

Research article

Temporal sampling shapes lesion-directed electric source imaging in temporal encephalocele epilepsy

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Abstract: Electric source imaging (ESI) is commonly reconstructed at selected time points of an interictal epileptiform discharge (IED), although the source may evolve during the discharge. We investigated whether temporal sampling alters the spatial relationship between the ESI maximum and a temporal encephalocele (TE). We performed a lesion-referenced secondary analysis of a previously reported TE cohort. Averaged IEDs were reconstructed independently with MUSIC and sLORETA. Source-to-TE distance at the main negative peak was compared with the earlier technically valid component, classified as onset, half-rise, or a preceding peak in polyphasic IEDs. The primary measure was paired change in source-to-TE distance ($\Delta D_{TE} = D_{peak} - D_{earlier}$). Complete paired measurements were available in 15 trajectories for each inverse method. Median source-to-TE distance increased from 13 to 28 mm with MUSIC (median $\Delta D_{TE} +10$ mm; Holm-adjusted $p=0.0032$) and from 15 to 26 mm with sLORETA (median $\Delta D_{TE} +5$ mm; adjusted $p=0.0032$). The peak source was farther from the TE in 12/15 MUSIC and 13/15 sLORETA trajectories. Direction of change agreed between methods in 11/12 jointly evaluable patients. The lesion-source relationship was time-dependent within the IED, indicating that temporal sampling materially influences lesion-directed ESI interpretation.

Keywords: electric source imaging, interictal epileptiform discharge, temporal sampling, temporal encephalocele; MUSIC; sLORETA

1. Introduction

Electric source imaging (ESI) is commonly calculated at selected time points of an interictal epileptiform discharge (IED), yet an IED is a temporally evolving event rather than a static source. Source estimates can change during the rising phase and peak as different neuronal populations are recruited and activity propagates. Simultaneous scalp-intracranial studies, high-density EEG studies, and time-resolved source-imaging work therefore show that ESI localization depends on the temporal component selected for reconstruction [5–10,17–19].

Temporal encephaloceles (TEs) provide a useful fixed anatomical reference with which to quantify this temporal dependence. In our previously reported cohort, semiautomated ESI localized to the TE in a subset of patients and spatial propagation of ESI maxima during the IED was described [1]. Those observations established that source localization can evolve during the discharge, but did not quantify whether that evolution systematically changes the source maximum's spatial relationship to the lesion. The present study addresses this distinct lesion-referenced question.

We therefore investigated whether temporal sampling within the IED alters source-to-TE distance. The primary endpoint was the paired change in source-to-TE distance

(ΔD_{TE}) between an earlier technically valid component and the main negative peak, analyzed independently with MUSIC and sLORETA. We additionally characterized the change according to whether the earlier component was onset, half-rise, or a preceding peak in a polyphasic IED, and assessed whether its direction was reproduced across inverse methods.

2. Materials and Methods

2.1 Study population

This secondary analysis used the previously reported cohort of 32 patients with temporal lobe epilepsy and TEs [1]. Ethics approval and consent procedures were as reported previously [1].

2.2 EEG acquisition, IED detection, and averaging

Long-term scalp EEG used the 10–20 system with additional T1/T2 electrodes. Persyst 14c detected and clustered IEDs. Clusters were ranked by detected spike count, and the two largest clinically valid clusters were selected and averaged; when only one major valid cluster was present, only that cluster was analyzed. Sphenoidal electrodes were not included in ESI [1].

2.3 Electric source imaging and temporal definitions

ESI was performed in Curry 9 using patient-specific realistic three-compartment head models. Source maxima were reconstructed independently with MUSIC and sLORETA. Only solutions with signal-to-noise ratio >2 and explained signal $>60\%$ were included in quantitative analyses [1].

Source maxima were evaluated at onset, half-rise, and the main negative peak. Onset and half-rise followed the predefined waveform criteria [1]. For this analysis, the earlier technically valid component was classified as onset (O-P), half-rise (H-P), or a preceding peak in a polyphasic IED (P-P).

2.4 Lesion-referenced distance

The TE served as the fixed anatomical reference. Source-to-TE distance was measured from the ESI source maximum to the TE center; for multiple ipsilateral TEs at the same temporal pole, the largest TE was used. The primary endpoint was $\Delta D_{TE} = D_{peak} - D_{earlier}$. Positive values indicate a source farther from the TE at the main peak.

2.5 Statistical analysis

Earlier and peak source-to-TE distances were compared separately for MUSIC and sLORETA using two-sided Wilcoxon signed-rank tests, with Holm correction across the two primary tests. Rank-biserial effect sizes were calculated. O-P, H-P, and P-P trajectories were summarized descriptively because subgroup sizes were small and did not support inferential comparison. Cross-method robustness was assessed by agreement in the direction of ΔD_{TE} among patients with complete paired measurements for both methods. Associations of ΔD_{TE} with IED frequency and the number of spikes contributing to the analyzed average were exploratory robustness checks only.

Ethics approval and consent procedures for the original cohort were as previously reported [1].

3. Results

3.1 Analysis population

Of the original 32-patient cohort, 20 had TE-directed ESI by at least one inverse method, as previously reported [1]. The present temporal analysis included 16 MUSIC and 17 sLORETA method-specific datasets with temporal source-to-TE measurements.

Complete earlier-versus-peak distance measurements were available in 15 cases for each method; cases without a technically valid earlier quantitative measurement were excluded from the paired analysis.

3.2 Primary lesion-distance analysis

With MUSIC (n=15), median source-to-TE distance increased from 13.0 mm (IQR 11.0–20.5) at the earlier component to 28.0 mm (24.0–33.0) at the main peak. Median ΔD_{TE} was +10.0 mm (5.5–23.0), with a rank-biserial effect size of 0.924 ($p=0.0023$; Holm-adjusted $p=0.0032$). The peak source was farther from the TE in 12/15 trajectories, unchanged in one, and closer in two.

With sLORETA (n=15), median source-to-TE distance increased from 15.0 mm (IQR 11.0–20.0) to 26.0 mm (18.0–30.0). Median ΔD_{TE} was +5.0 mm (4.5–15.0), with a rank-biserial effect size of 0.925 ($p=0.0016$; Holm-adjusted $p=0.0032$). The peak source was farther from the TE in 13/15 trajectories and closer in two.

3.3 Influence of temporal sampling and cross-method consistency

The earlier component was onset (O-P) in 7, half-rise (H-P) in 6, and a preceding peak (P-P) in 3 MUSIC datasets; corresponding counts for sLORETA were 8, 7, and 2. Among complete pairs, median ΔD_{TE} was +22 mm for MUSIC O-P, 0 mm for H-P, and +13 mm for P-P; corresponding sLORETA values were +15 mm, +3 mm, and +9 mm. Thus, both inverse methods showed the same descriptive pattern: onset-to-peak trajectories had the largest lesion-relative change, whereas half-rise-to-peak trajectories showed little additional change. Because these groups were small and represented different IED morphologies rather than repeated sampling of all phases in every patient, no inferential comparison among temporal categories was performed.

Twelve patients had complete paired measurements with both inverse methods. The direction of ΔD_{TE} agreed in 11/12 (91.7%), supporting reproducibility of the temporal effect across MUSIC and sLORETA.

As exploratory robustness checks, ΔD_{TE} was not associated with IED frequency or with the number of spikes contributing to the analyzed average (all $p>0.38$).

The primary paired source-to-TE distance results are summarized in Table 1. Individual paired trajectories are shown in Figure 1.

3.4. Figures, Tables and Schemes

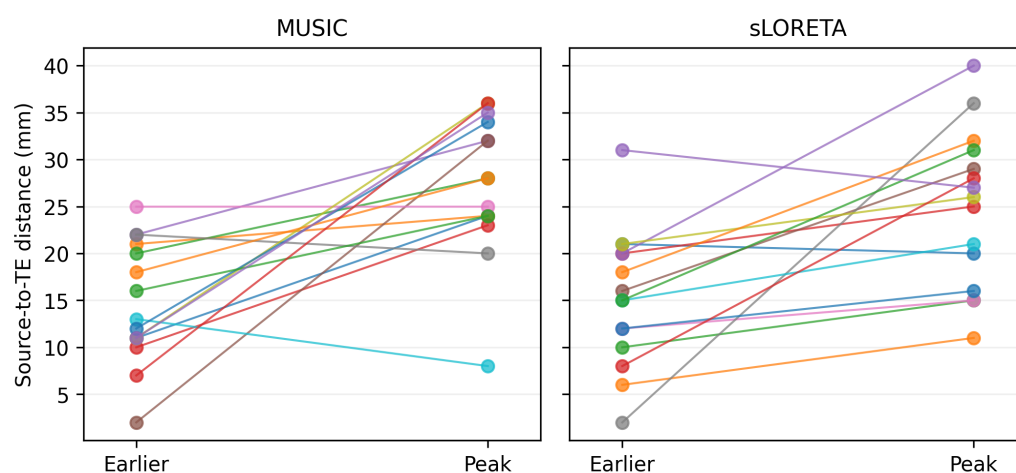


Figure 1. Paired source-to-TE distance at the earlier technically valid IED component and the main negative peak. Each line represents one complete patient-method trajectory.

Table 1. Primary paired source-to-TE distance analysis

Measure	MUSIC	sLORETA
Complete pairs, n	15	15
Earlier component, median (IQR), mm	13.0 (11.0-20.5)	15.0 (11.0-20.0)
Main peak, median (IQR), mm	28.0 (24.0-33.0)	26.0 (18.0-30.0)
ΔD_{TE} , median (IQR), mm	+10.0 (5.5-23.0)	+5.0 (4.5-15.0)
Peak farther / equal / closer	12 / 1 / 2	13 / 0 / 2
Rank-biserial correlation	0.924	0.925
Wilcoxon p; Holm-adjusted p	0.0023; 0.0032	0.0016; 0.0032

4. Discussion

The principal finding is that the spatial relationship between an ESI source maximum and a TE changes systematically across the IED. From an earlier technically valid component to the main negative peak, median source-to-TE distance increased by 10 mm with MUSIC and 5 mm with sLORETA. The peak source was farther from the TE in 12/15 and 13/15 trajectories, respectively, with large rank-biserial effect sizes and Holm-adjusted $p=0.0032$ for both methods. Moreover, the direction of change agreed across inverse methods in 11/12 patients with complete paired data. This paired lesion-referenced analysis extends the previous cohort report by quantifying the consequence of temporal sampling for the apparent source-lesion relationship rather than re-evaluating TE localization or propagation prevalence [1].

The temporal-category analysis adds a second observation. With both inverse methods, onset-to-peak trajectories showed the largest descriptive increase in source-to-TE distance, whereas half-rise-to-peak trajectories showed little additional change; preceding-peak-to-main-peak trajectories were intermediate. This pattern is consistent with the broader literature showing that ESI estimates can change substantially over the rising phase of an IED and that the selected reconstruction time point influences localization [7–10,17–19]. However, the present subgroups are small and consist of different IED morphologies. They therefore do not establish that onset is an optimal sampling point or that displacement occurs predominantly before half-rise. Rather, they show that the magnitude of the lesion-relative difference is sensitive to which earlier component is sampled.

The use of a TE as a fixed anatomical reference allows this temporal effect to be expressed in millimetric lesion-relative terms. Cox et al. reported ESI sources approximately 22–23 mm from the TE center and proposed propagated activity as one possible explanation for source-lesion offset [11]. Our analysis addresses the complementary within-IED question: in the same patient-method trajectory, the apparent source-lesion distance can change materially according to the sampled component. Importantly, proximity to the TE should not be equated with electrophysiological accuracy; the TE is an anatomical reference rather than direct intracranial ground truth.

Several features support the robustness of the primary observation. The analysis is paired, so each trajectory serves as its own anatomical reference; the effect is present with two independent inverse methods; and the direction of change is concordant across methods in 91.7% of jointly evaluable patients. The magnitude of ΔD_{TE} was not related to IED frequency or the number of spikes contributing to the average, although these exploratory checks are not evidence of equivalence. Absolute millimetric localization remains influenced by electrode density, head modeling, source depth, signal quality, and inverse method [2–4,12–14]. Earlier components may also be less affected by propagation while having lower signal-to-noise ratio [4,17,19].

The principal limitations are the retrospective secondary design, the small number of complete paired trajectories, standard-density EEG, and missing earlier measurements when technical quality criteria were not met. The temporal categories were too small for inferential comparison and were not repeated measurements of onset,

half-rise, and peak in every patient; consequently, the subgroup pattern should be considered hypothesis-generating. In addition, the TE is a structural anatomical reference rather than intracranial electrophysiological ground truth. These limitations restrict claims about accuracy or an optimal reconstruction time point, but do not negate the paired observation that source-to-TE distance changes across the IED.

5. Conclusions

Source-to-TE distance changed systematically across the IED and usually increased from an earlier technically valid component to the main negative peak with both MUSIC and sLORETA. The direction of this change was highly concordant across inverse methods, while descriptive differences among onset-, half-rise-, and preceding-peak trajectories indicate that the apparent lesion-source relationship is sensitive to the temporal component selected for reconstruction. Temporal sampling should therefore be considered explicitly when interpreting lesion-directed interictal ESI; these data do not establish a universally optimal sampling point.

Supplementary Materials: No additional supplementary material is provided.

Author Contributions: Conceptualization, D.-C.A.; methodology, D.-C.A.; formal analysis, D.-C.A.; data curation, D.-C.A.; visualization, D.-C.A.; writing—original draft preparation, D.-C.A.; writing—review and editing, D.-C.A. and I.-D.C.; supervision, I.-D.C. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Research Ethics Committee of the University of Medicine and Pharmacy from Iasi (324/18.06.2023)

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: Deidentified derived data supporting the secondary analyses are available from the corresponding author upon reasonable request and subject to the consent framework, institutional authorization, and data-protection requirements governing the original Freiburg cohort.

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Conflicts of Interest: The authors declare no conflict of interest.

References

1. Antal DC; Altenmüller DM; Dümpelmann M, et al. Semiautomated electric source imaging determines epileptogenicity of encephaloceles in temporal lobe epilepsy. *Epilepsia* 2024, 65, 651–663. <https://doi.org/10.1111/epi.17879>.
2. Michel CM; Brunet D. EEG source imaging: a practical review of the analysis steps. *Front Neurol.* 2019;10:325. <https://doi.org/10.3389/fneur.2019.00325>.
3. Brinkmann BH. Technical considerations in EEG source imaging. *J Clin Neurophysiol* 2024, 41, 2–7. <https://doi.org/10.1097/WNP.0000000000001029>.
4. Vogrin SJ; Plummer C. EEG source imaging-clinical considerations for EEG acquisition and signal processing for improved temporo-spatial resolution. *J Clin Neurophysiol* 2024, 41, 8–18. <https://doi.org/10.1097/WNP.0000000000001023>.
5. Tao JX; Ray A; Hawes-Ebersole S; Ebersole JS. Intracranial EEG substrates of scalp EEG interictal spikes. *Epilepsia* 2005, 46, 669–676. <https://doi.org/10.1111/j.1528-1167.2005.11404.x>.
6. Ray A; Tao JX; Hawes-Ebersole SM; Ebersole JS. Localizing value of scalp EEG spikes: a simultaneous scalp and intracranial study. *Clin Neurophysiol* 2007, 118, 69–79. <https://doi.org/10.1016/j.clinph.2006.09.010>.
7. Lantz G; Spinelli L; Seeck M; Grave de Peralta Menendez R; Sottas CC; Michel CM. Propagation of interictal epileptiform activity can lead to erroneous source localizations: a 128-channel EEG mapping study. *J Clin Neurophysiol* 2003, 20, 311–319. <https://doi.org/10.1097/00004691-200309000-00003>.

8. Măliia MD; Meritam P; Scherg M, et al. Epileptiform discharge propagation: analyzing spikes from the onset to the peak. *Clin Neurophysiol* 2016, 127, 2127–2133. <https://doi.org/10.1016/j.clinph.2015.12.021>.
9. Vorderwülbecke BJ; Carboni M; Tourbier S, et al. High-density electric source imaging of interictal epileptic discharges: how many electrodes and which time point? *Clin Neurophysiol* 2020, 131, 2795–2803. <https://doi.org/10.1016/j.clinph.2020.09.018>.
10. van de Velden D; Heide EC; Bouter C; Bucerius J; Riedel CH; Focke NK. Effects of inverse methods and spike phases on interictal high-density EEG source reconstruction. *Clin Neurophysiol* 2023, 156, 4–13. <https://doi.org/10.1016/j.clinph.2023.08.020>.
11. Cox BC; Agashe SH; Smith KM, et al. EEG source localization in temporal encephalocles: concordance with surgical re-section and clinical outcomes. *J Clin Neurophysiol* 2024, 41, 515–521. <https://doi.org/10.1097/WNP.0000000000001021>.
12. Unnwongse K; Rampp S; Wehner T, et al. Validating EEG source imaging using intracranial electrical stimulation. *Brain Commun.* 2023, 5, fcad023. <https://doi.org/10.1093/braincomms/fcad023>.
13. Horrillo-Maysonnial A; Avigdor T; Abdallah C, et al. Targeted density electrode placement achieves high concordance with traditional high-density EEG for electrical source imaging in epilepsy. *Clin Neurophysiol* 2023, 156, 262–271. <https://doi.org/10.1016/j.clinph.2023.08.009>.
14. Heers M; Chowdhury RA; Hedrich T, et al. Localization accuracy of distributed inverse solutions for electric and magnetic source imaging of interictal epileptic discharges in patients with focal epilepsy. *Brain Topogr* 2016, 29, 162–181. <https://doi.org/10.1007/s10548-014-0423-1>.
15. Matarrese MAG; Loppini A; Fabbri L, et al. Spike propagation mapping reveals effective connectivity and predicts surgical outcome in epilepsy. *Brain* 2023, 146, 3898–3912. <https://doi.org/10.1093/brain/awad118>.
16. Hyppönen J; Eronen H; Saarela A, et al. Clinical utility of semi-automated EEG electric source imaging of interictal discharges in presurgical evaluation and surgical treatment decision making. *Front Neurol.* 2025;16:1598265. <https://doi.org/10.3389/fneur.2025.1598265>.
17. Aydin Ü; Vorwerk J; Dümpelmann M, et al. Combined EEG/MEG can outperform single modality EEG or MEG source reconstruction in presurgical epilepsy diagnosis. *PLoS One.* 2015, 10, e0118753. <https://doi.org/10.1371/journal.pone.0118753>.
18. Wang G; Worrell G; Yang L; Wilke C; He B. Interictal spike analysis of high-density EEG in patients with partial epilepsy. *Clin Neurophysiol* 2011, 122, 1098–1105. <https://doi.org/10.1016/j.clinph.2010.10.043>.
19. Strobbe G; Carrette E; López JD, et al. Electrical source imaging of interictal spikes using multiple sparse volumetric priors for presurgical epileptogenic focus localization. *Neuroimage Clin* 2016, 11, 252–263. <https://doi.org/10.1016/j.nicl.2016.01.017>.