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# Classification of electrical status epilepticus in sleep based on EEG patterns and spatiotemporal mapping of spikes

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**ABSTRACT**

***Objective.*** We firstly aimed to describe and classify EEG patterns in electrical status epilepticus in sleep (ESES), and secondly subclassify EEG patterns based on analysis of spikes using spatio-temporal mapping and electrical source analysis.

***Methods.*** Overnight EEGs (minimum: eight hours) of 30 children, aged 2-12 years, with ESES (spike-wave index: at least 50%) were selected. Average reference montage was used for dipole analysis and mapping. The location and orientation of the dipoles were determined by mapping positive and negative poles and applying the rules of mapping. The onset and propagation of the spikes and the latency between the two hemispheres (for bisynchronous spikes) were determined (based on source analysis using BESA research 7.1).

***Results.*** (1) ESES was classified as "generalised" (80%) and focal (20%) patterns; (2) the bisynchronous subtype in the "generalised" pattern was due to apparently synchronous bilateral activation of spikes (with lead-in of 20-60 ms from one hemisphere) with a tangential/oblique dipole (source analysis localised these spikes to around the peri-rolandic cortex); (3) the classic description of ESES spikes as "diffuse" spikes with bifrontal maxima is a misinterpretation using the 10-20 EEG system .Using voltage mapping and source analysis, cortical activation in the rolandic cortex was identified which imparts diffuse frontal negativity and parieto-occipital positivity; (4) ESES spikes showed intraspike and interspike dipole instability and the orientation of dipoles changed due to local spike propagation around the source and into the depth of the sulcus (which we refer to herein as "dancing dipoles"); and (5) focal ESES were classified as parietal, occipital and temporo-occipital patterns; a frontal ESES pattern was not seen.

***Significance.*** Based on detailed mapping and source analysis of ESES, we have successfully reinterpreted various misconceptions in the literature. We have simplified the interpretation of complicated EEG patterns by extracting the primary and propagated sources which aid the classification of ESES. As the dipole is always stable in self-limited childhood epilepsy with centrotemporal spikes, we believe that the phenomenon of an intrinsically unstable dipole is a reliable qualitative EEG marker of ESES.

**Key words:** epileptic encephalopathy, ESES, CSWS, electrical source analysis, voltage mapping, EEG synchronisation

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Electrical status epilepticus in sleep (ESES) refers to an epileptic encephalopathy in children with a marked potentiation of epileptiform activity in sleep leading to an EEG pattern of (near) continuous spikes and waves during non-rapid eye movement (non-REM) sleep [1-4]. Though initially, the term "ESES" was introduced as a purely "electrical" phenomenon [1], later studies [4-6] indicated that "electrical status epilepticus" was not entirely subclinical (as it initially appears due to a lack of direct electroclinical correlation during sleep). On the contrary, it was hypothesized to have an indirect and delayed effect on cognition, determined by the extreme activation of epileptiform abnormalities during sleep [7]. The EEG pattern of (near) continuous activation in sleep and its related patterns are also observed in other electroclinical conditions, such as Landau-Kleffner syndrome (LKS) and atypical benign partial epilepsy (pseudo-Lennox syndrome). In 1989, the Commission on Classification and Terminology (CCT) of the International League Against Epilepsy (ILAE) adopted the term "continuous spikes and waves during slow sleep" (CSWS) for the electroclinical syndrome with global neurocognitive regression and maintained the term "LKS" for epileptic encephalopathy with mainly language regression. Since then, ESES/CSWS have been used interchangeably in the literature. There has been an ongoing debate in various articles regarding these two terminologies and related concepts. Some authors [8, 9] have used "ESES" when referring to the EEG pattern and "CSWS" when referring to epileptic encephalopathy with global regression, while others [10] have contradicted this, stating that "CSWS" is the acronym that refers to an EEG pattern (*i.e.*, continuous spike-and-wave during sleep) and that it lacks any clinical implication. These authors added that "status epilepticus" (SE) is an established term that refers to an electroclinical condition, and not a mere EEG pattern. With an objective to settle this terminological and conceptual chaos, the latest ILAE position paper [11] has grouped together ESES/CSWS, LKS and related syndromes which show similar EEG patterns as "developmental and/or epileptic encephalopathy with spike-wave activation in sleep" (D/EE-SWAS). However, in our study we have maintained the term "ESES" to refer to the electroclinical syndrome with spike-wave activation in sleep, and as our study is based on EEG parameters, we have used the term "ESES" mainly to refer to the electrical correlate of this syndrome.

In the original series [5, 6, 12, 13], the EEG pattern of ESES was described as consisting of "generalized" or "diffuse" slow spike-waves at 1.3-2 Hz. Thereafter, various studies described ESES spikes in different ways, and the concept of secondary bilateral synchrony [2, 14-16] and focal ESES [5, 17, 18] patterns was described by some authors. Along with the clinical correlation, various quantitative EEG variables, such as the spike-wave index (SWI), spike frequency and spike strength [19], *etc.*, have been used extensively to electrically define ESES [7, 15, 20, 21] and used as EEG correlates of clinical evolution of childhood epilepsy with centrotemporal spikes (CECTS). However, many authors have elucidated the promising role of qualitative EEG variables, especially those which utilise independent component analysis for better electroclinical correlation. Such authors have suggested that an improved combination of clinical data and computer-aided EEG analysis will offer an opportunity to recognize "dangerous" EEG features early in the course of the syndrome, and thus it may be possible to foresee (and possibly prevent) evolution into ESES in patients at risk, but without overt encephalopathy [10, 21]. Although dipole analysis and source localisation have already been used in many previous studies for other childhood epileptic syndromes, such as Panayiotopoulos syndrome and self-limited CECTS [22-28], there are only very few studies in the literature that have utilised source analysis and spatio-temporal dynamics in ESES [19-31]. To our knowledge, until now, no serious efforts have been taken to classify EEG patterns in ESES based on the spatio-temporal dynamics of their spikes, in order to simplify the interpretation of these complicated EEG patterns. In this study, we aimed to firstly describe and classify EEG patterns in ESES, and secondly subclassify these EEG patterns based on analysis of spikes using spatio-temporal mapping and electrical source analysis.

## Methods

This study protocol was reviewed and approved by the institutional ethical committee (IEC) of the Government Medical College, Kozhikode, Kerala, India.

Overnight EEGs of 30 children, diagnosed with ESES, were included in the study. This sample was part of a larger group of patients followed at our clinical neurophysiology laboratory for several years using diverse modalities, including repeated overnight video-EEG and neuropsychological assessments for the purpose of various ongoing studies. For those children on immunomodulatory therapy (steroids), in addition to conventional antiepileptic medications, only EEGs taken before the initiation of this therapy were included in this study.

A child was diagnosed with ESES if he/she had all of the following parameters along with the presence or absence of seizures [2, 4, 11, 32]:

- 2-12 years of age.

• Overnight EEG monitoring for a minimum of eight hours including at least one hour of awake recording showing ESES with a SWI of at least 50% [4, 11].
• Neurological regression in at least two domains of development [21, 32] (cognitive, behavioural and/or motor domains). Children with abnormal baseline development were included if they had lost or shown regression in previously established developmental milestones in more than one domain. This was assessed by formal neuropsychological testing by our neuropsychiatry team. The following cognitive assessments were performed according to the child's age and degree of collaboration: the Standardized Raven's Progressive Matrices to quantify intelligence (IQ), the Vineland Adaptive Behaviour Scale (VSMS) to measure adaptive behaviour of the child, the Finger Tapping Test to assess motor speed, the Hand Tapping Test for motor coordination, the Colour Cancellation Test for sustained attention, the Spatial Span Board Test (WMS) for visual working memory, the Digit Span Test for focused attention, the Auditory Verbal Learning Test (AVLT) for verbal learning and memory, the REELS for receptive and expressive language skills, and the Child Behaviour Checklist (CBCL) to assess externalizing and internalizing behavioural problems.

Brain MRI with particular emphasis on an epilepsy protocol was performed in all 30 children.
Clinical data are summarised in *supplementary table 1*.
The SWI was used as the quantification technique to assess epileptiform activity [8, 20]. EEG recording was performed using the Natus video-EEG system with a sampling rate of 512 Hz and 25 recording electrodes placed according to the 10-20 system (F9, T9, P9, F10, T10, and P10 were added to "low rows") at a low frequency filter of 1 Hz and high frequency filter of 70 Hz, and reviewed with notch filter of 50 Hz. For study inclusion, EEG quantification was initially performed by visual scoring by two neurologists after reviewing the EEG in longitudinal bipolar and average reference montages. If a discrepancy of more than 10 points in SWI was present, a third reviewer calculated the epileptiform activity and the overall mean was calculated. Manual SWI was determined by looking for epileptiform discharges during the first 30 minutes of the first NREM sleep cycle. SWI was thus calculated by dividing the number of seconds with one or more spike-wave complexes in the 30-minute period by 1,800 and multiplying by 100 to express the results in percentage. When a spike-wave complex was located between two different one-second bins, it was only counted in the bin where the peak of the spike was located. We adopted this method from a previous published study [8], however, we only used the first NREM cycle as it is well known that SWI tends to be maximal in this cycle and is reduced in subsequent NREM cycles [7, 21, 32].

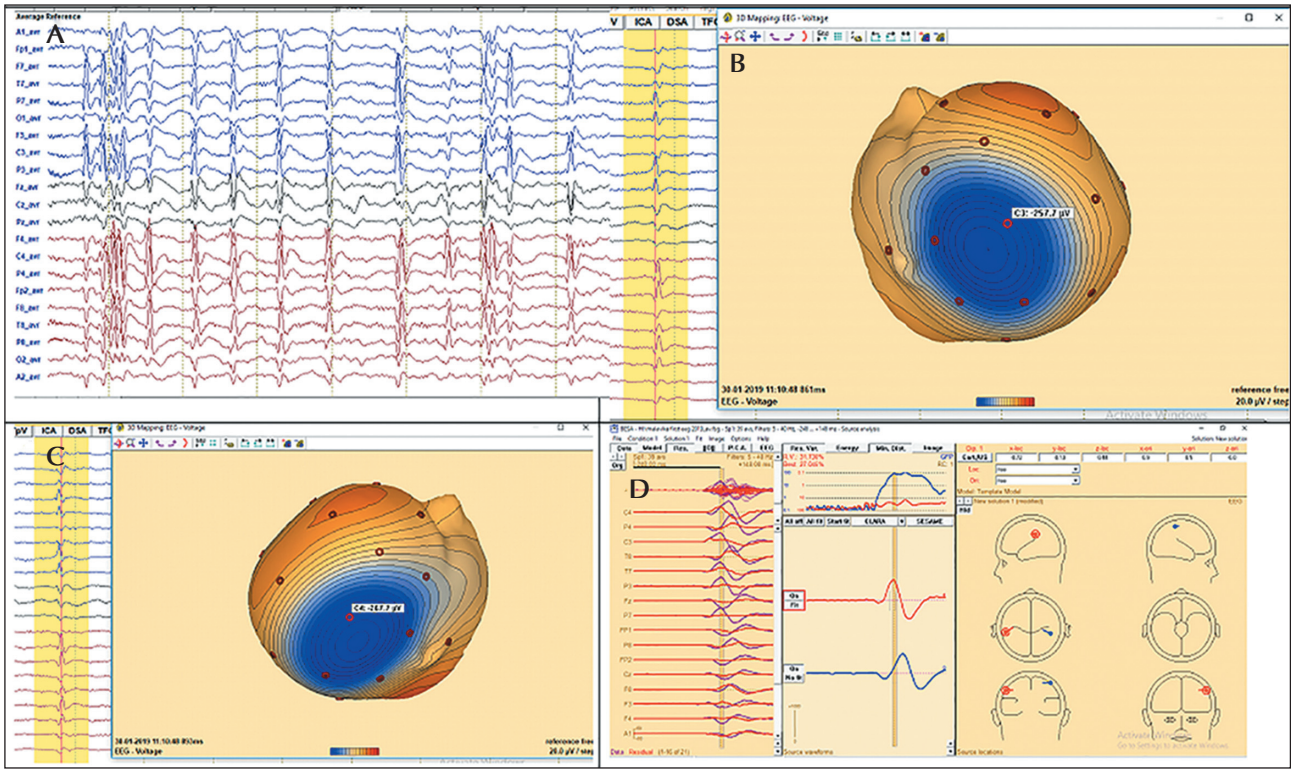
## Mapping, averaging and source analysis

Averaging of spikes and source localisation was performed by importing the raw EEG data into BESA (Brain Electrical Source Analysis) Research 7.1 software (BESA GmbH, Grafelfing, Germany). The same 30 minutes of EEG in the first NREM cycle, which was used to calculate the manual SWI, was selected for mapping, averaging and analysis.
Based on detailed visual analysis using the virtual average reference montage in BESA, a typical spike in ESES (template spike) was selected. This montage is a standard option in BESA software, based on estimating the voltage at defined locations of a sphere using spherical spline interpolation from the original EEG signal. The template is made by marking one typical spike from onset to the "positive" peak, and voltage topography of the template spike is assessed by 3D voltage mapping from the onset to peak. In case of radial orientation of voltage topography, source is taken at peak negativity. In case of tangential/oblique orientation, the source is localised using the following steps [33]:
• Peak negativity is connected to peak positivity
• The area with highest gradient (where the isoelectric lines are closest to each other) is identified.

The source is represented under this area and the surface of the cortical generator is located towards the negative polarity. Voltage mapping was also performed randomly on some of the morphologically similar "typical" spikes, and maps were compared for interspike variability. If any spikes from a different focus other than template spikes were found, they were also analysed by voltage mapping and the source was determined.
Using the template spike, a spatiotemporal pattern-matching algorithm combined with visual inspection was then used to identify similar spikes throughout the 30-minute EEG recording with a similarity threshold of 60% (this can be autoset in BESA) [19]. We did not use the entire sleep recording for pattern matching, as for maintaining uniformity, and as the ESES spikes were very frequent, the 30-minute EEG recording itself provided an adequate number of averages for source localisation. Template matchings were performed using a spatio-temporal search, as implemented by Besa. The spatio-temporal search implies that a principal component analysis (PCA) is used. Based on visual analysis, only the spikes with interspike interval of >one second were selected for

averaging. After template matching, spikes were averaged using zero-phase filters (low cut-off: 2 Hz; slope: 12 dB/octave; high cut-off: 35 Hz; slope: 24 dB/octave) and the total number of averages thus obtained was divided by 1,800 and multiplied by 100 to obtain the automated SWI. If there was a discrepancy of greater than 10% between the manual and automated SWIs, spikes were re-analysed visually and the template matching was either restarted with a modified template or additional templates were used depending on the nature of the discrepancy. More than one focus required more templates.

The averaged spike was used for source localization with a block epoch of -250 ms +150 ms around the spike peak. We used filters for source localization (low cut-off: 5 Hz; slope: 6 dB/octave; forward filter; high cut-off: 40-Hz zero phase; slope: 12 dB/octave). PCA was used to identify the number of components to be expected in the source model. Approximately, a 25-ms epoch (sampling rate: 200 Hz; five data points) was selected from the visually identified spike onset (0 ms) of the averaged spike. Using the single equivalent current dipole (ECD) model, the dipole onset was fitted and fitting interval adjusted such that one component dominated in the fit interval (approximately >=95% of activity on EEG). A second dipole was fitted to the peak interval similarly by keeping the onset dipole fixed in the model. Similarly, further dipoles were fitted to other peaks (if PCA showed other major components). The time interval between onset dipole and peak dipole and the interval between the peak dipoles (if any) was determined. If the time interval between the peak dipoles from the opposite hemisphere was >10 ms, the intraburst time difference variation was calculated. For this, we selected a minimum of 10 spike bursts of 4-6 seconds in the pre-averaged template-matched EEG data and calculated the latency between the peak from both hemisphere at the onset of burst, at 1.5 seconds from the beginning, and at the end [14, 34]. For each of the bursts, we studied whether the time differences were consistently present throughout the burst or not.

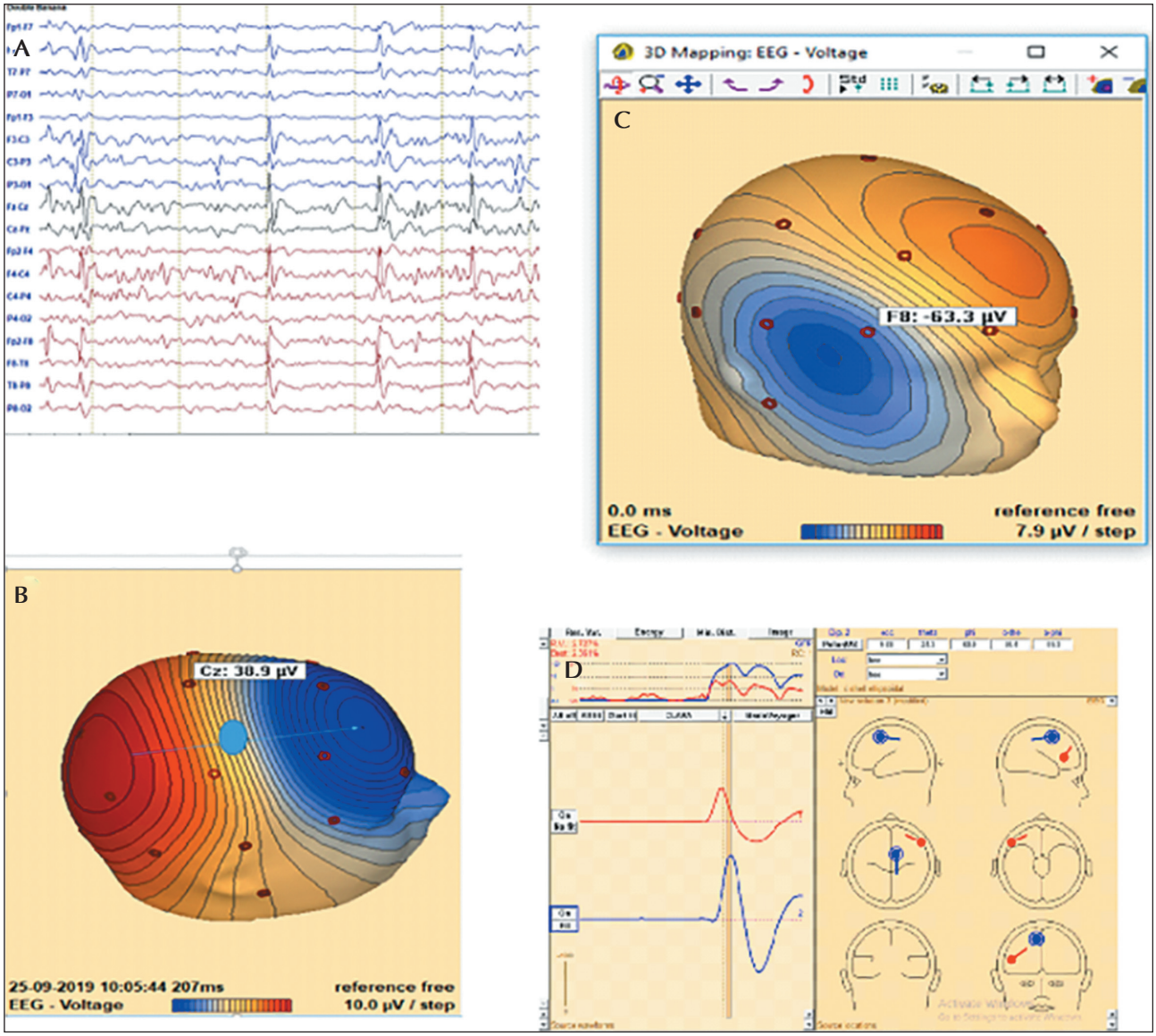



■ **Figure 1.** Bisynchronous ESES spikes. (A) Bilateral synchronous activation of centrotemporal spikes using the 10-20 EEG system. (B) Voltage mapping at the initial peak of the bisynchronous spike; the source in the left central region is shown after applying the rules of mapping. (C) Voltage mapping at the second peak of the bisynchronous spike shows a lag of 20 ms and source in the right central region with similar dipolar orientation. (D) Source analysis showing activation of bilateral peri-rolandic cortex with similar dipolar orientations.

We used realistic approximation models to match the age of the child for inverse problem-solving because individual brain MRI and digitized electrode position data were not available.

## Results

Based on preliminary visual analysis of spikes in the raw EEG data using the 10-20 system in average reference montage, EEG patterns in ESES were broadly




■ **Figure 2.** Focal-onset ipsilaterally propagated ESES spikes. (A) "Double banana" bipolar montage shows "generalised" spikes with bifrontal maxima. (B) 3D voltage mapping on the averaged spike. At the suspected "frontal" peak, the voltage map shows a tangential map with frontal diffuse negativity and parieto- occipital positivity. Applying the rules of mapping, the source is localised in the right centromedial region. These spikes give the false impression of "generalised" spikes with bifrontal predominance using the 10-20 system. This signifies the importance of considering the positive pole whenever mapping a spike with a tangential dipole. (C) Further analysis of the averaged spike at "onset" shows that the onset of the spike is in the right infero-lateral frontal region which is then propagated to the right centro-medial region. (D) Source analysis showing dipole onset in the right infero-lateral frontal region with propagation to the right medial central region (peak dipole).

▼ **Table 1.** Focal-onset limited propagated ESES spikes. Spikes are classified based on their foci of onset.

| Foci of onset | Number of cases | Percentage of unilateral propagated spikes (%) | Percentage of total generalised pattern (%) |
|---|---|---|---|
| Perirolandic | 4 | 40 | 16.67 |
| Parietal | 4 | 40 | 16.67 |
| Temporal | 1 | 10 | 4.17 |
| Parieto-Occipital | 2 | 20 | 8.33 |
| Frontal | 1 | 10 | 4.17 |

classified as "generalised" in 24 children (80%) and focal in six children (20%). The "generalised" pattern had diffuse EEG activity when visualised in average montage, with negative peaks present in both hemispheres across two or more non-contiguous regions of the brain. The focal pattern had limited focal EEG activity with negative peaks in ≤two contiguous regions in the brain (unilateral or bilateral).

## The "generalised" pattern

On further analysis based on voltage mapping and source analysis, the "generalised" pattern was further sub-classified as:

- ***"Bisynchronous" ESES spikes***

This was due to the "apparently" synchronous bilateral activation of spikes with a tangential/oblique dipole. This was seen in 10 children (33.33% of the total and 41.67% of those with the "generalised'" pattern). In all 10 children, voltage mapping performed on the template spikes before averaging showed shifting asymmetry in the leading hemisphere. Source analysis localised these spikes around the peri-rolandic cortex (*figure 1*) in eight children and the parieto-occipital cortex (*supplementary figure 1*) in two children. All 10 children showed activation of spikes from bilateral homologous areas of cortex with minor variations in orientation of their dipoles. Independent unilateral spikes with dipoles, similar to the apparently bisynchronous spike, were found in all these children. The time interval between the peak dipoles from both hemispheres was found to be 20.0-60.0 ms. There was no intraburst variation in time difference in any of our 10 children. As the interhemispheric time difference was longer than 10 ms without any intraburst variation in time difference, a mechanism of "secondary interhemispheric bilateral synchrony" type 1 [14, 34], compatible with transcallosal propagation, was postulated to be involved in the generation of these spikes.

- ***Focal-onset, ipsilaterally propagated ESES spikes***

These were seen in 12 children (40% of the total and 50% of those with the "generalised" pattern); the ESES spikes showed a consistent unilateral focal onset and ipsilateral spike propagation to a contiguous region in the brain or ultra-local spread to the opposite wall of the adjoining sulcus. This was usually associated with rotation of the dipolar orientation from the onset to the dipole peak which in turn gave a false impression of a diffuse "generalised" spikes using the 10-20 EEG system. Based on voltage mapping, these spikes had widespread negativity and positivity, usually lying far from the actual source. The intraspike instability (*figure 2*) due to their focal propagation patterns appeared on a source map as though the onset and dipole peaks were changing in orientation and undergoing rotation (which we refer to as a "dancing dipole phenomenon" to describe the intrinsic instability of these spikes). Propagation of these spikes was seen to the ipsilateral hemisphere in 10 children and to the midline cortex in two children. Widespread propagation across non-contiguous brain regions was not seen. The interval between dipole onset and peak was found to be 12.0-26.3 ms (mean: 20.3 ms). Although the spikes had an intrinsically unstable dipole which underwent propagation and rotation, interspike variability was not found in these spikes. This synchronising EEG phenomenon with consistent foci of onset and a homogeneous intrahemispheric propagation pattern, which is well preserved in thousands of ESES spikes and is consistently associated with a time interval between onset and the peak dipoles of >10 ms, points towards a possible mechanism of "secondary intrahemispheric synchrony" in the generation of these spikes.
Based on the different foci of onset, these spikes can be classified accordingly (as summarised in *table 1*).

- ***Mixed pattern***

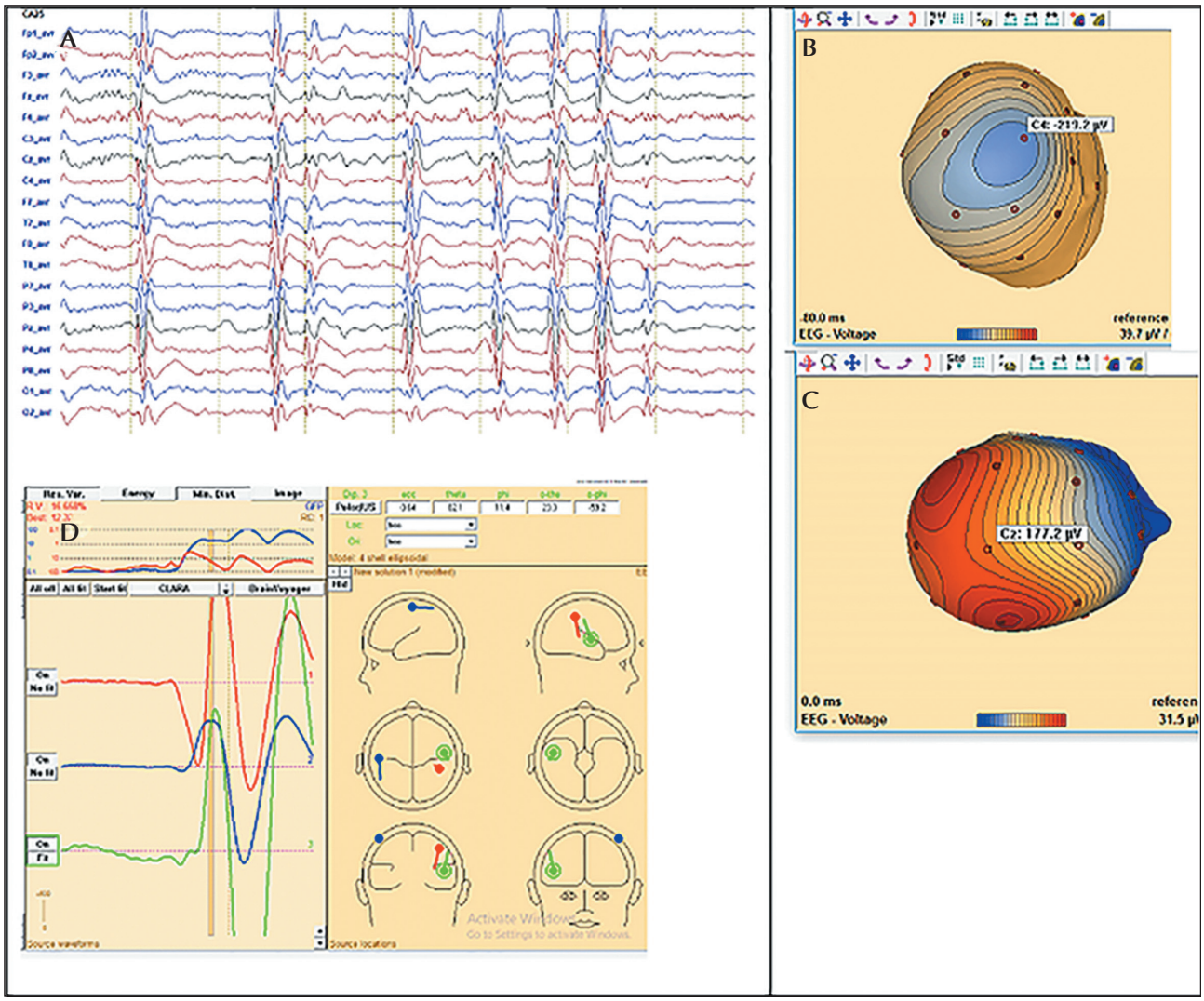
A mixed pattern was seen in two children in whom there was both bisynchronous activation along with

some intrahemispheric propagation and rotation of dipoles leading to complicated patterns (*figure 3*).

Some further observations were made regarding the "generalised" pattern which are summarised below:

• Based on analysis of 30 children with ESES, we did not observe any true "generalised" EEG pattern in ESES. All apparently "generalised" patterns observed in the 10-20 EEG system were actually "pseudo" generalised diffuse EEG activity due to either one of the mechanisms detailed above.

• We observed that the classic description of ESES, as generalised spikes with bifrontal maxima [2, 4, 11], was usually a misinterpretation in the 10-20 EEG system; using voltage mapping and source analysis, that it was generally due to cortical activation in the rolandic cortex which imparted diffuse frontal negativity and parieto-occipital positivity with positive phase reversal seen across the central region on average referential montage (*figure 2*).



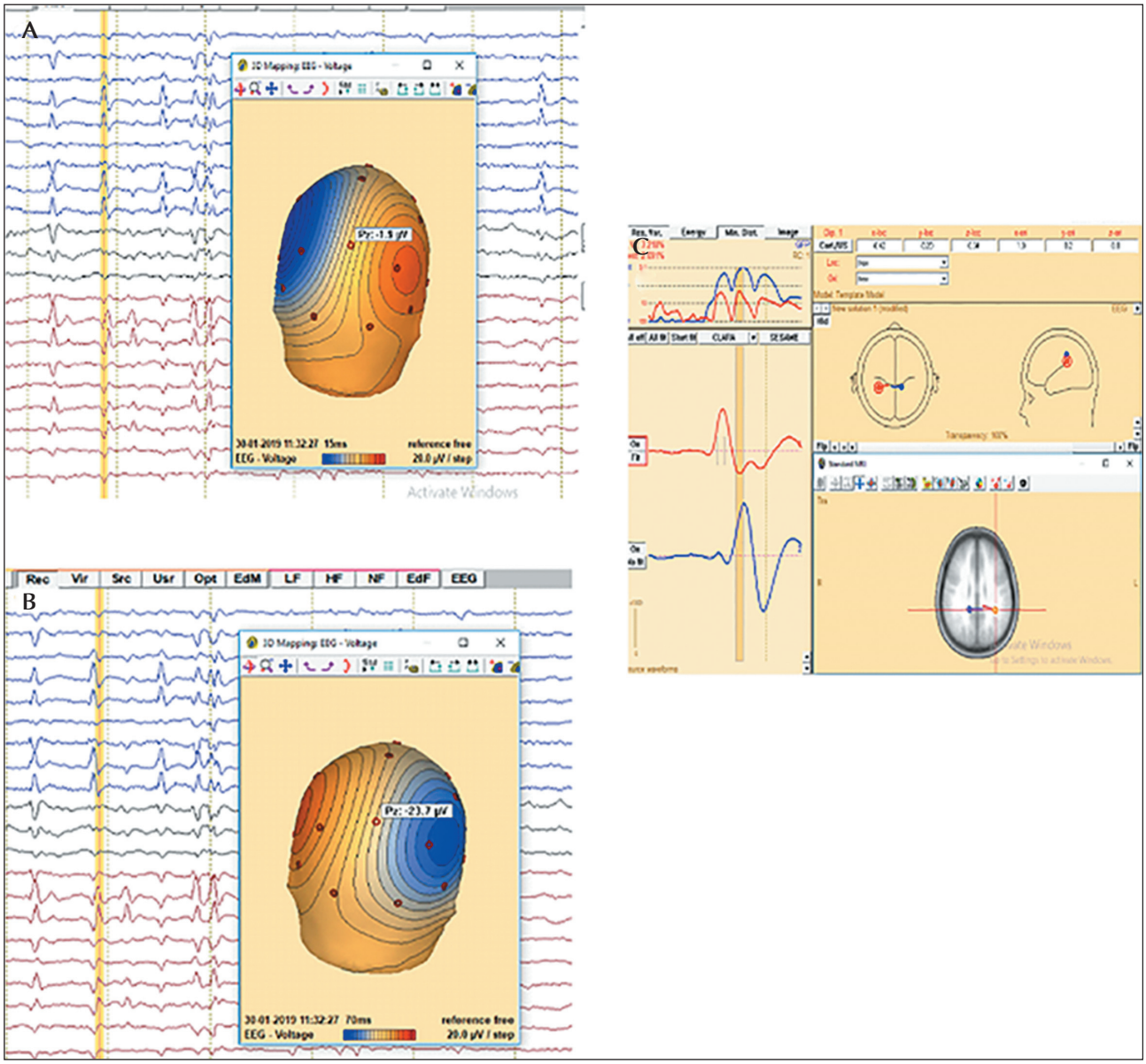

■ **Figure 3.** Mixed pattern. (A) ESES spikes on average reference montage showing "generalised" frontal predominant spikes. (B) Voltage mapping performed for averaged spikes showing onset in the right central region (radial dipole). (C) Voltage mapping performed at the peak of the spikes showing diffuse frontopolar negativity and parieto-occipital positivity. (D) Source analysis showing dipole onset (red) in the right perisylvian cortex, followed by activation of left rolandic cortex (blue tangential dipole), which is then followed by a peak (green dipole) associated with rotation of the dipole in the right perisylvian cortex. This depicts a complicated mixed pattern with bisynchronous activation along with intrahemispheric focal spike propagation in the right perisylvian cortex.

• Just as we described intraspike dipole instability in focal-onset, ipsilaterally propagated ESES spikes (the "dancing dipole" phenomenon), the bisynchronous type of ESES spikes was also observed to show interspike dipole variability, mostly due to the multiplication or diffusion of pre-existing localized spike discharges often seen in childhood focal epilepsies [35, 36] (*figure 4*).

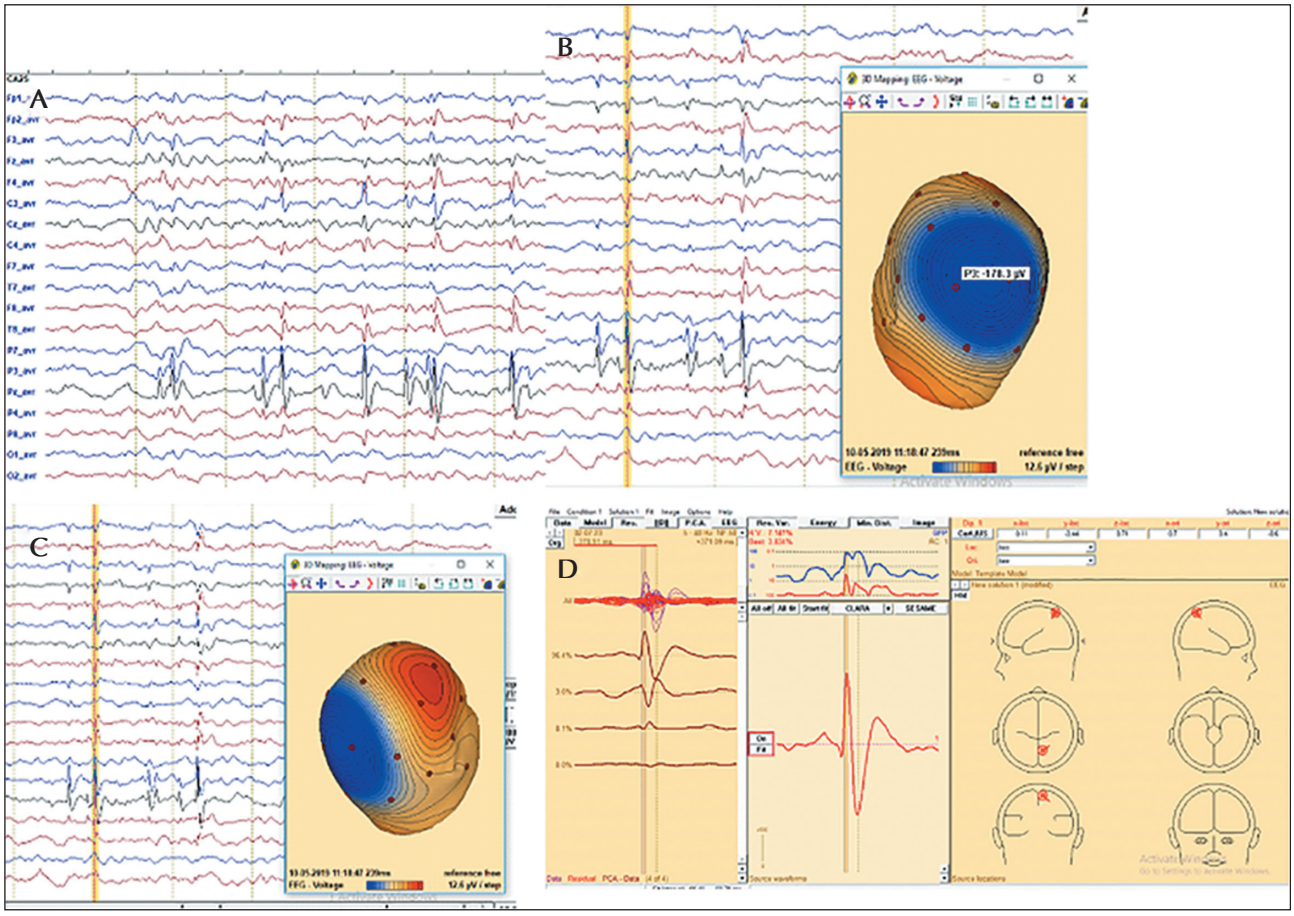
• In our series, we observed that the spikes associated with ESES demonstrated variable frequency, from 1-3.5 Hz or sometimes even higher in some of the epochs.

## The focal pattern

The focal pattern was seen in six children (20%). A parietal focal pattern was seen in four children (*figure 5, supplementary figure 2*), an occipital focal pattern in one child (*figure 6*), and a temporo-occipital focal




■ **Figure 4.** Interspike variability in ESES. (A-C) An almost identical bisynchronous spike in the same patient as in *Figure 1*, when viewed using the 10-20 EEG system, but voltage mapping shows a more posterior and medial localisation to bilateral parietal regions with a time difference of 55 ms.



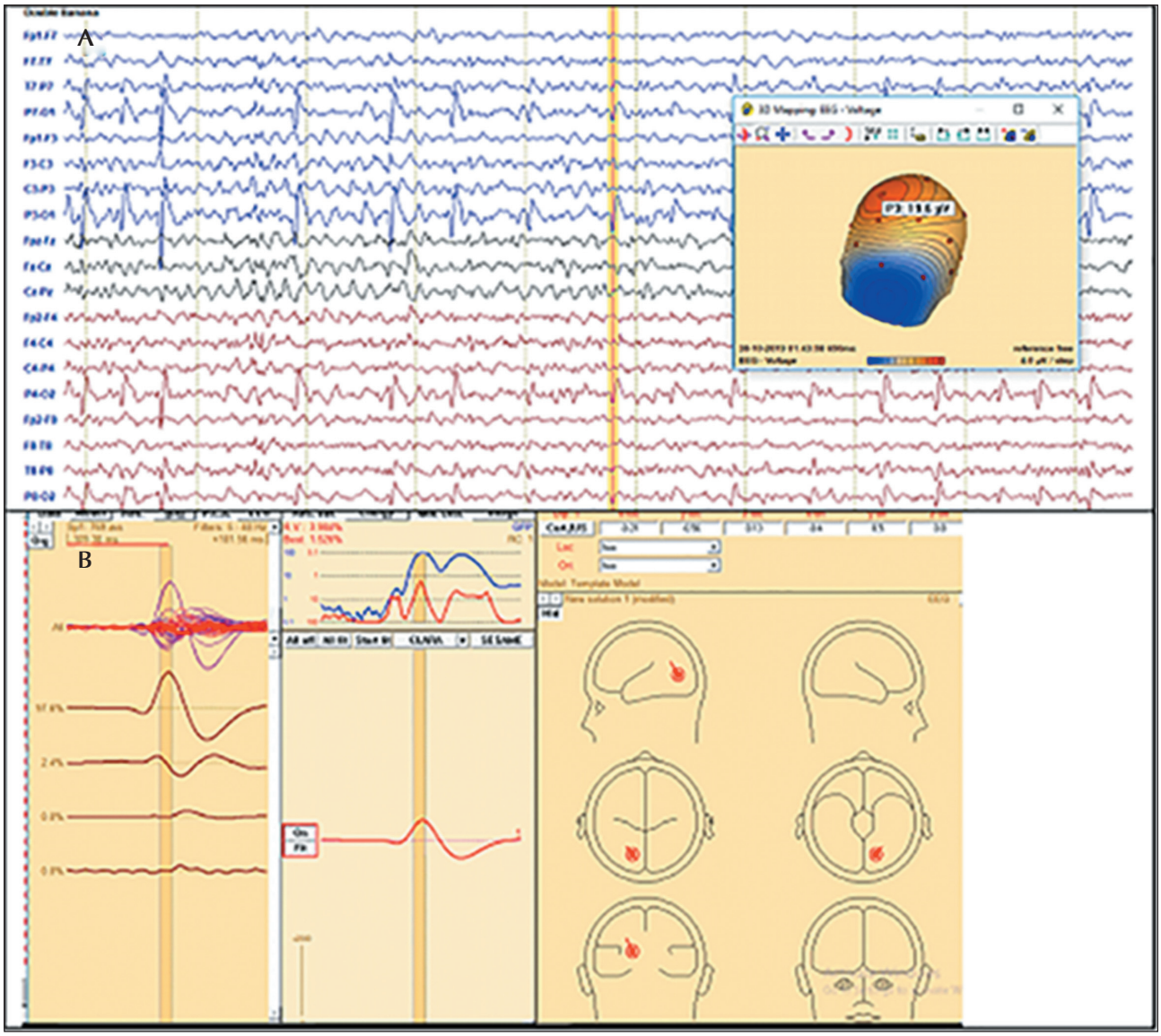

■ **Figure 5.** Parietal focal pattern in ESES. A) Focal ESES on average referential montage, seen as left parieto-central spikes. (B) Mapping performed on the peak of a spike giving the impression it is a left parietal spike. (C) Considering the positive pole and applying the rules of mapping, source is seen in the right medial parietal region. (D) Source localisation shows dipole onset in the right medial parietal cortex which then propagates to the left mesial parietal cortex (*supplementary figure 2*). This case illustrates that the 10-20 EEG system can show false lateralisation.

pattern in one child; a frontal focal ESES pattern was not seen.

## Discussion

Classification of ESES makes the interpretation of these complicated EEG patterns easier. As illustrated by various examples in our case series, it is not possible to classify the complicated EEG patterns in ESES and guess the "source" and propagation by using the 10-20 EEG system alone. Not taking into account the tangential dipolar nature of these spikes and considering only the negative poles while ignoring the positive poles has led to various misconceptions and misinterpretations in previous studies with regards to the spatio-temporal distribution of spikes in ESES. Based on detailed voltage mapping and source analysis in ESES, we have successfully re-interpreted some of these common misconceptions in the literature which are detailed below:

- Although most of the previous studies and reviews have concluded that ESES has "slow" spikes of 1-2.5 Hz [2, 4, 11, 26], in our case series, we observed that the spikes in ESES showed variable frequency, from 1-3.5 Hz or sometimes even higher in some of the epochs.
- Although various previous studies have already correctly described the diffuse ESES spikes as "apparently" bilateral synchronous and shown that ESES spikes are the result of secondary bilateral synchrony [2, 14, 15, 34, 37], many studies and reviews still continue to refer to ESES spikes as "generalised"




■ **Figure 6.** Occipital focal pattern in ESES. (A) Bipolar double "banana montage" showing continuous activation of bilateral occipital spikes with an "end-of-chain" phenomenon (inset), and voltage mapping at the peak of the spike. (B) Source analysis showing activation of the left mesial occipital cortex. Although the 10-20 EEG system showed bilateral occipital spikes, mapping and source localisation helped to lateralise to the left medial occipital region.

[4, 11, 17]. Our case series has shown that by analysing EEG spikes of 30 cases with ESES, none of them had a true "generalised" pattern and that "pseudo" generalisation, due to mechanisms detailed above, is the cause of this misinterpretation.

• Even though the role of disrupted thalamo-cortical connectivity, especially due to a perinatal insult as one of the inducers of the cortical generator focus in ESES, is substantiated by various previous studies, other studies have also shown that widespread spike activity in ESES results from secondary propagation, and the apparently generalized spike-wave is due to secondary bilateral synchronization, with interhemispheric delays compatible with transcallosal propagation [14, 15, 34]. Our study substantiates this finding as the bisynchronous type of ESES spikes in our study all demonstrated an interhemispheric time difference of >10 ms without any intraburst variation in time difference.

• Secondary intrahemispheric synchrony has been postulated, for the first time, as a predominant mechanism in the generation of spikes in ESES, other than secondary bilateral synchrony. This mechanism has been previously used to explain the secondary synchronous occipito-frontopolar spikes that occur in Panayiotopoulos syndrome [35]. Though the appearance in the 10-20 EEG system is a diffuse "generalized" pattern of spikes, voltage mapping and spatio-temporal analysis can help to sub-classify these spikes as "focal-onset ipsilaterally propagated", and as we have illustrated, they tend to have consistent foci of onset and a homogeneous propagation pattern. This can help clinicians to arrive at a hypothesis in order to plan structural and functional imaging studies to detect focal lesions. This also has scope to open a window of opportunity for early detection and surgical management in children with drug-resistant ESES due to structural causes. Few of the previous studies have already shown that callosotomy and resective surgery may be beneficial in drug-resistant ESES with structural causes [38]. Likewise, certain studies have also proven the efficacy of multiple subpial intracortical transections in patients with Landau-Kelffner syndrome [39].

• Focal ESES has previously been described in various studies as an unusual EEG pattern [5, 17, 18, 25, 37]. Compared to previous studies which mostly concluded that frontal localisation is most common in focal ESES, in our series, we found that the parietal focal pattern was the most common. Also, it is noteworthy that frontal localisation was absent in our cases with focal ESES. It is possible that this contradictory finding obtained in our series may be due to the utilisation of dipole analysis and voltage mapping for source localisation which were applied on ESES spikes in a few previous studies [29, 31].

• Self-limited CECTS is the most frequent idiopathic focal epilepsy of childhood and is the most frequent epilepsy syndrome in school-aged children. An increasing number of reports have previously shown a not so "benign" outcome and atypical evolution of this type of epilepsy. Some of the previous studies [22, 26, 27] have used averaged dipole analysis as a marker for predicting atypical outcome in patients with self-limited CECTS at diagnosis. The spikes of self-limited CECTS appear morphologically similar to those of ESES using the 10-20 EEG system, and as in ESES, show profound activation in sleep. Building on this aspect further, many previous studies have shown that self-limited CECTS is characterised by constantly stable dipoles [28]. Therefore, we believe that the phenomenon of intrinsic instability of dipoles associated with ESES spikes (the "dancing dipole phenomenon") can be used as a reliable qualitative EEG marker to identify spikes in ESES and to differentiate them from those associated with self-limited CECTS.

## Future prospects

In this study, only EEG criteria were considered for the classification of ESES, and future studies should be planned to incorporate clinical correlations with *e.g.* history, aetiological factors, treatment factors and evolution for further categorization. In future studies, it is desirable that different quantitative and qualitative EEG measures are calculated serially in the same population in order to determine the best EEG correlate (alone or in combination) of the clinical evolution of ESES. ■

## Key points

- EEG patterns in ESES were broadly classified as "generalised" and focal patterns.
- "Generalised" ESES spikes were further subclassified as bisynchronous, focal with limited propagation, and mixed patterns.
- Secondary bilateral synchrony and secondary intrahemispheric synchrony are important mechanisms for the generation of ESES spikes.
- Intrinsic instability of dipoles can be used as a qualitative EEG marker in ESES.

**Supplementary material.**

Supplementary data and summary slides accompanying the manuscript are available at www.epilepticdisorders.com.

**Disclosures.**

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## TEST YOURSELF

**(1) Which of the following are the terms used of the broad classification of ESES based on EEG patterns?**

A. Generalised and focal patterns
B. **Generalised and mixed patterns**
C. Generalised and limited patterns
D. Focal and diffuse patterns

**(2) How can the interpretation of ESES spikes be improved, relative to the 10-20 EEG system?**

A. By viewing in transverse montage
B. By applying voltage mapping and source analysis
C. By increasing the number of channels on EEG
D. By using invasive EEG

**(3) What are the mechanisms underlying the generation of ESES spikes?**

A. Thalamo-cortical synchrony and bilateral synchrony
B. Secondary intrahemispheric synchrony and secondary bilateral synchrony
C. Thalamo-cortical synchrony and intrahemispheric synchrony
D. Cortico-cortical synchrony and interhemispheric synchrony

**(4) Which of the following is the newly proposed qualitative EEG marker for ESES spikes, illustrated in this study?**

A. The dancing dipole phenomenon
B. The singing dipole phenomenon
C. The dipole orientation phenomenon
D. The stable dipole phenomenon

*Note: Reading the manuscript provides an answer to all questions. Correct answers may be accessed on the website, www.epilepticdisorders.com.*