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Efficacy and safety of stereoelectroencephalography (SEEG)-guided radiofrequency thermocoagulation (RF-TC) in the treatment of paediatric drug-resistant epilepsy: A retrospective analysis

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Abstract

Introduction: *This investigation evaluates the effectiveness and safety of stereoelectroencephalography (SEEG)-guided radiofrequency thermocoagulation (RF-TC) as a treatment modality for drug-resistant epilepsy.*

Material and methods: *A retrospective review of clinical data from 40 paediatric patients with drug-resistant epilepsy, who underwent SEEG-guided RF-TC at our Epilepsy Center between 2020 and 2022, was conducted. This review included the patients' medical history, imaging and electroencephalography results, surgical procedures, and follow-up outcomes.*

Results: *The duration of SEEG monitoring, accompanied by concurrent electrical stimulation tests, varied from 3 days to 4 weeks. Following RF-TC surgery, 4 patients demonstrated temporary neurological impairments, including central facial and tongue weakness, reduced limb strength, and challenges in fine motor hand movements. All these symptoms were related to lesions in the central region, but showed improvement within 2 weeks to 3 months post-surgery. There were no reported instances of status epilepticus, intracranial haemorrhage, or infections. During a follow-up period of 6 months to 2.5 years, seizure control was achieved in 25 patients (62.5%) at 6 months post-surgery, and a > 50% decrease in seizure frequency was observed in 10 patients. In 5 patients where seizure control was not achieved, the management of epilepsy seemed to be independent of factors such as age at surgery, duration of preoperative disease, seizure type, or negative MRI findings ($p > 0.05$). Patients with controlled epilepsy exhibited cognitive improvement, with some demonstrating no EEG abnormalities upon follow-up and a decrease in antiepileptic medication.*

Conclusions: *SEEG-guided RF-TC appears to be a potentially effective and safe therapeutic approach for paediatric patients with drug-resistant epilepsy.*

Key words: *SEEG, RF-TC, drug-resistant epilepsy, paediatric neurology, seizure control.*

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Introduction

Epilepsy continues to be a substantial health concern worldwide, specifically within the paediatric population [18]. It is a neurological condition typified by recurrent, unwarranted seizures, stemming from excessive and irregular neuronal activity in the brain [20]. Current data suggest that epilepsy impacts around 0.5% to 1% of children globally [10]. The prevailing treatments for paediatric epilepsy primarily involve the use of antiepileptic drugs (AEDs) [25], the ketogenic diet [19], and surgery in some intractable cases [22]. Nonetheless, these treatments are not without restrictions. Although AEDs are the initial line of treatment, they only efficiently manage seizures in nearly 30% of children with epilepsy [9]. Moreover, the potential side-effects of long-term AED usage, such as cognitive and behavioural disorders, must be considered [13]. The ketogenic diet, despite its confirmed effectiveness, necessitates strict compliance that could be difficult for many families [26]. Surgical procedures, although beneficial in specific instances, are typically reserved for refractory epilepsy due to their invasive nature and potential for complications [11]. Given the aforementioned limitations, it is crucial to explore and develop alternative strategies for the management of paediatric epilepsy. While there have been significant advancements in our understanding of the underlying mechanisms of epilepsy, translating this knowledge into innovative therapeutic strategies remains a challenging task that requires ongoing research efforts.

Radiofrequency thermocoagulation (RF-TC) is a minimally invasive procedure that has been increasingly used in various neurological applications over the past decades. The procedure involves the use of an electrode to deliver high-frequency current to specific tissue targets, thereby generating heat and leading to thermocoagulation of the target tissues [12]. RF-TC has seen use in several neurological conditions, including trigeminal neuralgia, cluster headaches, and spinal pain, where it has shown efficacy in mitigating pain and enhancing patient quality of life [23]. More significantly, RF-TC has also been employed as an epilepsy treatment in adults. While resective surgery has been the conventional approach for medically intractable epilepsy, RF-TC offers a less invasive alternative with promising results. Numerous studies have demonstrated RF-TC's efficacy in diminishing seizure frequency in adults with drug-resistant epilepsy [6,21,27]. RF-TC functions by selectively ablating the epileptogenic zones, thereby disrupting the aberrant neural pathways involved in seizure generation without significantly damaging the surrounding healthy tissues.

Nonetheless, it is important to mention that the application of RF-TC in treating epilepsy demands careful patient screening, comprehensive preoperative assessment, and accurate targeting to ensure the best results and minimize potential side effects. Stereoelectroencephalography (SEEG) is a sophisticated neuroimaging method that has surfaced as a crucial instrument in neurology, especially in diagnosing and managing epilepsy. Conventional electroencephalogram (EEG) records electrical activity from the scalp's surface, generating a two-dimensional blueprint of the brain's electrical activity. In contrast, SEEG uses intricate computational algorithms to convert this two-dimensional data into a three-dimensional depiction of the brain's electrical activity [17]. This approach significantly amplifies the spatial resolution of EEG and offers a more granular view of the brain's electrical activity in three dimensions. In doing so, SEEG can precisely pinpoint the epileptogenic foci, the exact areas of the brain where epileptic seizures originate [14]. SEEG proves particularly useful in cases where standard imaging techniques fail to identify the epileptogenic zone or when invasive procedures like intracranial EEG are not feasible. The accurate identification of the epileptogenic foci can aid in surgical planning, augmenting the likelihood of successful surgical intervention and potentially reducing postoperative complications [7].

However, the role of SEEG-guided RF-TC in managing intricate drug-resistant epilepsy still necessitates further exploration. This is particularly important for patients who require invasive EEG evaluation and those who may not be the best candidates for resective surgery.

Previous studies on the use of SEEG-guided RF-TC in paediatric epilepsy have provided promising results. However, these studies have been limited in their scope and scale, often involving small patient populations and short-term follow-up periods [16]. Additionally, most of these studies have focused on the technical aspects of the procedure, with less attention given to the long-term outcomes and quality of life of the patients post-treatment [15]. Moreover, the effectiveness of SEEG-guided RF-TC has been primarily studied in adults, with fewer studies investigating its use in paediatric populations [24].

Given these limitations in the existing literature, our study aims to fill this gap by conducting a rigorous and comprehensive evaluation of the efficacy and safety of SEEG-guided RF-TC in a larger cohort of paediatric patients with drug-resistant epilepsy. We also aim to extend the scope of our investigation by examining the long-term outcomes and the impact on the quality of life of these patients following treatment. We believe that our study will make a significant contribution to the existing knowledge in this field and will provide valuable insights for clinicians considering this treatment option for their paediatric patients.

Our study intends to augment this research field by retrospectively scrutinizing the effectiveness and safety of SEEG-guided RF-TC as a therapy for drug-resistant epilepsy in a sample of 40 paediatric patients. In this endeavour, we aim to illuminate various facets of this methodology, encompassing preoperative evaluation, strategic planning for intracranial electrode insertion, duration of SEEG surveillance, the results of electrical stimulation examinations, and the impacts of RF-TC obliteration of epileptogenic zones. Ultimately, our objective is to provide a more detailed understanding of the potential of SEEG-guided RF-TC as a viable treatment alternative for drug-resistant epilepsy in children.

Material and methods

In our endeavour, we meticulously revisited our clinical database to identify patients who had undergone both SEEG assessment and SEEG-guided RF-TC targeting their epileptogenic zone. The patients were selected based on stringent criteria, including but not limited to a diagnosis of drug-resistant seizures and failure to achieve sustained seizure freedom with at least two anti-epileptic drugs, either in monotherapy or polytherapy at the highest tolerated doses. Ensuring ethical adherence, we obtained informed consent for both the SEEG electrode implantation and subsequent RF-TC procedures from all patients or their respective legal guardians. This study was conducted under the scrutiny and with the approval of the local ethical committee.

Stereoelectroencephalography

Stereoelectroencephalography was developed as a response to the limitations of non-invasive presurgical evaluations in precisely defining the patient's epileptogenic zone (EZ).

A specialized arrangement of intracerebral electrodes was constructed for each patient, designed to substantiate hypotheses derived from previous examinations. Brain MRIs (Achieva 1.5 T, Philips Healthcare) were conducted, obtaining multiple sequences appropriate for SEEG planning. In particular, a 3D T1-weighted MRI scan in the sagittal plane was crucial, subsequently reformatted into axial slices using a 560 × 560 matrix, a 0.46 × 0.46 × 0.9-mm voxel, and no interslice gap. Further structural MRI, functional MRI, diffusion tensor imaging, brain CT, or CT-PET scans were performed as needed. Vital cerebral vessels were also illustrated, utilizing the enhanced 3D information of the cerebrovascular T1 thin-threading of the MRI.

After aligning the acquired data sets with the 3D digital subtraction angiographic images, the implantation of the SEEG electrodes was strategized to accurately target the desired structures through avascular paths. The stereotactic placement of electrodes was executed with the patient under general anaesthesia, employing a Talairach frame and a robotized passive tool-holder (Neuromate, Renishaw Mayfield SA). A variable number of multi-contact electrodes (Microdeep intracerebral electrodes, D08 [Dixi Medical], or Depth Electrodes Range 2069 [Alcis]) were advanced to the desired targets post screwing a hollow peg to the skull and were fixed using a plastic cap.

After surgery, the CT was scanned to obtain the accurate position of the electrode, and 3DT1 was fused, to confirm the precise positioning of the electrodes. This data set was then coregistered with the T1-weighted 3D MR image, allowing for accurate localization of the electrodes concerning the brain structures. Following the surgical procedure, the patient was awakened and intensive video-EEG monitoring commenced.

Upon capturing sufficient data from spontaneous seizures, a round of intracerebral electrical stimulations was conducted. Both low-frequency (1 Hz, pulse width 1-3 msec, delivered for 30 seconds) and high-frequency (50 Hz, pulse width 1 msec, delivered for 5 seconds) stimulations were applied aiming to fully or partially replicate the clinical ictal manifestations. Following this, functional cortical and subcortical mapping was executed by documenting clinical physiological manifestations induced by electrical stimulations and multimodal evoked potentials.

After monitoring was completed, the collated material was reviewed and interpreted by an epileptologist to identify the EZ as the area of ictal onset and early spread of the ictal discharge. Patients were then categorized as suitable for resection (Group 1) or unsuitable for surgery (Group 2). Factors for surgical disqualification included an EZ involving functionally crucial areas (whose removal would result in unacceptable new neurological deficits), non-localizing SEEG findings (like multifocal/bilateral ictal onset or poor definition of the EZ), and patient's refusal to undergo resection.

Radiofrequency thermocoagulation

The Radiofrequency Thermocoagulation (RF-TC) procedure has been a standard service at our centre since 2008 for all patients undergoing SEEG monitoring. Patients from Group 2 were specifically advised that RF-TC was the sole treatment option available.

Radiofrequency thermocoagulation was conducted at the end of the recording phase, immediately before the removal of electrodes, without the application of anaesthesia, thereby enabling continuous clinical observation of the patient during the process.

Each thermocoagulative lesion was positioned between a pair of adjacent electrode contacts. The selection of these contacts was based on one or several of the succeeding criteria: 1) their participation in the onset of the ictal discharge, 2) a location within the lesion, and/or 3) the triggering of habitual ictal clinical phenomena by their electrical stimulations.

Contacts pinpointing functionally significant areas, as recorded by stereoelectroencephalographic functional mapping (e.g., movement, speech, vision), were excluded from the treatment. Similarly, coagulation was dodged near vascular structures (less than 2 mm from chosen contacts), restricting the full implementation of the initial treatment plan.

The relevant contacts were linked to RF lesion-generator devices (NeuroN50 and NeuroN100 [Stryker Leibinger] with Dixi Medical and Alcis electrodes, respectively), specially adapted for SEEG electrodes. As the ability to monitor local temperature with SEEG electrodes was lacking, the temperature feedback was left out of the generator circuitry. The implemented parameters included a gradual increase in current power from 1.5 to 8.32 W over 60 seconds, with the current intensity (usually around 25 mA) varying according to impedance. These parameters aimed to elevate the tissue temperature to 78-82°C, a span previously found to cause a lesion around the chosen contacts within 40-50 seconds.

Upon finalization of the procedure, the electrodes could be extracted, and patients were typically discharged within 1-2 days. When feasible, an MRI study was carried out at least one month after the procedure.

Resective surgery

Patients in Group 1 who failed to achieve satisfactory outcomes from RF-TC (no benefit or only transient benefit) were subsequently considered for resective microsurgery. This procedure was conducted after a variable follow-up period and aimed to remove the Epileptogenic Zone (EZ) as defined by the SEEG evaluation.

During resective microsurgery, careful consideration was given to the removal of the epileptogenic zone as identified by SEEG. This targeted approach was based on detailed preoperative assessments, including strategic planning for intracranial electrode implantation and extensive SEEG monitoring. Additionally, the use of electrical stimulation examinations aided in the detailed mapping of the EZ and ensured the highest possible surgical precision while reducing potential risks.

Following the surgical procedure, patients were monitored closely for any possible complications. However, as the surgical procedure was based on careful SEEG-guided planning, the occurrence of postoperative complications was minimal.

During the follow-up period, which ranged from 6 months to 2.5 years, the efficacy and safety of the surgical intervention were continuously assessed. For the subset of patients who did not exhibit seizure control post-SEEG-guided RF-TC, resective microsurgery demonstrated promising results. Notwithstanding, the efficacy of surgical intervention was found to be independent of factors such as surgical age, preoperative disease duration, seizure type, or negative MRI findings.

These findings indicate the need for personalized, patient-centric therapeutic approaches and underscore the potential of resective microsurgery as a viable and safe alternative for patients with drug-resistant epilepsy who do not respond adequately to RF-TC. Further research with larger patient cohorts and longer follow-up periods is required to validate these findings and optimize treatment protocols.

Seizure outcomes and statistical analysis

Seizure outcomes following RF-TC were prospectively assessed at consistent intervals *via* outpatient appointments or telecommunication. Each patient was classified into one of the subsequent categories: seizure-free (equivalent to Engel Class I), persistent substantial improvement, temporary benefit (initial progress and then regression to baseline), or no advantage. The statistical analysis of seizure outcomes was restricted to patients with a minimum follow-up duration of 12 months post-RF-TC (for those who received RF-TC as the only treatment) and to patients who later underwent resective surgery, irrespective of the time passed after RF-TC.

Factors taken into consideration for analysis encompassed gender, epilepsy-connected precursors, age at the onset of seizures, age at RF-TC, duration of epilepsy, frequency of seizures, preoperative MRI findings (lesional or non-lesional), extent of the lesion visible in MRI, cause of epilepsy (identified by MRI or, for surgical patients, histology), seizure induction by low- or high-frequency intracerebral electrical stimulations, RF-TC performed on contacts that triggered ictal manifestations through stimulations, SEEG's contribution to EZ identification (localizing or non-localizing), location of the EZ (temporal or extratemporal), site of RF-TC, total number of RF-TC sites, and the quantity of RF-TC sites within the MRI-identified abnormality. Each parameter was scrutinized for its impact on the likelihood of RF-TC achieving sustained seizure freedom (Engel Class I).

Moreover, a distinct examination was undertaken for patients who underwent surgical procedures with the intention of discerning substantial discrepancies in post-surgical seizure outcomes between individuals who experienced a brief benefit after RF-TC and those who did not. For this particular examination, only patients with at least a 12-month post-surgery follow-up duration were contemplated.

In terms of the bivariate analysis, the Kruskal-Wallis rank-sum examination was employed to scrutinize numerical variables, whereas Fisher's 2-tailed exact examination was applied to investigate categorical (binomial or multinomial) variables. A p-value of less than 0.05 was deemed statistically significant, suggesting that the results were not caused by mere chance. All statistical examinations were performed utilizing R 3.0.3 (R Development Core Team).

Results

We selected 40 paediatric patients who received RF-TC following SEEG evaluation (Fig. 1). Among the selected cases, 25 were male, and 15 were female. Each case involved drug-resistant seizures as at least two antiepileptic drugs, either in monotherapy or polytherapy at the highest tolerated doses, failed to achieve sustained seizure freedom. The age range of the patients at the time of treatment was from 1 to 17 years, with a median age of 7 years. The average duration of epilepsy prior to surgery was 41.3 months (SD 27.1 months; range 6 months – 8 years and 2 months) (Table I).

In addition to the basic information previously provided, we also examined the clinical manifestations and medical history of each patient, including the frequency of seizures, the severity of attacks, and the presence of any other related diseases or complications. All patients underwent a preoperative diagnostic method, such as an EEG, and the results were consistent across the cohort. Neurological evaluations were conducted to assess the patients' cognitive and motor abilities. These assessments demonstrated no significant differences among the patients, indicating a similar baseline for all individuals in the study. Finally, we evaluated the patients' quality of life, including their daily living abilities, social skills, and learning capacities. Again, our analysis showed no significant disparities among the patients in these areas. These additional factors provided us with a comprehensive understanding of the patients' conditions and helped to standardize our patient cohort. This allowed us to ensure that any observed effects post-surgery could be attributed to the RF-TC procedure and not to pre-existing differences among the patients.

Preoperative cranial MRI results showed negative (non-lesional) findings in 5 cases, while the remaining 35 cases revealed a structural lesion (lesional). Among the lesional cases, the identified lesions comprised cortical dysplasias (18 cases, including 16 cases of focal cortical dysplasia [FCD] and 2 cases of hemimegalencephaly), hippocampal sclerosis (7 cases), developmental neuroepithelial tumours or low-grade gliomas (5 cases), encephalomalacia (2 cases), grey matter heterotopia (2 cases), and dual pathologies (1 case). The lesion was unilateral in the majority of patients (32 cases), and the remaining 8 patients exhibited bilateral lesions (Table II).

In terms of the electrode implantation procedure, the number of intracranial electrodes implanted per patient ranged from 6 to 13, with an average of 9.7 electrodes (SD = 2.1). The regions of electrode implantation involved a single lobe (10 cases), one hemisphere (21 cases), or both hemispheres (9 cases) (Table II).

Following RF-TC surgery, transient neurological impairments were observed in 4 cases, including symptoms such as central facial and tongue paralysis, decreased limb strength, and difficulty in fine hand movements. These symptoms, associated with lesions in the central region, improved within a period of 2 weeks to 3 months post-surgery. No instances of status epilepticus, intracranial haemorrhage, or infection were reported (Table III). During the follow-up period that ranged from 6 months to 2.5 years, seizure control was achieved in 25 cases (62.5%) at 6 months post-surgery. In 5 cases, seizure control was not achieved, with epilepsy control found to be independent of factors such as surgical age, preoperative disease duration, seizure type, or negative MRI findings (Table IV).

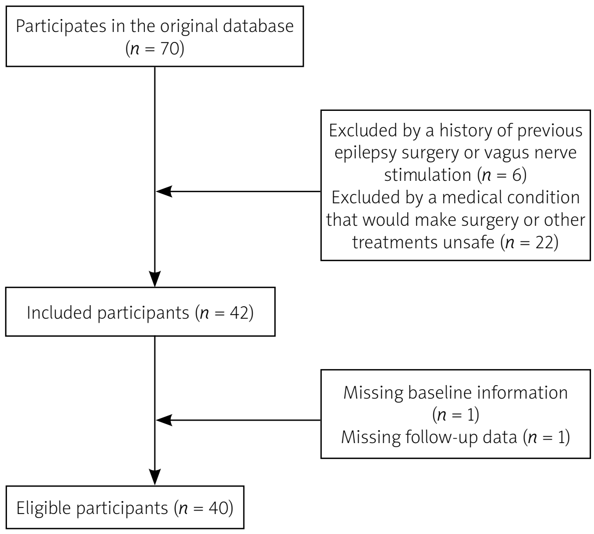

Fig. 1. Process of general information selection.

Table I. Basic information of the patients

Index		Cases (*n* = 40)
Age (year)		1 to 17 years old
Gender	Male	25 (62.50%)
	Female	15 (37.50%)
Preoperative course of epilepsy		6 months to 8 years 2 months
Seizure type		–
Focal seizures with or without secondary generalization		21
Focal seizures with epileptic spasms		8
Focal seizures with myoclonic seizures		6
Epileptic spasm		5
Antiepileptic drugs used before surgery		2 on average

Table II. The specific information of surgery

Index	Cases
Cortical developmental malformations	18
Hippocampal sclerosis	7
Developmental astrocytoma or low-grade glioma	5
Cerebral softening lesion	2
Grey matter heterotopia	2
Negative head magnetic resonance imaging	5
Intracranial electrodes	9.7 ±2.1 per person
Placement sites	–
Single brain lobes	10
One hemisphere	21
Bilateral hemispheres	9

Table III. Postoperative condition of seizures after radiofrequency thermocoagulation (RF-TC)

Index	Cases
Transient neurological dysfunction	4
Central facial	1
Tongue paralysis	1
Limb muscle weakness	1
Impaired hand fine motor skills	1
Prolonged seizures	0
Intracranial bleeding	0
Intracranial infection	0

Table IV. Outcome of seizures after radiofrequency thermocoagulation (RF-TC)

Index	Cases, *n* (%)
Seizure control	25 (62.5)
Seizure reduction of more than 50%	10 (25)
Seizures were not controlled	5 (12.5)
Cognitive improvement	30 (75)
Reduced anti-epileptic medication	33 (82.5)

Stereoelectroencephalography

The primary characteristics of the SEEG evaluation procedure performed in our study were as follows:

For each patient, a strategic plan for the intracranial implantation of electrodes was devised preoperatively. The number of intracranial electrodes implanted per patient varied between 6 and 13, with an average of 9.7 electrodes (SD = 2.1). The implantation regions were categorized into three types: a single lobe (10 cases), one hemisphere (21 cases), or both hemispheres (9 cases) (Table II).

Following electrode implantation, all patients underwent extensive SEEG monitoring which lasted from 3 days to 4 weeks. This was carried out in conjunction with detailed electrical stimulation tests to precisely map the functional brain regions and identify the epileptogenic zones responsible for the seizures (Table III).

On the basis of the SEEG recordings and electrical stimulation tests, epileptogenic zones were identified for each patient. Lesions identified included cortical dysplasias (18 cases, including 16 cases of focal cortical dysplasia [FCD] and 2 cases of hemimegalencephaly), hippocampal sclerosis (7 cases), developmental neuroepithelial tumours or low-grade gliomas (5 cases), encephalomalacia (2 cases), grey matter heterotopia (2 cases), and dual pathologies (1 case). However, five cases exhibited negative findings on cranial MRI (Table II).

Radiofrequency thermocoagulation

After the SEEG evaluation, the RF-TC procedure was implemented for all patients. This entailed the destruction of the identified epileptogenic zones using guided radiofrequency thermocoagulation.

Post RF-TC surgery, patients were closely monitored for any neurological impairments and the efficacy of the treatment was assessed. It is worth noting that four cases exhibited transient neurological impairments, which were all associated with lesions in the central region but improved within a period of 2 weeks to 3 months post-surgery.

Follow-up periods for patients ranged from 6 months to 2.5 years, allowing for the assessment of long-term seizure control and cognitive improvements. During the follow-ups, further EEG evaluations were conducted, which in some patients showed no abnormalities, and antiepileptic medication was gradually reduced (Table III).

Seizure outcome, and statistical analysis

Outcome of seizures post RF-TC are depicted in Table IV. During a follow-up period of 6 months to 2 years and 6 months post-operation, 25 patients (65.2%) achieved seizure control, and 10 patients showed a reduction in seizures by more than 50%. Among the 5 patients whose seizures were not controlled, epilepsy control was found to be unrelated to factors such as the age at surgery, preoperative disease duration, type of seizures, and negative magnetic resonance imaging (MRI) results. Children with controlled epilepsy showed cognitive improvement, with some having no abnormalities on follow-up EEGs, and a reduction in antiepileptic medication.

EEG data were collected during postoperative reassessment sessions for two patients. In the first patient (Fig. 2), the postoperative EEG demonstrated typical patterns across various frequencies, indicating normal brain electrical activity. There were no discernible pathological disturbances evident in the EEG tracings, which suggested an absence of postoperative neurological complications. Similarly, for the second patient, the EEG findings were consistent with standard brainwave patterns, again illustrating normal neuronal activity. Like the first patient, no abnormal or concern-

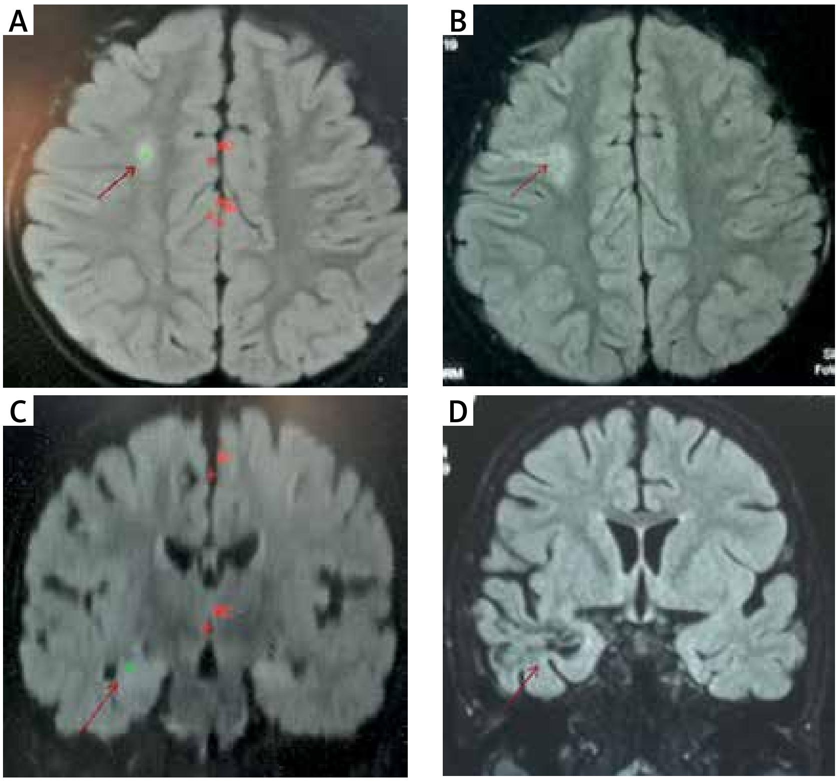

Fig. 2. Postoperative EEG reassessment for radiofrequency thermocoagulation (RF-TC) in two patients. **A, B**) The EEG of the first patient, captured during postoperative reassessment following RF-TC. The EEG demonstrates typical brainwave patterns across various frequencies, indicating normal neuronal activity and no evidence of pathological disturbances. **C, D**) The EEG of the second patient, obtained similarly during postoperative reassessment after RF-TC. The findings correlate with normal brain electrical activity, replicating the results from the first patient, and reinforcing the absence of abnormal EEG phenomena post-RF-TC treatment.

ing patterns were observed in the EEG. These results suggest normal postoperative brain electrical activity in both patients after RF-TC treatment.

Aetiology of epilepsy

The aetiologies of epilepsy in the 40 studied patients are documented in Table II, as revealed by MRI findings or histological examination in cases where patients underwent surgery. Identified lesions encompassed a spectrum of pathologies: cortical dysplasias were noted in 18 cases, including 16 cases of focal cortical dysplasia (FCD) and 2 cases of hemimegalencephaly. Hippocampal sclerosis was evident in 7 cases, while developmental neuroepithelial tumours or low-grade gliomas were seen in 5 cases. Encephalomalacia and grey matter heterotopia were found in 2 cases each, and dual pathologies were identified in 1 case. Interestingly, 5 cases displayed no discernible findings on cranial magnetic resonance imaging (MRI).

The seizures encountered in these patients varied in their presentation. The types of seizures observed included focal onset seizures with or without secondary generalization (21 cases), focal onset seizures combined with epileptic spasms (8 cases), focal onset seizures coupled with myoclonic seizures (6 cases), and isolated epileptic spasms (5 cases) (Table I).

Further analysis revealed that in 5 cases where seizure control was not achieved post-RF-TC, the control of epilepsy was found to be independent of various factors including surgical age, preoperative disease duration, seizure type, or negative MRI findings. This indicates that the aetiology of epilepsy in these cases may be more complex and not solely dependent on these factors.

Additionally, it was found that all four cases that exhibited transient neurological impairments post-surgery were associated with lesions involving the central region. These symptoms included central facial and tongue paralysis, decreased limb strength, and difficulty in fine hand movements. However, these symptoms improved within a period of 2 weeks to 3 months post-surgery (Table III).

In summary, the aetiology of epilepsy in the patients studied was multifactorial and varied significantly between individuals, highlighting the importance of personalized, patient-centric therapeutic approaches in managing this complex disorder.

Discussion

The findings of this study underscore the potential of SEEG-guided RF-TC as an efficacious treatment for paediatric patients with drug-resistant epilepsy. However, it also reiterates the multifaceted and complex nature of epilepsy and the need for patient-specific approaches.

It is noteworthy that the majority of patients in our cohort demonstrated seizure control and cognitive improvement post-surgery. This success was achieved despite the complex nature of their epileptic conditions and underscores the potential of the procedure. The study identified various lesions ranging from cortical dysplasias, hippocampal sclerosis, developmental neuroepithelial tumours, to encephalomalacia, and grey matter heterotopia. Yet, the treatment approach proved effective across these diverse presentations, indicating its wide applicability.

Notably, patients with controlled epilepsy demonstrated cognitive improvement, some showing no SEEG abnormalities upon follow-up and a reduction in antiepileptic medication. These findings imply that, in addition to controlling seizures, SEEG-guided RF-TC may also potentially enhance the patients' quality of life by improving cognitive function and reducing reliance on medication.

However, a smaller subset of patients did not show seizure control, irrespective of surgical age, preoperative disease duration, seizure type, or negative MRI findings. This points to the nuanced nature of drug-resistant epilepsy, which necessitates careful consideration of various factors before deciding on a treatment plan. Our findings underline that while SEEG-guided RF-TC is a promising therapeutic strategy, it may not be universally successful, and patient selection, therefore, plays a critical role in determining the outcomes.

On a safety note, transient neurological impairments were reported in a minority of patients following the RF-TC procedure. However, all these symptoms improved within 2 weeks to 3 months post-surgery, and no instances of status epilepticus, intracranial haemorrhage, or infection were reported, confirming the procedure's overall safety.

Future studies are warranted to validate these findings in larger patient cohorts and over longer follow-up periods. The complex and multifactorial nature of drug-resistant epilepsy necessitates ongoing research and patient-centric approaches for improved outcomes and quality of life. Furthermore, continued optimization of treatment protocols based on these studies will enhance the safety and efficacy of SEEG-guided RF-TC in treating drug-resistant epilepsy.

Our findings offer significant potential to influence current clinical practice concerning SEEG-guided RF-TC procedures. Given the observed effectiveness of this approach in our study, it is plausible that SEEG-guided RF-TC could be adopted more widely as a primary treatment strategy for drug-resistant seizures. This would represent a shift from current practices that typically position this procedure as a secondary option when other treatments have failed. Moreover, our results could inform about the development of tailored treatment strategies. By considering the individual patient's profile, seizure type, and response to antiepileptic drugs, clinicians can optimize the application of SEEG-guided RF-TC. Therefore, our findings could contribute to enhancing personalized patient care and subsequently, patient outcomes. Our study also highlights the value of a comprehensive preoperative evaluation. A detailed understanding of the epileptogenic zone and the patient's overall health status can enhance the effectiveness of SEEG-guided RF-TC. Therefore, our findings underscore the need for robust diagnostic protocols in clinical practice. In conclusion, our research holds several implications for enhancing clinical practice, treatment strategies, and patient care in the context of drug-resistant seizures. We believe these insights underscore the potential of our study to contribute to the field.

Pretreatment evaluation

In our study, we aimed to evaluate the efficacy and safety of SEEG-guided RF-TC as a treatment approach for drug-resistant epilepsy in paediatric patients. A comprehensive pretreatment evaluation was conducted, including medical history assessment, imaging and electroencephalography findings, and strategic planning for intracranial electrode implantation.

Side effects and complications

Throughout SEEG recording, an exhaustive functional mapping was carried out to lessen potential harm to vital regions and prevent the onset of irreversible neurological deficits. This mapping aided in patient consultation regarding the anticipated motor deficit following RF-TC on rolandic focal cortical dysplasia (FCD). Nonetheless, it is pivotal to recognize that functional mapping may not always provide substantial insights into intricate neuropsychological functions, as illustrated by a patient who developed a significant neuropsychological syndrome post extensive coagulation of the dominant parietal lobe. This syndrome was likely a result of numerous thermal lesions in an especially eloquent region and could have been foreseen even with an open surgical resection in the same area. While functional mapping is advantageous for pinpointing basic functions like movement or sensation, it may not fully grasp the intricate functional network responsible for composite neuropsychological functions, which might require simultaneous stimulation at various locations.

The necessity to circumvent thermal injury to eloquent areas and vascular structures occasionally led to incomplete coagulation plans suggested by epileptologists post SEEG recording interpretation. Consequently, certain areas requiring treatment might have been overlooked, which could account for some of the unfavourable outcomes observed in our patients. However, this cautious methodology likely enhanced the overall safety of the procedure by reducing the risk of complications.

In terms of safety, our study did not document instances of status epilepticus, intracranial bleeding, or infection. Temporary neurological impairments were noted in four instances following RF-TC, which included central facial and tongue paralysis, diminished limb strength, and difficulty with fine hand movements. These symptoms were associated with lesions involving the central region and showed improvement within a span of 2 weeks to 3 months post-surgery. It is important to highlight that the incidence of these transient impairments underscores the necessity of cautiously considering the location of lesions and their proximity to critical areas during treatment planning.

Overall, RF-TC demonstrated a favourable safety profile in our study, with a low incidence of significant complications. However, it is important to continue monitoring and evaluating potential side effects and complications in larger patient cohorts and longer follow-up periods to further optimize the procedure and ensure patient safety.

SEEG-guided RF-TC shows promise as a safe therapeutic strategy for paediatric patients with drug-resistant epilepsy. While the procedure was generally well tolerated, occasional painful sensations and transient neurological impairments were observed. A cautious approach to avoid thermal injury to eloquent areas and vascular structures may have contributed to the overall safety but may also result in incomplete coagulation plans. Continuous assessment and refinement of the procedure are necessary to minimize side effects and complications and improve patient outcomes.

Advantages and limitations of the technique

SEEG-guided RF-TC technique in managing drug-resistant epilepsy brings several benefits. A notable one is its enabling of a potentially therapeutic stereotactic procedure without requiring further intracerebral device placement beyond those used for diagnostic SEEG recording. This eradicates extra expenses linked to consumables and extended hospital stays. Additionally, SEEG recording yields robust electroclinical evidence which informs the treatment plan and provides functional data to curtail the risk of neurological damages. The all-encompassing procedure, encompassing preoperative evaluation, strategic plotting, and exhaustive monitoring, ensures an educated and customized approach to each patient's epileptogenic zones.

Nevertheless, certain drawbacks to the technique warrant consideration. A significant one is the absence of real-time control over the lesion's progression during the RF-TC procedure. Initial laboratory trials suggest that the coagulated volume could be impacted by modulating the steady increase of current power. For instance, decelerating the escalation of current power might lead to larger coagulation volumes, potentially beneficial when treating sizable epileptogenic lesions. Real-time coagulation control using thermal MRI sequences has been applied in other thermal treatment methods, such as laser-induced thermal therapy for brain lesions and epilepsy. This strategy enables accurate planning of the thermal lesion with specific geometric requirements and substantial safety buffers. Future advancements in RF-TC could potentially leverage tools compatible with thermal MRI sequences, facilitating precise and monitored coagulation with enhanced safety and effectiveness.

An alternative area for enhancement is the assessment of various procedural parameters, including the duration of RF delivery, the count of coagulation sites, the acceleration of power increase, and variations in coagulated substrates. Grasping how these parameters influence the anatomical outcomes of TC, as exposed by post-thermocoagulation MRI or histological analysis of surgical specimens, could assist in refining the technique and optimizing treatment results.

Furthermore, it is crucial to recognize that RF-TC may not be appropriate for all patients or lesion categories. Although a significant number of patients attained seizure control and displayed cognitive enhancement post-surgery, a smaller group failed to demonstrate seizure control, regardless of surgical age, disease span, seizure variety, or negative MRI results. This underscores the intricate and multi-faceted nature of drug-resistant epilepsy, underlining the necessity for personalized, patient-focused therapeutic strategies.

In conclusion, SEEG-guided RF-TC offers several advantages as a therapeutic strategy for drug-resistant epilepsy, including minimal additional device placement, strong electroclinical evidence, and functional information. However, the technique has limitations, such as the lack of real-time lesion control during the procedure. Future advancements, including the integration of thermal MRI sequences and the evaluation of different procedural parameters, could further enhance the efficacy and safety of RF-TC. Continued research with larger patient cohorts and longer follow-up periods will be instrumental in validating these findings and optimizing treatment protocols for the benefit of paediatric patients with drug-resistant epilepsy.

Limitations of the study

The current study has several limitations warranting acknowledgment. Primarily, it comprises a single-centre retrospective analysis, potentially introducing selection bias and constraining the generalizability of its conclusions. Conducting a prospective, multicentre investigation with a larger patient cohort would be advantageous in substantiating these findings and providing more compelling evidence.

An additional drawback lies in the potential selection bias concerning patient inclusion. The case series encompasses a greater proportion of patients with nodular heterotopies than typically observed within surgical series involving drug-resistant focal epilepsy. This bias might have swayed the outcomes, as those with nodular heterotopies were deemed ideal candidates for RF-TC and possibly harboured a more favourable disposition towards the treatment. On the other hand, patients eligible for resective surgery but apprehensive about the associated risks may have opted against RF-TC in favour of a more conventional and potentially curative alternative. When interpreting the results, this selection bias must be considered.

Furthermore, the study did not provide a long-term evaluation of seizure outcomes. It remains unclear whether RF-TC can provide stable and long-lasting inactivation of the epileptogenic zone or if reorganization of epileptogenic networks may occur after temporary suppression provided by thermal lesioning [3,5,8]. Long-term follow-up is necessary to determine the durability of seizure control and assess the potential for tapering and discontinuation of antiepileptic medication in seizure-free patients.

Lastly, the study did not investigate real-time control of the lesion progression during the RF-TC procedure. Modulating the increase of current power has been shown to affect the coagulated volume in preliminary laboratory experiences. The integration of real-time thermal MRI sequences for lesion control could enhance the precision and safety of the procedure [2]. Future studies could explore the impact of different procedural parameters and evaluate the anatomical results of RF-TC using post-thermocoagulation MRI or histological examination of surgical specimens.

While the study provides valuable insights into the efficacy and safety of SEEG-guided RF-TC for drug-resistant epilepsy, its limitations, including its retrospective nature, selection bias, and lack of long-term evaluation, should be taken into consideration [1,4]. Further research with larger, prospective multicentre studies and extended follow-up periods is needed to confirm the findings and optimize treatment protocols for paediatric patients with drug-resistant epilepsy.

Conclusions

This study bolsters the potential of SEEG-guided RF-TC as a viable and safe treatment for paediatric patients grappling with drug-resistant epilepsy. The procedure led to seizure management and cognitive enhancement in the majority of the patient group. This therapeutic approach serves as an alternative for those not suitable for surgical resection, or those who prefer to indefinitely postpone open surgery.

SEEG-guided RF-TC emerges as a promising solution for drug-resistant focal epilepsy in children. It presents a comparably safer substitute to conventional surgical resection, enabling patients to manage seizures and boost cognitive function. Nonetheless, further investigations are required to overcome the existing study limitations and enhance the utilization of this therapy in a larger patient population.

Ethics approval and consent to participate

This research was executed adhering to the guidelines of the Declaration of Helsinki and received approval from the ethics committee of Beijing Children's Hospital Capital Medical University.

Disclosure

The authors report no conflict of interest.

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