, Bingaman W, Najm I. Stereoelectroencephalography in the "difficult to localize" refractory focal epilepsy: early experience from a North American epilepsy center. Epilepsia 2013;54:323–30.
[25] Gintz RE. Historical background of injury as it relates to the workmen's compensation law. Ind Med Surg 1966;35:943–5.
[26] Ortler M, Sohm F, Eisner W, Bauer R, Dobesberger J, Trinka E, et al. Frame-based vs frameless placement of intrahippocampal depth electrodes in patients with refractory epilepsy: a comparative in vivo (application) study. Neurosurgery 2011;68:881–7 [discussion 887].
[27] Munyon C, Sweet J, Luders H, Lhatoo S, Miller J. The 3-dimensional grid: a novel approach to stereoelectroencephalography. Neurosurgery 2015;11(Suppl. 2):127–33 [discussion 133-4].
[28] Wellmer J, von der Groeben F, Klarmann U, Weber C, Elger CE, Urbach H, et al. Risks and benefits of invasive epilepsy surgery workup with implanted subdural and depth electrodes. Epilepsia 2012;53:1322–32.
[29] Hamer HM, Morris HH, Mascha EJ, Karafa MT, Bingaman WE, Bej MD, et al. Complications of invasive video-EEG monitoring with subdural grid electrodes. Neurology 2002;58:97–103.
[30] Mathon B, Clemenceau S, Hasboun D, Habert MO, Belaid H, Nguyen-Michel VH, et al. Safety profile of intracranial electrode implantation for video-EEG recordings in drug-resistant focal epilepsy. J Neurol 2015;262:2699–712.
[31] Spyrantis A, Cattani A, Strzelczyk A, Rosenow F, Seifert V, Freiman TM. Robot-guided stereoelectroencephalography without a computed tomography scan for referencing: analysis of accuracy. Int J Med Robot 2018;14(2). https://doi.org/10.1002/rcs.1888 Epub 2018 Jan 8.
[32] De Benedictis A, Trezza A, Carai A, Genovese E, Procaccini E, Messina R, et al. Robot-assisted procedures in pediatric neurosurgery. Neurosurg Focus 2017;42:E7.
[33] Serletis D, Bulacio J, Bingaman W, Najm I, Gonzalez-Martinez J. The stereotactic approach for mapping epileptic networks: a prospective study of 200 patients. J Neurosurg 2014;121:1239–46.
[34] Rosenow F, Bast T, Czech T, Feucht M, Hans VH, Helmstaedter C, et al. Revised version of quality guidelines for presurgical epilepsy evaluation and surgical epilepsy therapy issued by the Austrian, German, and Swiss working group on presurgical epilepsy diagnosis and operative epilepsy treatment. Epilepsia 2016;57:1215–20.
[35] Kay L, Reif PS, Belke M, Bauer S, Frund D, Knake S, et al. Intranasal midazolam during presurgical epilepsy monitoring is well tolerated, delays seizure recurrence, and protects from generalized tonic–clonic seizures. Epilepsia 2015;56:1408–14.
[36] Schmitt FC, Voges J, Buentjen L, Woermann F, Pannek HW, Skalej M, et al. Radiofrequency lesioning for epileptogenic periventricular nodular heterotopia: a rational approach. Epilepsia 2011;52:e101–5.
[37] Ollivier I, Behr C, Cebula H, Timofeev A, Benmekhbi M, Valenti MP, et al. Efficacy and safety in frameless robot-assisted stereo-electroencephalography (SEEG) for drug-resistant epilepsy. Neurochirurgie 2017;63:286–90.
[38] Munari C. Depth electrode implantation at Hospital Sainte Anne, Paris. Surgical treatment of the epilepsies. New York: Raven Press; 1987. p. 583–8.
[39] Bekelis K, Desai A, Kotlyar A, Thadani V, Jobst BC, Bujarski K, et al. Occipitotemporal hippocampal depth electrodes in intracranial epilepsy monitoring: safety and utility. J Neurosurg 2013;118:345–52.
[40] Munari C, Hoffmann D, Francione S, Kahane P, Tassi L, Lo Russo G, et al. Stereo-electroencephalography methodology: advantages and limits. Acta Neurol Scand Suppl 1994;152:56–67 [discussion 68–9].
[41] Fernandez G, Hufnagel A, Van Roost D, Helmstaedter C, Wolf HK, Zentner J, et al. Safety of intrahippocampal depth electrodes for presurgical evaluation of patients with intractable epilepsy. Epilepsia 1997;38:922–9.
[42] Bourdillon P, Ryvlin P, Isnard J, Montavont A, Catenoix H, Mauguiere F, et al. Stereotactic electroencephalography is a safe procedure, including for insular implantations. World Neurosurg 2017;99:353–61.
[43] Peyvandi F, Duga S, Akhavan S, Mannucci PM. Rare coagulation deficiencies. Haemophilia 2002;8:308–21.
[44] Mirzayan MJ, Gharabaghi A, Samii M, Tatagiba M, Krauss JK, Rosahl SK. Response of C-reactive protein after craniotomy for microsurgery of intracranial tumors. Neurosurgery 2007;60:621–5 [discussion 625].
[45] Kraft CN, Kruger T, Westhoff J, Luring C, Weber O, Wirtz DC, et al. CRP and leukocyte-count after lumbar spine surgery: fusion vs. nucleotomy. Acta Orthop 2011;82:489–93.
[46] Cossu M, Cardinale F, Colombo N, Mai R, Nobili L, Sartori I, et al. Stereoelectroencephalography in the presurgical evaluation of children with drug-resistant focal epilepsy. J Neurosurg 2005;103:333–43.
[47] Mehta AD, Labar D, Dean A, Harden C, Hosain S, Pak J, et al. Frameless stereotactic placement of depth electrodes in epilepsy surgery. J Neurosurg 2005;102:1040–5.
[48] Gliemroth J, Kasbeck E, Kehler U. Ventriculocisternostomy versus ventriculoperitoneal shunt in the treatment of hydrocephalus: a retrospective, long-term observational study. Clin Neurol Neurosurg 2014;122:92–6.
[49] Chibbaro S, Tacconi L. Safety of deep venous thrombosis prophylaxis with low-molecular-weight heparin in brain surgery. Prospective study on 746 patients. Surg Neurol 2008;70:117–21 [discussion 121].
[50] Blauwblomme T, David O, Minotti L, Job AS, Chassagnon S, Hoffman D, et al. Prognostic value of insular lobe involvement in temporal lobe epilepsy: a stereo-electroencephalographic study. Epilepsia 2013;54:1658–67.
[51] Vadera S, Mullin J, Bulacio J, Najm I, Bingaman W, Gonzalez-Martinez J. Stereoelectroencephalography following subdural grid placement for difficult to localize epilepsy. Neurosurgery 2013;72:723–9 [discussion 729].
[52] Dylgjeri S, Taussig D, Chipaux M, Lebas A, Fohlen M, Bulteau C, et al. Insular and insulo-opercular epilepsy in childhood: an SEEG study. Seizure 2014;23:300–8.
[53] Dorfmuller G, Ferrand-Sorbets S, Fohlen M, Bulteau C, Archambaud F, Delalande O, et al. Outcome of surgery in children with focal cortical dysplasia younger than 5 years explored by stereo-electroencephalography. Childs Nerv Syst 2014;30:1875–83.
[54] Gonzalez-Martinez J, Mullin J, Bulacio J, Gupta A, Enatsu R, Najm I, et al. Stereoelectroencephalography in children and adolescents with difficult-to-localize refractory focal epilepsy. Neurosurgery 2014;75:258–68 [discussion 267-8].
[55] Nowell M, Rodionov R, Diehl B, Wehner T, Zombori G, Kinghorn J, et al. A novel method for implementation of frameless stereoEEG in epilepsy surgery. Neurosurgery 2014;10(Suppl. 4):525–33 [discussion 533-4].
[56] Taussig D, Chipaux M, Lebas A, Fohlen M, Bulteau C, Ternier J, et al. Stereo-electroencephalography (SEEG) in 65 children: an effective and safe diagnostic method for pre-surgical diagnosis, independent of age. Epileptic Disord 2014;16:280–95.
[57] Salado AL, Koessler L, De Mijolla G, Schmitt E, Vignal JP, Civit T, et al. sEEG is a safe procedure for a comprehensive anatomic exploration of the insula: a retrospective study of 108 procedures representing 254 transopercular insular electrodes. Oper Neurosurg (Hagerstown) 2018;14:1–8.
[58] Minkin K, Gabrovski K, Penkov M, Todorov Y, Tanova R, Milenova Y, et al. Stereoelectroencephalography using magnetic resonance angiography for avascular trajectory planning: technical report. Neurosurgery 2017;81:688–94.
[59] González-Martínez J, Bulacio J, Thompson S, Gale J, Smithason S, Najm I, et al. Technique, results, and complications related to robot-assisted stereoelectroencephalography. Neurosurgery 2016;78(2):169–80. https://doi.org/10.1227/NEU.0000000000001034.