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NEUROCRITICAL CARE SOCIETY

ORIGINAL WORK

# A Trial of Real-Time Electrographic Seizure Detection by Neuro-ICU Nurses Using a Panel of Quantitative EEG Trends

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## Abstract

**Background:** Non-convulsive seizures (NCS) are a common occurrence in the neurologic intensive care unit (Neuro-ICU) and are associated with worse outcomes. Continuous electroencephalogram (cEEG) monitoring is necessary for the detection of NCS; however, delays in interpretation are a barrier to early treatment. Quantitative EEG (qEEG) calculates a time-compressed simplified visual display from raw EEG data. This study aims to evaluate the performance of Neuro-ICU nurses utilizing bedside, real-time qEEG interpretation for detecting recurrent NCS.

**Methods:** This is a prospective, single-institution study of patients admitted to the Duke Neuro-ICU between 2016 and 2018 who had NCS identified on traditional cEEG review. The accuracy of recurrent seizure detection on hourly qEEG review by bedside Neuro-ICU nurses was compared to the gold standard of cEEG interpretation by two board-certified neurophysiologists. The nurses first received brief qEEG training, individualized for their specific patient. The bedside qEEG display consisted of rhythmicity spectrogram (left and right hemispheres) and amplitude-integrated EEG (left and right hemispheres) in 1-h epochs.

**Results:** Twenty patients were included and 174 1-h qEEG blocks were analyzed. Forty-seven blocks contained seizures (27%). The sensitivity was 85.1% (95% CI 71.1–93.1%), and the specificity was 89.8% (82.8–94.2%) for the detection of seizures for each 1-h block when compared to interpretation of conventional cEEG by two neurophysiologists. The false positive rate was 0.1/h. Hemispheric seizures (> 4 unilateral EEG electrodes) were more likely to be correctly identified by nurses on qEEG than focal seizures ($\leq$ 4 unilateral electrodes) ($p = 0.03$).

**Conclusions:** After tailored training sessions, Neuro-ICU nurses demonstrated a good sensitivity for the interpretation of bedside real-time qEEG for the detection of recurrent NCS with a low false positive rate. qEEG is a promising tool that may be used by non-neurophysiologists and may lead to earlier detection of NCS.

**Keywords:** Quantitative EEG, qEEG, Seizures, ICU, EEG, Non-convulsive seizures

## Introduction

Non-convulsive seizures (NCS) and non-convulsive status epilepticus (NCSE) occur in 8–48% of patients admitted to the intensive care unit (ICU) [1–4] and are associated with worse outcomes [5]. Early identification of NCS and NCSE enables timely intervention with improved likelihood of seizure control [6–8]. A cross-sectional study of patients affected by NCSE demonstrated that time to seizure control was prolonged by 2.7 h for each hour of treatment delay [6].

Prior studies have demonstrated that delays in treatment of NCS and NCSE are common [6, 9] despite guidelines for rapid treatment of SE [10, 11]. There are also significant delays in treatment for patients with NCSE compared to those with convulsive seizures [12]. Currently, the gold standard to identify NCS and NCSE is continuous electroencephalogram (cEEG) [2, 13]. cEEG is a complex signal that requires interpretation by a trained neurophysiologist, with interpretations provided

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to the clinical team in a post hoc fashion. In comparison, quantitative EEG (qEEG) could identify a NCS in real time at the patient's bedside. qEEG is a time-compressed simplified display based on aspects of the raw electroencephalography (EEG) signal created via mathematical and analytical techniques.

qEEG as a screening tool has been demonstrated to result in faster review time when used in conjunction with conventional cEEG review [14]. However, there remains a lengthy interval between intermittent cEEG reviews, which has been shown to be as long as 12 h [15, 16]. Given the high volume of cEEG studies performed in ICUs, relying on neurophysiologists to perform immediate cEEG/qEEG interpretation is impractical. On the other hand, ICU nurses are in an ideal situation to perform real-time qEEG interpretation given their near-constant presence at the bedside. It is universally accepted that the nurse's responsibilities include alerting the medical team to changes in the neurologic examination, hemodynamic parameters, and cardiac telemetry, to name a few. However, training nurses to interpret the bedside qEEG and alert the medical team about periods of concern is not a common practice [16], likely due to the paucity of data regarding their performance for seizure identification.

Our previous retrospective study showed that neurophysiologists and non-neurophysiologists (EEG technicians and Neuro-ICU nurses) had no significant difference in sensitivity and specificity for the identification of NCS on qEEG panels without access to the cEEG [17]. The sensitivities for neurophysiologists and Neuro-ICU nurses were 87.5% and 84.1%, respectively, when compared to conventional cEEG interpretation by neurophysiologists [17]. A similar study reported a 74% seizure detection rate by nurses interpreting a single qEEG trend, compressed spectral array [18]. This study also demonstrated feasibility of nurse interpretation of the qEEG [18]. More recently, Ganesan et al. [19] have performed a retrospective study demonstrating that critical care providers (ICU fellows and ICU nurses) were able to detect at least one seizure using aEEG and color density spectrum array (CDSA) in 94% of patients who had seizures in their EEG recordings, although they did not necessarily identify each individual seizure.

Based on these retrospective studies, qEEG could be a useful adjunct to the cEEG when evaluated first by bedside Neuro-ICU nurses who can screen for concerning signals and prompt earlier interpretation of the cEEG for NCS. In response to this opportunity, we conducted a single-institution prospective study evaluating the sensitivity and specificity of Neuro-ICU nurse interpretation of specific qEEG trends (rhythmicity spectrogram and amplitude-integrated EEG) for the identification of recurrent NCS in adult patients admitted to the Neuro-ICU.

## Methods

This single-institution prospective cohort study was approved by the Duke Institutional Review Board. Consent for participation in the study was obtained from the nurses. Patients admitted to the Duke Neuro-ICU between 2016 and 2018 who had NCS identified on cEEG monitoring were identified prospectively. A waiver of HIPAA authorization and consent was approved to collect patient and EEG data retrospectively.

Digital cEEG recordings (Natus Medical, Pleasanton, CA) were obtained with electrodes placed according to the International 10/20 electrode placement system. All cEEG recordings in the Neuro-ICU were subjected to the qEEG tools built into the Magic Marker software (version P12, Persyst Development Corporation, Prescott, AZ). qEEG panels were displayed on a bedside monitor of each identified patient adjacent to the cEEG panel displaying the last 1 h of data (Fig. 1). Each panel consisted of the following qEEG tools (based on all standard electrodes from left and right hemispheres): rhythmicity spectrogram (Persyst Inc., displayed for the left and right hemispheres; range 1–25 Hz, 3-s epochs with 1-s step size) and amplitude-integrated EEG (aEEG, displayed for the left and right hemispheres; time constant of 0.5 s with 1-s epochs).

The rhythmicity spectrogram is a proprietary qEEG tool from Persyst Inc. that highlights the frequency components of the CDSA that have the highest amplitude and rhythmicity at a given time point, allowing for the rhythmic activity of seizures to be emphasized (EEG time constant = 0.16 s, high-frequency filter = 35 Hz, rhythmicity sampling rate = 128 Hz, epoch duration = 3 s, epoch step = 2 s, y-axis range 1–25 Hz, y-axis scaling type = square root, z-axis scaling using μV/Hz, z-axis range 0–4 μV/Hz, z-axis color palette). aEEG depicts filtered, rectified, and smoothed EEG on a compressed time scale [20]. These trends were chosen to create a simplified display to allow ease of use and were reported by Neuro-ICU nurses to be the most helpful for seizure detection on a previous retrospective study [17]. All qEEG displays were subjected to "automated artifact reduction," which is a feature within Persyst Magic Marker that results in both conventional and qEEG trend calculations from EEG waveforms after applied algorithms to remove electrode and physiological artifact, referred to as "artifact reduced waveforms."

The patients were selected whenever they were determined to meet inclusion criteria (adult patients with NCS identified on cEEG admitted to the Neuro-ICU). The appearance of the qEEG had no influence on a patient being included in the study. Thus, there was no bias related

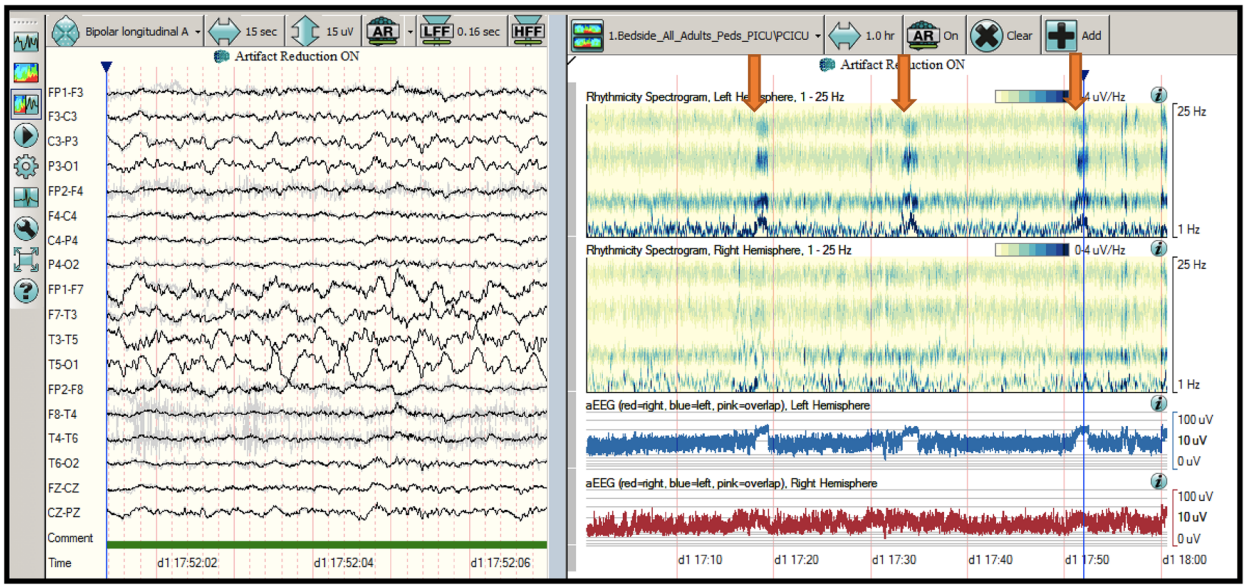


**Fig. 1** Bedside display of raw cEEG data and qEEG panel. Sample Persyst bedside monitor display with 5 s of conventional EEG on the left and 1 h qEEG panel on the right. The qEEG panel consists of the following qEEG tools: rhythmicity spectrogram (displayed for the left and right hemispheres) and aEEG (displayed for the left and right hemispheres). Vertical solid arrows denote 3 electrographic seizures. The conventional EEG corresponds to the third non-convulsive seizure marked by the vertical line below the third arrow and demonstrates a 70-s left temporal electrographic seizure with left hemispheric spread. In both the conventional cEEG and qEEG panels, the "artifact reduction" feature is turned ON

to selecting cases with more obvious seizures on qEEG that allowed for more advantageous interpretation by nurses.

Consented Neuro-ICU nurses underwent a 15-min qEEG training via a Powerpoint presentation. A 1-h qEEG panel printout containing the patient's most recent seizure(s) was displayed next to the bedside cEEG/qEEG acquisition monitor, and nurses were instructed to observe for similar patterns. For the duration of their shift, the nurses logged the number of seizures seen hourly based on their qEEG interpretation in the following categories: no seizures, 1–2 seizures, 3–5 seizures, 6–10 seizures, or > 10 seizures.

The corresponding conventional cEEG segments were reviewed independently by the study authors (C.B.S. and S.R.S) to identify and quantify seizures. Electrographic seizures were identified using published criteria [21]. Each 1-h segment of conventional EEG was placed in the same categories: no seizures, 1–2 seizures, 3–5 seizures, 6–10 seizures, or > 10 seizures. Interrater reliability was calculated. For some records, there was a discrepancy in categorization of seizure number. For these, the two authors (C.B.S. and S.R.S.) reviewed the studies together and established a consensus. The spatial extent of the seizures (focal, defined as ≤ 4 unilateral electrodes involved, hemispheric, defined as unilateral but > 4 electrodes involved, or generalized/bilateral) [22] and duration were determined by the author, C.B.S, from the corresponding conventional EEG segment.

Standard test characteristics (sensitivity, specificity, positive predictive value, negative predictive value, and error rates) were calculated for ability of the nurses to detect the presence of seizures compared to conventional cEEG review by neurophysiologists. Ninety-five percent confidence intervals (CI) were reported for each performance measure. The responses that included 1–2 seizures, 3–5 seizures, 6–10 seizures, and > 10 seizures were grouped as seizures being present for analyses that assessed for the presence or absence of seizures. Interrater reliability for seizure detection for the neurophysiologists reviewing the conventional cEEG was calculated. Contingency analysis was used to make comparisons of the mean diagnostic accuracy of seizure detection of the nurses by qEEG for seizures of different spatial extent (focal vs. hemispheric) and duration (< 1 vs. 1–5 min). There were no patients with generalized/bilateral seizures. Pearson $\chi^2$ Chi-square statistics were calculated for each of these analyses. For all calculations, a $p$ value < 0.05 was considered statistically significant. All statistical analyses were performed using JMP Pro 13 (version 13.1.0; SAS Institute).

## Results

Twenty-one adult patients were included in the study, but one was excluded due to technical issues with EEG acquisition. Table 1 summarizes the patient demographics and

EEG characteristics of the 20 patients from which the 174 1-h blocks of EEG were analyzed. Fourteen patients had at least one seizure during the study duration, and 6 did not have any seizures during their evaluated period. There was a diversity of diagnoses among the patients, with brain tumor being the most common. The average length of data collected per patient was 8.8 h. There were 47 1-h blocks out of 174 that contained seizures (27.0%). There was excellent agreement for the two neurophysiologists providing conventional EEG review (kappa = 0.96).

Table 2 describes the standard test characteristics for the seizure detection performance by nurses using qEEG compared to neurophysiologist review. Nurse sensitivity was 85.1% (95% CI 71.1–93.1%), and specificity was 89.8% (82.8–94.2%) for detecting the presence of recurrent seizure(s) for each 1-h block. The false alarm rate (FAR) was 0.10/h, which indicates that a false positive error was made once every 10 h. The number of overall errors was 20 (11.5%), with more false positive errors ($n = 13$, identifying a seizure where there was none) than false negative ($n = 7$, missed seizures). A visual depiction of the data collected for each patient, seizure quantification per hour, and hours incorrectly interpreted by nursing with the qEEG is available in supplementary material.

There was no significant difference in the nurse ability to detect a seizure based on its duration ($p = 0.09$), although there was a trend toward better detection of longer seizures (> 1 min). There was a significant difference in the nurse ability to detect a seizure based on its spatial extent (Table 3); hemispheric seizures were more likely to be correctly identified by nurses on the qEEG than focal seizures ($p = 0.03$). There were no patients with generalized/bilateral seizures in this sample. Only one patient (Patient 16) had more than one type of seizure pattern. For this patient, the nurse correctly guessed the first three epochs of seizures (hemispheric, hemispheric, and focal), but missed the fourth epoch of focal seizures (Supplementary Figure 1). The nurse then incorrectly noted seizures when there were none in the ensuing two blocks.

Nurse performance for seizure detection appeared to improve when there were more seizures in each panel (Fig. 2). The lower-performance category of 1–2 seizures per 1-h block could be explained by the fact that all the epochs that were inaccurate were due to the nurses marking an absence of seizures that were focal seizures on cEEG. Moreover, the majority of these focal seizures (4 out of the 5 epochs) were less than 1 min. As previously described, focal seizures lasting less than 1 min were more likely to be missed.

Despite their success in detecting seizures, nurses were less accurate when asked to identify the seizure quantification category per hour (1–2 seizures, 3–5 seizures, 6–10 seizures, and > 10 seizures) (Fig. 2). Overall, there were 37 epochs that were marked as incorrect quantification per hours. Seven of these epochs were due to a false negative interpretation, 13 due to false positive, 17 due to overcalling the number of seizures despite correctly identifying the presence of seizure, and 11 under calling the number of seizures despite correctly identifying the presence of seizure.

The timing of nurse training to the occurrence of the first seizure did not appear to affect their ability to detect seizures. Regardless of whether a seizure was detected

**Table 1 Patient and EEG characteristics**

| | |
|---|---|
| Total number of patients, *n* | 20 |
| Total number of 1-h blocks | 174 |
| Age, median (range), years | 63 (21–90) |
| Female, *n* (%) | 17 (85%) |
| Primary diagnosis, *n* | |
| Brain tumor | 5 |
| History of seizures with breakthrough seizures | 3 |
| Intracerebral hemorrhage | 3 |
| Ischemic stroke | 4 |
| Meningitis/encephalitis | 2 |
| Postoperative craniotomy | 1 |
| Subdural hematoma | 2 |
| Length of data collection per patient, median (range), (h) | 8.8 (6–18) |
| Number of 1-h blocks with seizures, *n* (%) | 47 (27%) |
| 1–2 seizures | 20 |
| 3–5 seizures | 17 |
| 6–10 seizures | 9 |
| > 10 seizures | 1 |
| Interrater reliability for cEEG seizure detection | |
| % agreement | 98.27% |
| Kappa (SE) | 0.96 (0.025) |

*EEG* electroencephalography, *SE* status epilepticus

**Table 2 Neuro-ICU nurse performance for seizure detection on qEEG**

| | Value |
|---|---|
| Sensitivity, *n* (95% CI) | 85.1% (71.1–93.3%) |
| Specificity, *n* (95% CI) | 89.8% (82.8–94.2%) |
| Positive likelihood ratio, *n* (95% CI) | 8.3 (4.9–14.1) |
| Negative likelihood ratio, *n* (95% CI) | 0.2 (0.1–0.3) |
| Positive predictive value, *n* (95% CI) | 75.5% (61.4–85.8%) |
| Negative predictive value, *n* (95% CI) | 94.2% (88.0–97.4%) |
| False alarm rate, *n*/h | 0.10/h |
| Number of 1-h blocks with RN errors, *n* (%) | 20 (11.5) |
| False positive error | 13 |
| False negative error | 7 |

*ICU* intensive care unit, *qEEG* Quantitative electroencephalogram, *RN* nurse

**Table 3 Neuro-ICU nurse performance based on additional EEG characteristics**

| EEG characteristics of blocks with seizures, ($n=47$) | RN correct, *n* (%) | *p* value |
|---|---|---|
| Location | | 0.03 |
| Focal ($n=23$) | 6 (26.1%) | |
| Hemispheric ($n=24$) | 13 (81.3%) | |
| Seizure duration | | 0.09 |
| < 1 min ($n=20$) | 6 (30.0%) | |
| 1–5 min ($n=27$) | 13 (68.4%) | |

Focal seizure defined as ≤ 4 unilateral electrodes involved and hemispheric seizures defined as unilateral but > 4 electrodes involved. There were no generalized/bilateral seizures in this dataset

*EEG* electroencephalography, *ICU* intensive care unit, *RN* nurse

within 1 h or within 4–6 h after a nurse was trained, the percent of correctly identified panels containing seizures was similar (87% and 92%, respectively) (Fig. 3). There were no seizures that occurred between 1 and 3 h. There was only one patient whose first seizure was between 3 and 4 h, and for this category, a least number of epochs of data were captured (9 out of 11 h of monitoring). For this patient, the nurse missed 2 h of data (more than any other nurse), and presumably, the error rate are inflated by the low sample of epochs and situational factors.

## Discussion

This is the first prospective study to demonstrate that with only brief training, Neuro-ICU nurses are able to detect the presence of recurrent electrographic seizures using a simplified panel of qEEG trends with good sensitivity and specificity (85.1% and 89.8%, respectively). This sensitivity was relatively higher than other studies evaluating Neuro-ICU nurse seizure detection performance with qEEG (55.7–87.5%), despite a lower percentage of 1-h blocks with seizures in this study (27.0 vs. 50–58%) [17, 18].

While it remains as the gold standard, the use of cEEG to detect electrographic seizures is limited by the neurophysiologist's capacity to sequentially review all real-time EEGs. Such a limitation sometimes leads to a delay in diagnosis of NCS. Two nationwide surveys revealed that cEEG studies are typically reviewed 2–3 times a day, which is similar in our institution unless alerted by the primary team for suspicious clinical seizure-like activity [15, 17]. Given that 92% of seizures in the Neuro-ICU patient population are non-convulsive [2], the delay in cEEG interpretation is a detrimental limitation.

The presence and duration of NCSE are associated with worse outcomes [5, 7, 23]. In a study of 402 patients with subarachnoid hemorrhage, every hour of seizure activity on cEEG was associated with 10% higher odds of disability and death at 3 months [24]. Seizure burden has also been

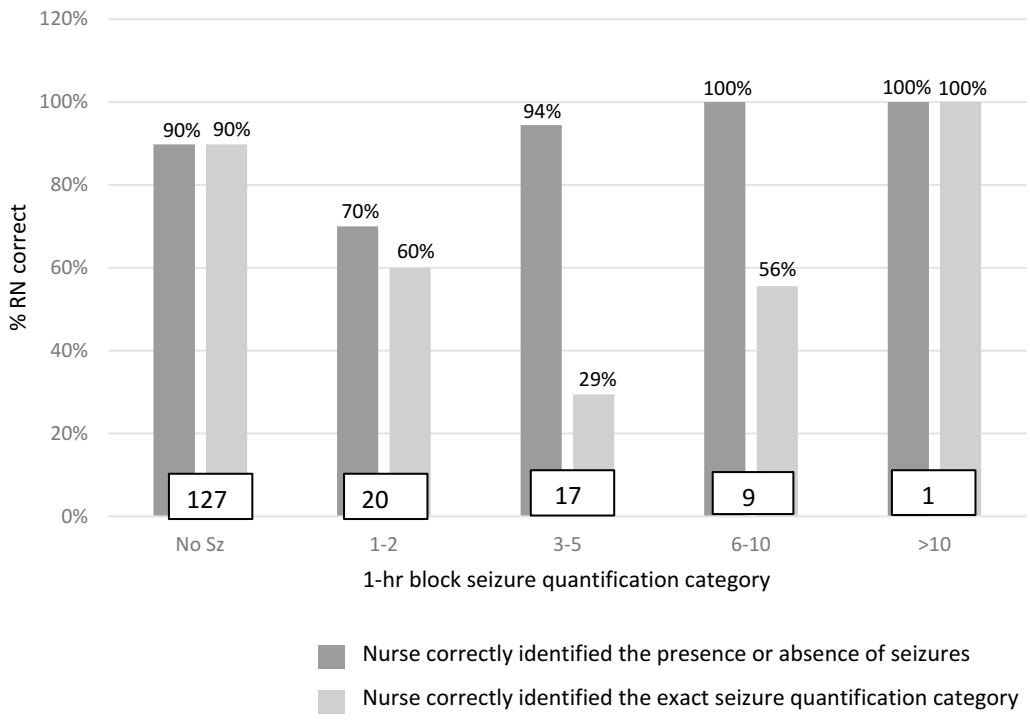


**Fig. 2** Neuro-ICU nurse performance based on number of seizures per hour. *sz* seizure, RN nurse

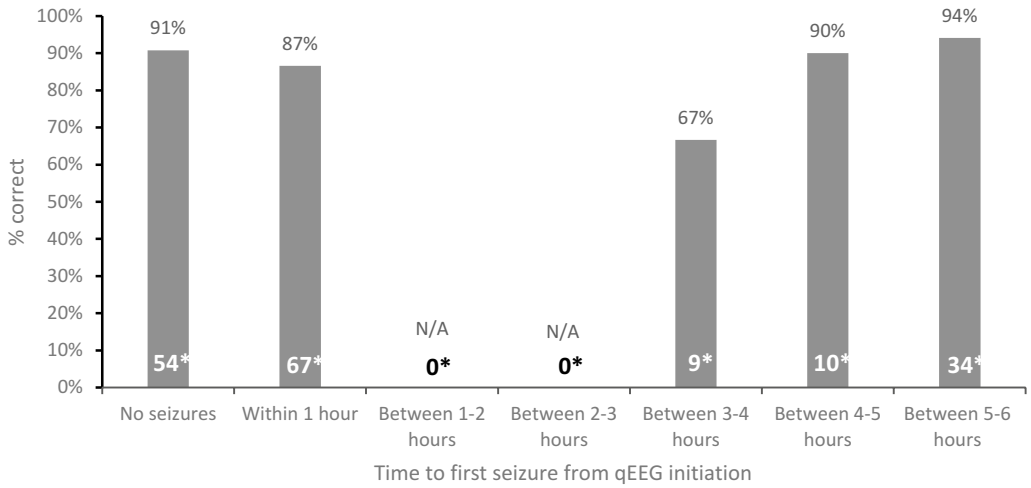


**Fig. 3** Neuro-ICU nurse performance based on latency between RN qEEG training and first seizure. RN nurse. *Number of 1-hour qEEG panels

associated with cognitive decline and neurodevelopmental outcomes in neonates and children [25–27]. This suggests that there is a dose–effect relationship between seizure activity and irreversible brain injury. Given that earlier antiseizure drug (ASD) administration has been associated with improved outcomes for patients with SE [28], it is imperative to identify methods to expedite seizure identification in critically ill patients to reduce seizure burden. Earlier detection of NCS by nurse-interpreted qEEG may result in earlier ASD treatment for critically ill patients with seizures.

This study demonstrated a high sensitivity and low false alarm rate of nurses screening the qEEG for NCS and thus supports the use of the qEEG as a screening tool to be used in conjunction with cEEG. One reason for the enhanced performance of nurses in this trial (sensitivity 85.1%) compared with prior studies (sensitivity range 44–83%) [29–34] is likely due to individualized nurse training sessions tailored for their patient's unique seizure patterns, or "seizure signature" on qEEG. Readers in previous retrospective studies were interpreting random, non-sequential qEEG isolated trends or qEEG panels [29–34].

Nurses had better accuracy interpreting hemispheric seizures compared to focal seizures and seizures greater than 1 min compared to less than 1 min. Only one patient had both hemispheric and focal seizures, and in accordance with the data, the nurse was able to identify both epochs of seizures that were hemispheric and one epoch of focal seizures where there were numerous (6–10) seizures (Supplementary Figure 1, Patient 16). The nurse did not identify the epoch of focal seizures when there were few (1–2) seizures. Moreover, in the two subsequent epochs, the nurse marked the presence of seizures when there were none. This poses the question regarding the influence of the presence of seizures at the onset of the study whether this improves the nurse's sensitivity to identify later seizures. One could argue that the presence of seizures on previously identified epochs would increase the nurse's vigilance of monitoring the qEEG and thus increase the sensitivity, but our one example actually suggests that when the seizures are small in number, the data can still be missed, and perhaps artifact may be overcalled. At the same time, this example does demonstrate that a nurse is able to identify seizures that differed from the given printout.

Something to note in this study is that the nurses did not get real-time feedback regarding any of their interpretations. Other than if a drug was administered around that time due to seizures being identified on the cEEG by the EEG fellow, one could say that the qEEG appearance itself should not have influenced the interpretation of ensuing epochs. Thus, this study cannot comment on the influence of the nurse correctly identifying a seizure on the qEEG and the likelihood that further epochs will be correctly identified. Although it would be difficult to quantify, this point can be addressed with further studies. Moreover, additional studies may also demonstrate whether additional training and experience may improve the detection of subtle seizures.

One concern about qEEG as a screening tool has been the potential for a high false alarm rate resulting in "alarm fatigue". The most common reason for false positive seizure diagnosis on qEEG has been demonstrated to be movement artifact [35]. However, the false alarm rate in this study was one in every 10 h of recording (FAR 0.10/h), which is lower compared to previous reports [14, 17]. We hypothesize this is due to multiple factors. First is the use of "automated artifact reduction" (AAR). AAR is a feature within Persyst Magic Marker that applies

algorithms to remove electrode and physiological artifact. Second, the limited number of hours each patient was monitored also may have reduced the likelihood of artifact from prolonged use of EEG leads. Third, electrode maintenance is performed whenever the electroencephalographer or EEG tech notices an issue, especially in patients with identified seizures. Last, customized training to the patient's known seizure identity and to examples of artifact tracing likely decreased the chance a nurse would have a false positive.

Although a beneficial screening tool, qEEG would not be an appropriate substitute for cEEG. This study did demonstrate two shortcomings of the qEEG. There were inaccuracies between the number of seizures identified on qEEG by nurses and cEEG by neurophysiologists. There was also a significant difference in the nurses' ability to identify hemispheric seizures than focal seizures, which is undoubtedly due to the more conspicuous patterns of hemispheric seizures on qEEG that draw attention. This was also a notable finding by Haider and colleagues [14]. Knowledge of the seizure burden has an impact on the aggressiveness of antiepileptic therapy chosen, and thus, knowing the exact number of seizures and identifying focal seizures would be important to guide therapies. Both of these issues may improve with additional training and experience, and should be addressed with further studies.

There are some notable limitations to this study. First, this study was limited by the number of patients ($n = 20$) and limited experience by each nurse in using the qEEG. It has been implied in previous studies that experience improves the accuracy of qEEG interpretation [17, 30]. Though the number of subjects being evaluated for the detection of seizures was limited (14 out of 20 subjects), it did allow us some comparison between patients who had seizures and those who did not.

There was no systemic bias of selecting ideal appearing EEG samples; however, the study examined a non-consecutive sample of patients, which always poses a risk of bias. The patients were only recruited on weekdays and when the study team was available.

The 1-h epochs were evaluated as independent entities, even though there was an unequal number of epochs with seizures per patient (6 patients had 0 epochs with seizures, 5 had 1 epoch, 1 had 2 epochs, 3 had 3 epochs, 2 had 4 epochs, and 3 had 7 epochs). This may question whether nurses paid variable attention to the qEEG based on the activity from the previous epoch, a factor that we noted earlier would be difficult to quantify. However, we feel this is a minor limitation overall since patients evaluated had already been identified as having seizures on the cEEG and the period of study was soon after identification. The nurse's vigilance should have been reasonably high for all patients from the onset of the study. Moreover, it is not clear how much impact this makes on our results since our nurses did not have real-time feedback from the cEEG data, which as earlier mentioned would theoretically affirm nurse's identification of seizures on the qEEG and perhaps motivate increased vigilance. Another related point is whether 1-h epochs was the most ideal way to study the data, as perhaps evaluating longer epochs may allow nurses to better appreciate changed in EEG on the aEEG or CDSA.

There are many types of qEEG vendors and qEEG displays, and this particular study evaluated a single vendor with specific displays based on our institutional preferences. Specifically, we chose to evaluate the rhythmicity spectrogram, CDSA and aEEG as part of the Persyst display. We acknowledge that other institutions may not have access to the same displays as we had available for our nurses, especially since rhythmicity spectrogram is a propriety algorithm and is only available through Persyst. Thus, the data do not allow us to reach conclusions regarding the relative diagnostic accuracy of the different available displays, and the results of this study would not necessarily be generalizable to institutions that carry different qEEG software.

There are a couple of limitations that may overestimate our sensitivity. First, these findings were based on patients who had an identified stereotyped seizure pattern on qEEG, a pattern that the nurse was provided and which likely improved his/her ability to detect future NCS. Thus, these results are not generalizable to all patients undergoing cEEG monitoring in the ICU beyond those monitored after a non-convulsive seizure has already been identified. Currently, it is unknown whether Neuro-ICU nurse interpretation of qEEG would have similar accuracy or higher false alarm burden if the presence of seizures was unknown. A prospective study addressing this is underway at our institution. Second, the timing of first seizure occurrence relative to receiving instructions was within 24 h; thus, nurses were not being asked to recall something learned several days or weeks ago.

## Conclusions

In conclusion, implementation of individualized bedside Neuro-ICU nurse training of the qEEG is feasible and associated with high sensitivity and specificity and low false alarm rate of detecting NCS. As an adjunctive form of neurophysiological monitoring, the use of qEEG could potentially offer much in terms of improving patient care in the Neuro-ICU. The simplified panel of qEEG trends can be used by Neuro-ICU nurses in real time to monitor for recurrent NCS in critically ill patients. This may facilitate earlier identification of NCS and improve timing of interventions. Nurse qEEG

educational efforts should focus on pattern recognition of less obvious (i.e., focal seizures) given that nurses were found to perform better with detecting hemispheric seizures as compared with focal seizures. At this time, qEEG would best be used as a screening tool that alerts the neurophysiologist to look at the qEEG/cEEG and confirm the presence of a seizure(s). Additional studies of qEEG in this context and the impact on timing of detection and treatment of NCS and patient outcomes are warranted, especially in patients without previously identified NCS on cEEG.

**Electronic supplementary material**
The online version of this article (https://doi.org/10.1007/s12028-019-00673-z) contains supplementary material, which is available to authorized users.

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**Authors' Contributions**
JHK: involved in acquisition of data, analysis and interpretation of data, drafting of manuscript, and final approval of version to be published. GCS: performed conception and design, acquisition of data, revision of manuscript critically for important intellectual content, and final approval of the manuscript to be published. CBS: carried out conception and design, acquisition of data, analysis of data, revision of manuscript critically for important intellectual content, and final approval of the version to be published. SRS: took part in conception and design, analysis of data, revision of manuscript critically for important intellectual content, and final approval of the version to be published.

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**Conflict of interest**
Jennifer H. Kang, MD, and G. Clay Sherill have none to declare. Christa B. Swisher, MD has received speaker's honorarium from UCB and Eisai. Saurabh R. Sinha, MD, Ph.D. reports grants and personal fees from UCB Pharmaceuticals, grants from Eisai Inc., personal fees from Cadwell Inc., personal fees from Monteris Inc., grants from Neuropace Inc., grants from Marinus Pharmaceuticals, personal fees from Springer Publishing, other from American Clinical Neurophysiology Society, other from American Board of Clinical Neurophysiology, and other from ABRET Neurodiagnostic Credentialing and Accreditation, outside the submitted work. None are related to this work.

**Ethical Approval**
This study was approved by the Duke Institutional Review Board prior to the initiation of participant enrollment.

## Publisher's Note



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