Sensitivity of quantitative EEG for seizure identification in the intensive care unit

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ABSTRACT

Objective: To evaluate the sensitivity of quantitative EEG (QEEG) for electrographic seizure identification in the intensive care unit (ICU).

Methods: Six-hour EEG epochs chosen from 15 patients underwent transformation into QEEG displays. Each epoch was reviewed in 3 formats: raw EEG, QEEG + raw, and QEEG-only. Epochs were also analyzed by a proprietary seizure detection algorithm. Nine neurophysiologists reviewed raw EEGs to identify seizures to serve as the gold standard. Nine other neurophysiologists with experience in QEEG evaluated the epochs in QEEG formats, with and without concomitant raw EEG. Sensitivity and false-positive rates (FPRs) for seizure identification were calculated and median review time assessed.

Results: Mean sensitivity for seizure identification ranged from 51% to 67% for QEEG-only and 63%–68% for QEEG + raw. FPRs averaged 1/h for QEEG-only and 0.5/h for QEEG + raw. Mean sensitivity of seizure probability software was 26.2%–26.7%, with FPR of 0.07/h. Epochs with the highest sensitivities contained frequent, intermittent seizures. Lower sensitivities were seen with slow-frequency, low-amplitude seizures and epochs with rhythmic or periodic patterns. Median review times were shorter for QEEG (6 minutes) and QEEG + raw analysis (14.5 minutes) vs raw EEG (19 minutes; $p = 0.00003$).

Conclusions: A panel of QEEG trends can be used by experts to shorten EEG review time for seizure identification with reasonable sensitivity and low FPRs. The prevalence of false detections confirms that raw EEG review must be used in conjunction with QEEG. Studies are needed to identify optimal QEEG trend configurations and the utility of QEEG as a screening tool for non-EEG personnel.

Classification of evidence review: This study provides Class II evidence that QEEG + raw interpreted by experts identifies seizures in patients in the ICU with a sensitivity of 63%–68% and FPR of 0.5 seizures per hour. *Neurology*® 2016;87:935–944

GLOSSARY

ACNS = American Clinical Neurophysiology Society; **aEEG** = amplitude-integrated EEG; **CCEMRC** = Critical Care EEG Monitoring Research Consortium; **CDSA** = color density spectral array; **cEEG** = continuous EEG; **CSA** = compressed spectral array; **FPR** = false-positive rate; **ICU** = intensive care unit; **LPD** = lateralized periodic discharge; **Q** = quantitative EEG alone; **QEEG** = quantitative EEG; **QR** = quantitative EEG with raw EEG; **R** = raw EEG without quantitative EEG; **SzD** = seizure detection algorithm.

Electrographic seizures occur in 8%–48% of critically ill patients[1–8] and can be found in any critical care setting.[3] Minimizing delay to diagnosis of nonconvulsive status epilepticus is critical as therapeutic interventions are most effective when initiated early.[9,10]

Increasing awareness of electrographic seizures has led to a growing demand for continuous EEG (cEEG) monitoring, but this is a labor and time-intensive process. To facilitate interpretation of prolonged EEG recordings, several quantitative EEG (QEEG) tools have been developed. QEEG is the visual representation of statistically transformed raw EEG signals. The most

Supplemental data at Neurology.org

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commonly used QEEG tool is compressed spectral array (CSA), which consists of a color display representing power in various frequency bands. Other QEEG techniques display EEG data based on amplitude (amplitude-integrated EEG [aEEG]; envelope trend), rhythmicity (rhythmicity spectrogram), or spectral symmetry (asymmetry index and spectrogram). These tools are used to highlight significant electrographic events on cEEG and identify subtle EEG changes over prolonged periods of time. There have been few studies assessing the sensitivity of QEEG for seizure identification and most are single-center, pediatric studies,[11–21] or focused on the utility of single trends, such as aEEG[22] or CSA.[23] A systematic assessment of the accuracy of a panel of QEEG trends used in daily clinical practice is lacking.

METHODS This study evaluated the sensitivity of a panel of commonly applied QEEG techniques, with and without the ability to see the corresponding raw EEG, for identification of seizures in critically ill patients when used by experts from multiple institutions.

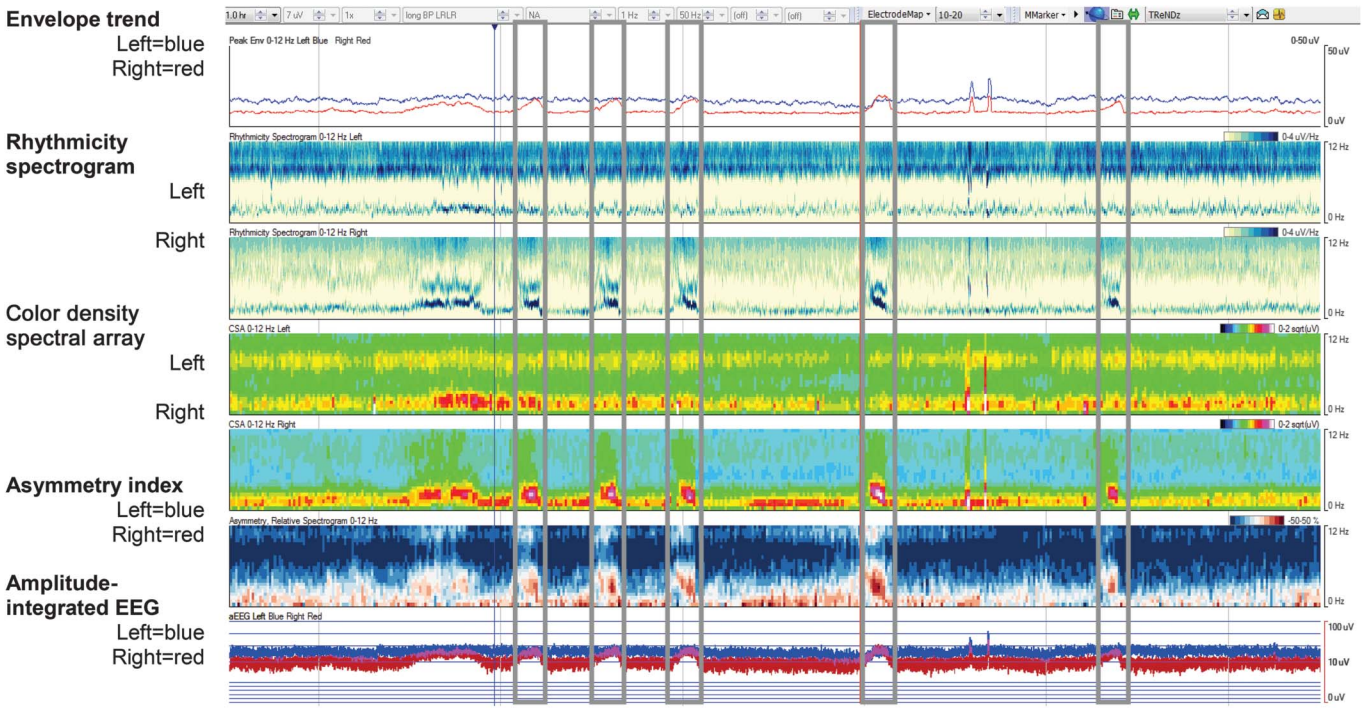
Standard protocol approvals, registrations, and patient consents. This study was approved by the institutional review board at Emory University and was granted a waiver of informed consent.

cEEG recordings. Using a clinical database, we identified cEEG recordings performed in patients admitted to the intensive care unit (ICU) between 2008 and 2010 for any of the following indications: treatment of refractory status epilepticus, suspicion of seizures, or management of intracranial pressure. Six-hour EEG epochs from 15 patients with and without seizures were selected by one of the authors (H.A.H.) to represent a variety of EEG findings commonly encountered in the critical care setting such as electrographic seizures, rhythmic delta activity, and periodic discharges. Digital EEG recordings were obtained using commercially available CT/MRI compatible electrodes that were placed according to the International 10–20 system.

All 15 EEG recordings (standardized 16-channels displayed, longitudinal bipolar montage, sampling rate 500 Hz) were analyzed with QEEG tools available in the Insight II EEG review software version 11 (Persyst Inc., Prescott, AZ). Specific QEEG tools included in the analysis for review were seizure probability, envelope trend, CSA, rhythmicity spectrogram, asymmetry spectrogram, and aEEG (figure 1; table e-1 at Neurology.org). One hour of QEEG data was displayed per screen on a 24-inch high-resolution (1,600 × 1,200 pixels) monitor, such that 4.4 horizontal pixels represented 10 seconds of raw EEG data.

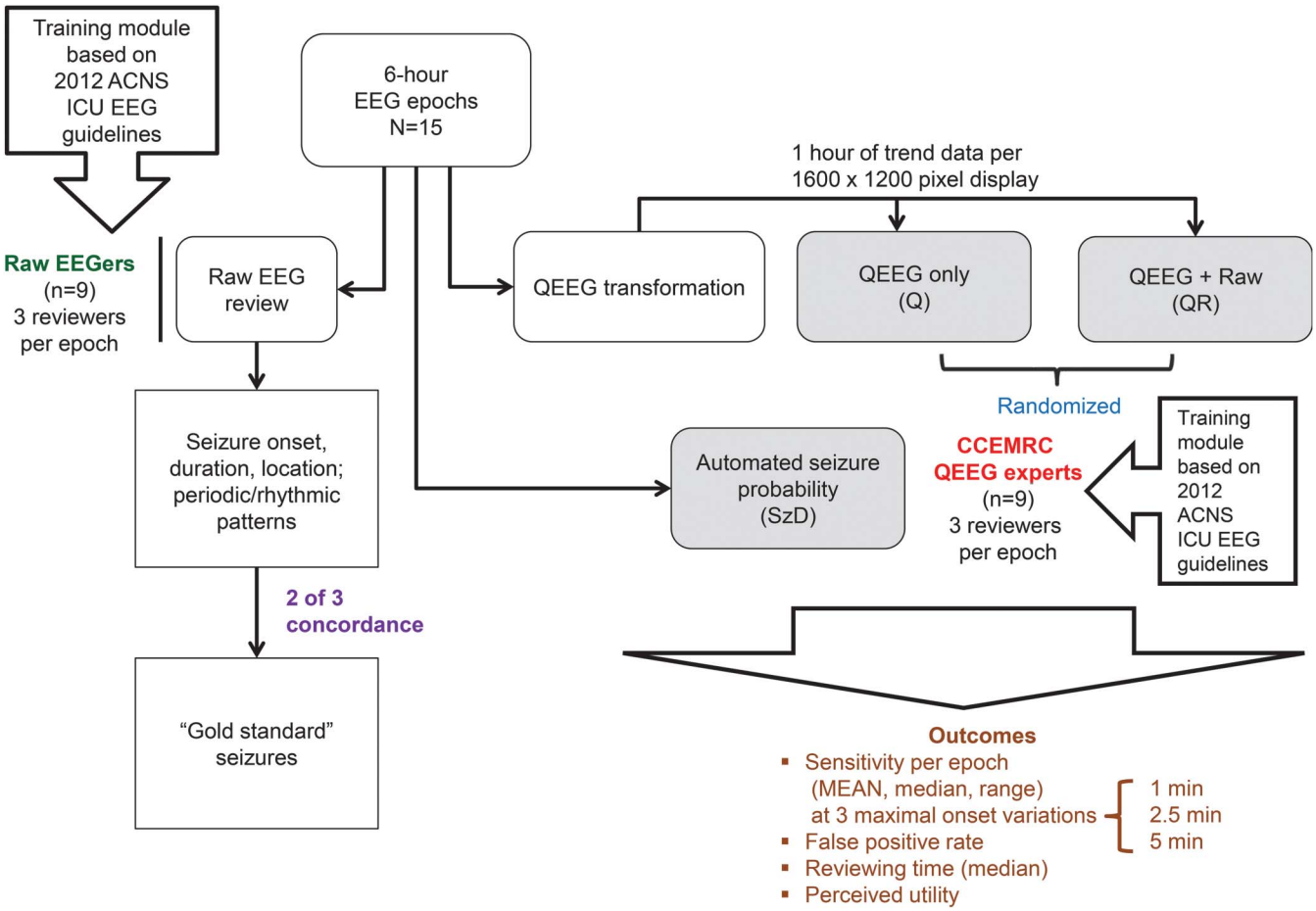
cEEG review. Each EEG epoch was reviewed in 3 formats: raw EEG without QEEG (R), QEEG with raw EEG (QR), and QEEG alone (Q) (figure 2). All 9 raw EEG reviewers were board-eligible or board-certified epileptologists selected from members of the Critical Care EEG Monitoring Research Consortium (CCEMRC). Each completed a training module[24] based on the 2012 version of the American Clinical Neurophysiology Society (ACNS) standardized ICU EEG nomenclature[25] with the aim of improving agreement on use of the following terms: seizures, evolution, periodic discharges,

Figure 1 Example of a 1-hour quantitative EEG (QEEG) panel without automated seizure detection (SzD) as viewed by the QEEG and QEEG + raw reviewers



All QEEG analyses are displayed as hemispheric averages with blue representing the left hemisphere and red representing the right hemisphere. Frequency scale ranges from 0 to 12 Hz. This recording contained 5 electrographic seizures (see gray boxes).

Figure 2 Study methodology: EEG formatting and review algorithm



ACNS = American Clinical Neurophysiology Society; CCEMRC = Critical Care EEG Monitoring Research Consortium; ICU = intensive care unit; QEEG = quantitative EEG; SzD = seizure detection algorithm.

and rhythmic delta activity. Based on published criteria,[25–28] electrographic seizures were defined as a paroxysmal change in EEG background lasting longer than 10 seconds with evolution in morphology, frequency, or spatial distribution.

Each R epoch was reviewed by 3 raw EEG reviewers who were asked to mark the onset and offset of all seizures as well as the maximal extent of seizure propagation: generalized (>8 channels), hemispheric (5–8 channels), or focal (≤4 channels).[29] They were also asked to mark any rhythmic or periodic patterns (as defined by the ACNS standardized critical care EEG terminology [25]). A gold standard seizure was defined as a seizure marked by 2 out of 3 of the raw reviewers with at least 50% overlap in seizure duration (figure e-1).

A separate panel of 9 QEEG experts were selected to review the Q and QR epochs, with 3 reviewers assigned to review each epoch. These QEEG experts had at least 1 year of experience using QEEG in high-volume clinical practices. Epochs were assigned such that no reviewer reviewed the same epoch in both Q and QR formats. Reviewers were instructed to mark onsets of any events on the QEEG that they thought were probable seizures. Q reviewers did not have access to raw EEG. QR reviewers had access to the entire raw EEG but were encouraged to only review the raw EEG corresponding to QEEG areas of interest. None of the reviewers had access to patient video, as we did not aim to have reviewers distinguish clinical from purely electrographic seizures.

Seizure identification was considered positive if onset was marked on a QEEG panel within either 1 or 2.5 minutes of the seizure onset determined by the raw EEG reviewers (termed maximal onset variation). Because the inherent limitations of screen resolution would artifactually lower sensitivity in the QEEG arm if using a maximal onset variation of just 1 minute, we allowed up to 2.5 minutes onset variation from the time of the seizure onset determined by the raw EEG reviewers.

For each Q and QR epoch, the sensitivity for seizure identification was averaged among the 3 reviewers. Subsequently, the mean and median sensitivity across all epochs was calculated. Sensitivities were computed in this way for both maximal onset variations. False-positive rates (FPRs) for seizure identification for the Q and QR groups were also calculated.

Automated seizure detection. We assessed the sensitivity and FPR of a proprietary automated seizure detection algorithm (SzD) (seizure probability, Insight II version 11, Persyst, Inc.), with the threshold for seizure detection set to a value of 1.0. None of the Q or QR reviewers had access to the SzD display (figure 1).

Review time and rating of QEEG utility. The time required by each R, Q, and QR reviewer to review each epoch was recorded. In addition, Q and QR reviewers were also asked to rate the utility of each QEEG technique on a Likert scale ranging from 1 to 5 (1 = least useful).

Statistical analysis. Means, medians, and interquartile ranges for sensitivities and FPR were reported for the Q, QR, and

SzD group, for 2 maximal onset variations (1 and 2.5 minutes). Median reviewing times and ranges for each epoch as well as overall were also reported for the Raw, Q, and QR reviewers. A nonparametric Friedman test of differences among repeated measures (Matlab; Mathworks, Natick, MA) was conducted to determine statistical significance.

RESULTS **Seizure characteristics.** Across 15 epochs, there were on average 10.5 gold standard seizures per epoch (total 126; range 0–49); 32% of seizures were generalized, 36% hemispheric, 28% focal, and the remaining 4% were marked as indeterminate.

Sensitivity and FPRs for seizure identification. Mean sensitivity for Q = 67% and QR = 68% was using the 2.5-minute maximal onset variation time. As expected, sensitivity declined with decreasing maximal onset variation: Q = 51% and QR = 63% when the maximal onset variation allowed was 1 minute (table 1). The mean FPRs across all epochs were 1/h for Q reviewers and 0.5/h for QR reviewers (table 1).

Compared to visual identification of seizures in Q and QR groups, SzD had a mean sensitivity of 27% and 25% when allowing maximal onset variations of 2.5 and 1 minute, respectively; mean FPR was 0.07/h.

Factors influencing sensitivity and FPRs for seizure identification. Compared to gold standard seizures detected on raw EEG review, the Q and QR review showed significant variability in sensitivity. This was primarily due to differing characteristics of the individual raw EEG recordings (table 1; figures e-1–e-3). The highest sensitivities were seen in samples with frequent, hemispheric seizures (epochs 5, 9, 11: Q sensitivity 97%, 92%, and 77%, and QR 97%, 79%, and 87%, respectively). These epochs also had few or no false-positive detections, which may reflect the infrequent occurrence of artifact and periodic patterns in these epochs.

Lower sensitivity was seen in epochs with low-frequency, slowly evolving, low-amplitude seizures, but sensitivities improved when reviewers had access to raw EEG (epoch 4: mean Q = 42%, median 25%; mean QR = 42%, median 50%; epoch 10: mean Q = 30.5%, QR = 69%).

Of epochs that demonstrated lower sensitivity on Q than QR, some epochs (e.g., 1 and 4) also had poor agreement among raw reviewers. Epoch 1 contained frequent, lateralized periodic discharges (LPDs) over the right temporal region that were clearly distinguished from background activity. However, at times the LPDs evolved to electrographic seizures with a QEEG signature very similar to the LPDs (figure 3). Consequently, 1 of 3 R reviewers labeled all electrographic seizures as LPDs alone, leading to poor raw EEG agreement for this epoch. Epoch 4 had occasional prolonged seizures in addition to frequent runs of rhythmic delta activity that did not meet ictal criteria as a source of poor agreement among raw reviewers. These are good examples of the controversial ictal-interictal continuum for which there is considerable variability in interrater agreement.

On the other hand, some epochs demonstrated good agreement on raw EEG review but Q sensitivity was still suboptimal even with concomitant raw EEG. In epoch 6 (figure e-2), seizures were brief and low-amplitude compared to background. Although this raw EEG pattern resulted in a subtle QEEG signal, it was stereotyped and characteristic of an ictal pattern. This is an example of the power of identifying an initial signature ictal pattern, which can lead to rapid identification of subsequent ictal events of similar morphology.

With certain epochs, the QR group displayed lower sensitivity compared to Q group (epochs 1, 7, 9). These epochs had a predominance of periodic patterns that might have led the reviewer to change impression from seizure to periodic patterns upon reviewing the raw EEG.

Review time and rating of QEEG utility. Median EEG review times (figure 4) were shorter for QEEG alone (6 minutes) and QR (14.5 minutes) compared to raw EEG review (19 minutes; $p = 0.00003$). Based on self-reported Likert scale ratings, CSA and rhythmicity spectrogram were perceived as the most helpful QEEG techniques for visual identification of seizures.

DISCUSSION This multicenter study provides Class II evidence that a panel of multiple QEEG trends viewed by experts can be used to identify seizures in critically ill adults with reasonable sensitivity and low FPR and significantly shortens review time compared to comprehensive raw EEG interpretation.

A prior study[23] investigating the sensitivity of a single QEEG trend (CSA) in 113 adults (39 with seizures) found a median sensitivity of 94.2% of seizures per recording. Although our study had lower sensitivity, our FPR was lower, as the aim of our study was to assess the accuracy of seizure identification by experts, and not just the performance of QEEG as a screening tool.

Other studies evaluating QEEG sensitivity were performed in pediatric patients. One study[12] reported a median sensitivity of 83.3% of seizures identified per recording using color density spectral array (CDSA) and 81.5% using aEEG. Missed seizures fell into the following categories: low voltage (<75 μV), short duration (<1 minute), focal, or seizures that occurred in the context of abundant interictal epileptiform discharges. Our study confirms that epochs with low-frequency and low-amplitude seizures had lower sensitivities.

Table 1 Characteristics of individual epochs, sensitivity (using a maximal onset variation of 2.5 and 1 minute), and false-positive rates

		Seizure characteristics						Sensitivity			False-positive rate, mean no. of seizures/h		
								Q	QR	SzD			
Epoch no.	No. of seizures	Duration	Amplitude (compared to background activity)	Maximal spatial extent	Typical frequency	Coexisting PDs or RDA	Maximal onset variation, min	Mean (median) % range across 3 reviewers		Mean %	Q	QR	SzD
1	23	Brief	High	Focal	1-2 Hz	Frequent LPDs	2.5	97 (95.7) 95.7-100	52.2 (60.8) 0-95.7	22	0.68	0.17	0.00
							1	89.8 (91.3) 78.2-100	39.1 (21.7) 0-95	13.04			
2	1	Prolonged	High	Generalized	Obscured by muscle	No	2.5	100 (100) 100-100	100 (100) 100-100	100	0.00	0.00	0.00
							1	33 (0) 0-0	100 (100) 100-100	100			
3	1	Prolonged	Low	Generalized/ hemispheric	2-3 Hz	Frequent RDA	2.5	33 (0) 0-100	33 (0) 0-100	0	3.91	0.39	0.17
							1	0 (0) 0-0	33 (0) 0-100	0			
4	4	Prolonged	Low	Focal	≤1 Hz	Frequent RDA	2.5	42 (25) 25-75	42 (50) 25-50	0	0.23	2.89	0.00
							1	42 (25) 25-75	42 (50) 25-50	0			
5	49	Brief	High	Hemispheric	4-6 Hz	No	2.5	97 (95.9) 95.9-100	97 (98) 93.8-100	24.5	0.00	0.00	0.00
							1	97 (95.9) 93.8-100	97 (98) 93.8-100	22.4			
6	7	Brief	Equal	Focal	6-8 Hz	No	2.5	71 (85.7) 28.6-100	33 (0) 0-100	0	0.00	0.00	0.00
							1	71 (85.7) 28.6-100	33 (0) 0-100	0			
7	4	Brief	Equal/low	Hemispheric	3-4 Hz	No	2.5	33.3 (50) 0-50	58 (75) 0-100	0	6.99	1.0	0.18
							1	16.6 (25) 0-25	50 (50) 0-100	0			
8	1	Brief	High	Hemispheric	2-3 Hz	Abundant PDs	2.5	67 (100) 0-100	100 (100) 100-100	100	0.91	0.00	0.00
							1	67 (100) 0-100	100 (100) 100-100	100			
9	13	Brief	High	Generalized/ hemispheric	2-3 Hz	No	2.5	92 (92) 84.6-100	79 (84.6) 69.2-84.6	53.9	0.83	0.00	0.00
							1	87 (85) 76.9-100	76.9 (76.9) 69.2-84.6	46.2			
10	12	Brief	Low	Focal	1 Hz	No	2.5	30.5 (33) 16.6-41.6	69 (83.3) 41.7-83.3	0	0.16	0.60	0.00
							1	30.5 (33) 16.6-41.6	69 (83.3) 41.7-83.3	0			
11	10	Intermediate	High	Focal	2-2.5 Hz	No	2.5	77 (80.0) 70-80	87 (90.0) 80-90	20	0.00	0.11	0.33
							1	73 (70) 70-80	87 (90.0) 80-90	18			
12	1	Intermediate	High	Focal	3-5 Hz	Abundant GPDs	2.5	67 (100) 0-100	67 (0) 0-100	100	1.16	1.44	0.00
							1	0 (0) 0-0	33.3 (0) 0-100	0			
13	0	NA	NA	NA	NA	NA		NA	NA	NA	61.0	0.33	0.33

Continued

Table 1 Continued

Epoch no.	No. of seizures	Seizure characteristics							Sensitivity				False-positive rate, mean no. of seizures/h		
		Duration	Amplitude (compared to background activity)	Maximal spatial extent	Typical frequency	Coexisting PDs or RDA	Maximal onset variation, min	Q	QR	SzD	Q	QR	SzD
								Mean (median) % range across 3 reviewers		Mean %			
14	0	NA	NA	NA	NA	NA		NA	NA	NA	1.67	0.00	0.00
15	0	NA	NA	NA	NA	NA		NA	NA	NA	2.0	0.33	0.17
Mean overall	126							51%–67%	63%–68%	26.2%–26.7%	2.09	0.12	0.08

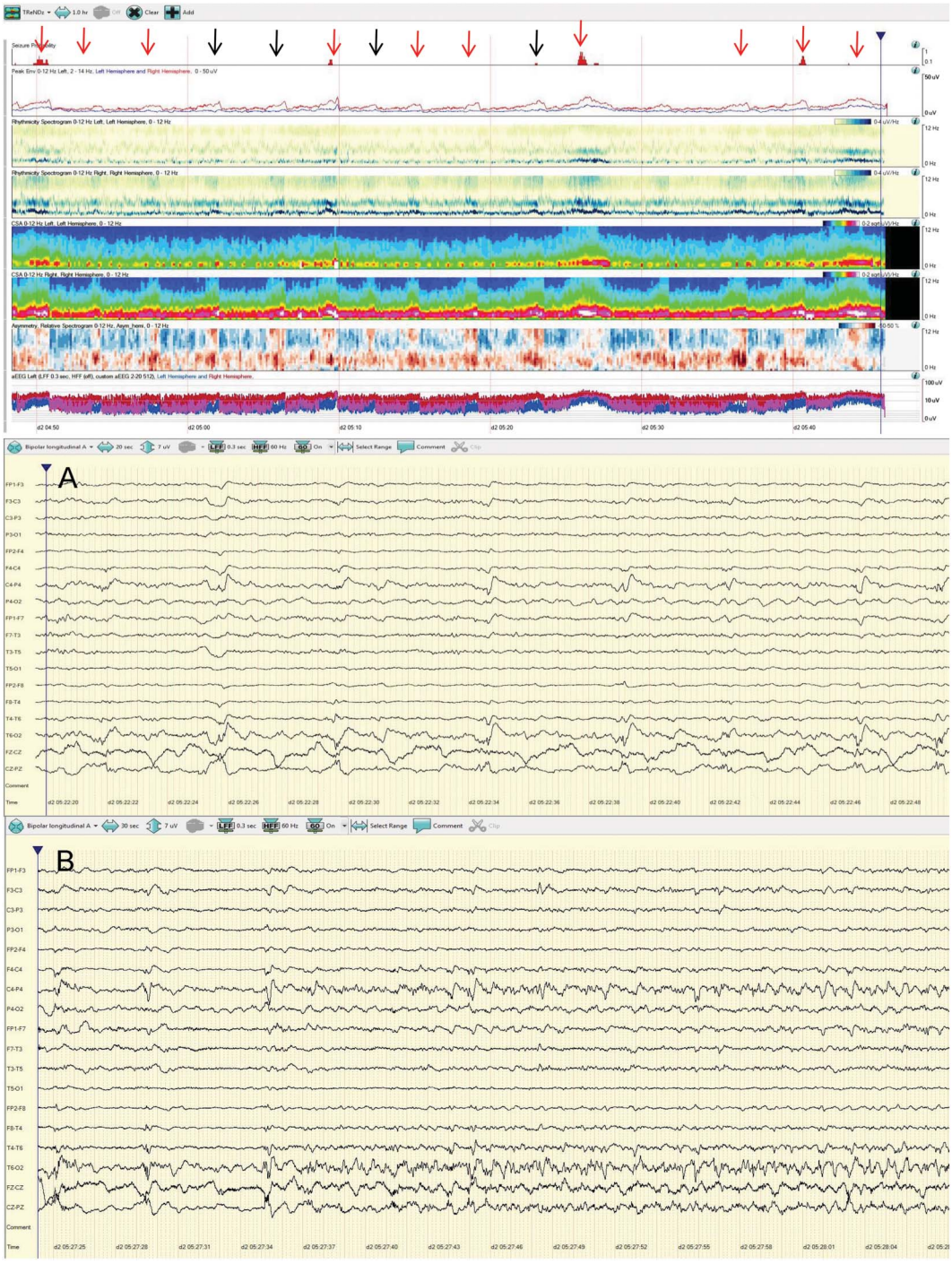
Abbreviations: GPD = generalized periodic discharge; LPD = lateralized periodic discharge; PD = periodic discharge; Q = quantitative EEG alone; QR = quantitative EEG with raw EEG; RDA = rhythmic delta activity; SzD = seizure detection algorithm.
Duration of seizures defined as follows: brief 10–60 seconds; intermediate 1–5 minutes; prolonged >5 minutes.

In another single-center study,[11] experienced QEEG readers were significantly more accurate than inexperienced readers, particularly when reviewing the envelope trend (87% vs 52%). Our study supports similar seizure detection rates by experienced QEEG reviewers. Despite the fact that the QEEG panel utilized in our study consisted of a larger number of QEEG trends (5 trends vs 2 or fewer in prior studies), the accuracy of seizure identification was no better than prior studies. This reflects the complexity and variation in our EEG samples: seizures of different morphology and spatial extent may be best identified using one QEEG trend display over another.

This study incorporated several methodologic details in an attempt to answer specific clinical questions. We recruited several experienced electroencephalographers who routinely utilize QEEG from various centers across the CCEMRC. Our methods were more stringent compared to real-life practice, as we asked QEEG reviewers to mark only probable or likely seizures in an effort to ascertain a more realistic FPR. It was our expectation that expert reviewers would be more discerning with better differentiation of nonictal patterns (such as mechanical artifact and arousal patterns) from seizures. We also chose to withhold access to concurrent video recording in order to provide a more focused evaluation of the EEG interpretation alone, without clinical bias. Allowing access to the video recording may have decreased the rate of false-positive detections by allowing proper identification of seizure-mimicking artifacts, but would have come at the expense of increased review time. Despite these stringent conditions, sensitivities for seizure identification were comparable to several of the aforementioned studies, and FPRs were much lower. EEG data was selected by only one investigator, which may introduce selection bias; however, the EEG epochs were intended to contain seizures of various frequencies, durations, and locations in order to replicate the diversity of seizure patterns seen in daily clinical practice. In addition, some epochs contained abundant rhythmic and periodic patterns, which are known to be difficult to differentiate from electrographic seizures.

Prior studies have shown low to moderate interrater agreement for detection of electrographic seizures in critically ill patients, even among experts[30,31]; hence, our analysis required raw EEG agreement among at least 2 reviewers to determine gold standard seizures. It follows, however, that some reduction in QEEG sensitivity may arise from suboptimal interrater agreement on some QEEG epochs due to the nature of the patterns they contain, and not necessarily a limitation of using QEEG itself. This is supported by the fact that epochs with abundant rhythmic or periodic patterns as well as periods of reactivity exhibited not only a higher FPR overall

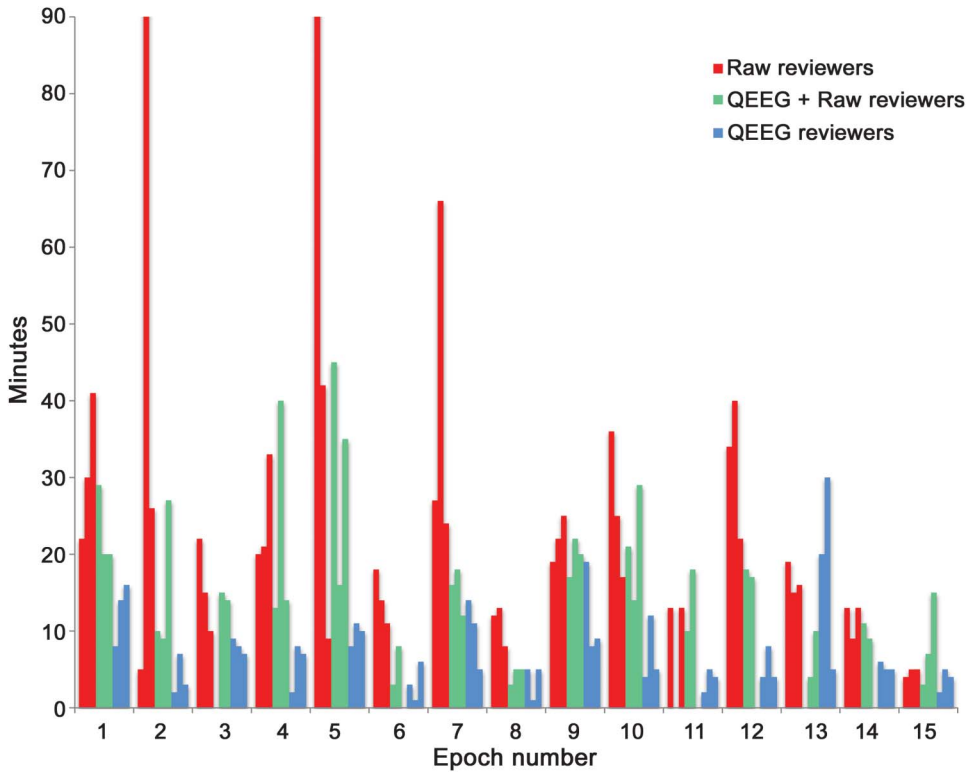
Figure 3 Epoch 1: Periodic discharges mimicking electrographic seizures on quantitative EEG (QEEG)



This epoch contained frequent, brief lateralized periodic discharges (LPDs) over the right temporal region that were occasionally nonevolving (black arrows), but often evolved into electrographic seizures (red arrows). The QEEG signature seen at the time of nonevolving periodic discharges (black arrow/event A; raw EEG panel A) is very similar to the QEEG pattern seen during the ictal pattern (red arrow/event B, raw EEG panel B). One of 3 raw EEG without QEEG reviewers labeled all electrographic seizures as LPDs alone. Automated seizure detection identified very few of the electrographic seizures. (Note that seizure detection algorithm trend ["seizure probability" at the top of the figure] is included here for comparison, but was not visible to quantitative EEG alone or quantitative EEG with raw EEG reviewers).

but also a wider range of FPRs among reviewers, suggesting interrater disagreement in QEEG interpretation. This highlights an important observation that periodic patterns may frequently resemble seizures on QEEG and accurate distinctions can be difficult even with concomitant raw EEG review, especially when periodic patterns evolve into seizures. This supports findings from a prior study of

Figure 4 Comparison of reviewing time for reviewers when using raw EEG without quantitative EEG, quantitative EEG with raw EEG, and quantitative EEG alone



Note that epochs 2 and 5 required significantly more time for raw review by one reviewer. Both of these epochs contained prolonged seizures that were marked as such by 2 of the raw EEG reviewers. However, one reviewer annotated both of these epochs as containing multiple, short seizures. We suspect that the additional review time was required by this reviewer in order to distinguish and annotate each seizure.

interrater agreement of the ACNS ICU EEG terminology, where interrater agreement for evolution of periodic patterns was only fair (21%).[32]

An important feature of our study was the assessment of an automated seizure detection algorithm (SzD). Sensitivity of SzD was much lower compared with human identification with Q or QR review. Similar to human review, lower sensitivities for SzD were seen in epochs with low amplitude, slowly evolving seizures, or with abundant periodic patterns. Adjusting the manufacturer's default settings for the SzD algorithm may have increased its sensitivity, at the expense of a higher FPR. Our results suggest that automated seizure detection in the ICU setting will require further advances to improve sensitivity in the ICU setting before approaching the performance of expert QEEG users.

QEEG analysis saves significant review time, either alone or in conjunction with raw EEG, corroborating the results of another recent study by Moura et al.[33] They reported a sensitivity of 87.3% for seizure detection using CDSA and significant time-savings comparing QEEG to conventional EEG review (8 ± 4 minutes for CSA-guided review vs 38 ± 17 minutes for conventional review; $p < 0.005$). Similar to this study,[33] our study demonstrates that time-savings of QEEG over raw EEG review was greater for epochs with no or few seizures, compared to epochs with multiple seizures. This may partly have been due to instructions to mark all seizures, no matter how brief, which is not usually done in routine practice.

Prior research suggests that although QEEG displays are a useful screening tool for seizure identification, there is potential for false-positives, especially when used by inexperienced personnel.[23,34] Our study demonstrates that expert review of a panel of QEEG trends leads to lower FPRs with acceptable sensitivity similar to prior studies. However, intermittent raw EEG assessment is still necessary to confirm seizures suspected on QEEG. Hence, we recommend that QEEG be used as a screening tool to guide directed raw EEG review by an experienced neurophysiologist, in order to maximize sensitivity while minimizing false-positive detections. Additional guidance on the use of QEEG in clinical practice can be found in the ACNS Consensus Statement on Continuous EEG in Critically Ill Adults and Children.[35]

This study demonstrates reasonable overall sensitivity of QEEG for seizure detection but is variable based on the electrographic pattern. Sensitivity is highest for

frequent seizures of higher amplitude than background activity and propagation beyond initial onset. Lower sensitivities were seen for brief, low-amplitude, focal seizures. Knowing which patterns are identified less readily on QEEG allows the reviewer to understand the limitations of QEEG review. What remains to be determined is the clinical impact, if any, of failing to detect brief, focal, and infrequent electrographic events. Further investigations are needed to optimize the use of QEEG as a screening tool for identification of seizures as well as other rhythmic and periodic patterns that may not clearly meet seizure criteria but may still be of clinical significance. Efforts should include investigating which trend combinations as well as time, frequency, and amplitude scales provide a panel that optimally displays various seizure types and improves interrater agreement. Finally, research is needed to evaluate the feasibility of using QEEG in real time at the bedside with interpretation performed by personnel with no formal EEG training. Although automated seizure detection software is rapidly evolving with advances in artifact rejection to reduce false detections, improvements in sensitivity are still needed. These advances in the use of QEEG in the ICU setting have potential for improving outcomes of critically ill patients by reducing time to accurate recognition and treatment of electrographic seizures.

AUTHOR CONTRIBUTIONS

Hiba Arif Haider: drafting/revising the manuscript, study concept or design, analysis or interpretation of data, accepts responsibility for conduct of research and final approval, acquisition of data, study supervision, obtaining funding. Rosana Esteller: drafting/revising the manuscript, analysis or interpretation of data, accepts responsibility for conduct of research and final approval, statistical analysis. Cecil David Hahn: drafting/revising the manuscript, study concept or design, analysis or interpretation of data, accepts responsibility for conduct of research and final approval, acquisition of data. Michael Brandon Westover: drafting/revising the manuscript, accepts responsibility for conduct of research and final approval. Jonathan J. Halford: drafting/revising the manuscript, analysis or interpretation of data, accepts responsibility for conduct of research and final approval. Jongwoo Lee: drafting/revising the manuscript, analysis or interpretation of data, accepts responsibility for conduct of research and final approval, acquisition of data. Mouhsin M. Shafi: drafting/revising the manuscript, analysis or interpretation of data, accepts responsibility for conduct of research and final approval, Nicolas Gaspard: drafting/revising the manuscript, analysis or interpretation of data, accepts responsibility for conduct of research and final approval. Susan T. Herman: drafting/revising the manuscript, accepts responsibility for conduct of research and final approval, review of EEG data samples. Elizabeth E. Gerard: drafting/revising the manuscript, analysis or interpretation of data, accepts responsibility for conduct of research and final approval, acquisition of data. Lawrence J. Hirsch: drafting/revising the manuscript, accepts responsibility for conduct of research and final approval. Joshua Andrew Ehrenberg: drafting/revising the manuscript, study concept or design, accepts responsibility for conduct of research and final approval, acquisition of data. Suzette M. LaRoche: drafting/revising the manuscript, study concept or design, analysis or interpretation of data, accepts responsibility for conduct of research and final approval, acquisition of data, study supervision.

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DISCLOSURE

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