ORIGINAL RESEARCH

Limited-Montage EEG as a Tool for the Detection of Nonconvulsive Seizures

Nicholas Swingle,* Aditya Vuppala,* Proleta Datta,* Swetha Pedavally,* Arun Swaminathan,* Sachin Kedar,* Kaeli K. Samson,† Christopher S. Wichman,† Jacob Myers,‡ and Olga Taraschenko*

*Department of Neurological Sciences, University of Nebraska Medical Center, Omaha, Nebraska, U.S.A.; †Department of Biostatistics, University of Nebraska Medical Center, Omaha, Nebraska, U.S.A.; and ‡Clinical Neurophysiology Laboratory, Nebraska Medicine, Omaha, Nebraska, U.S.A.

Purpose: Prefabricated arrays with a limited number of electrodes offer an opportunity to hasten the diagnosis of seizures; however, their accuracy to detect seizures is unknown. We examined the utility of two limited-montage EEG setups for the detection of nonconvulsive seizures.

Methods: Thirty previously interpreted EEG segments with nonconvulsive seizures from 30 patients and 60 segments with background slowing or normal EEG from 60 patients were rendered in a bipolar "double banana" montage, a double distance "neonatal" montage, and a circumferential "hatband" montage. Experts reviewed 60 to 180 seconds long segments to determine whether seizures were present and if the EEG data provided were sufficient to make a decision on escalation of clinical care by ordering an additional EEG or prescribing anticonvulsants. The periodic patterns on the ictal-interictal continuum were specifically excluded for this analysis to keep the focus on definite electrographic seizures.

Results: The sensitivities for seizure of the neonatal and hatband montages were 0.96 and 0.84, respectively, when compared with full montage EEG, whereas the specificities were 0.94 and 0.98, respectively. Appropriate escalation of care was suggested for 96% and 92% of occurrences of seizure patterns in neonatal and hatband montages, respectively. When compared with clinical EEG, the sensitivities of the neonatal and hatband montages for seizure diagnosis were 0.85 and 0.69, respectively.

Conclusions: Nonconvulsive seizures were detected with high accuracy using the limited electrode array configuration in the neonatal and hatband montages. The sensitivity of the neonatal montage EEG in detecting seizures was superior to that of a hatband montage. These findings suggest that in some patients with nonconvulsive seizures, limited-montage EEG may allow to differentiate ictal and slow patterns.

Key Words: Reduced montage EEG, Double distance montage, Status epilepticus, Prefabricated EEG devices.

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Status epilepticus, defined as 5 or more minutes of uninterrupted clinical seizure activity or recurrent seizures without a return to baseline between events, is a neurological emergency. Persistent seizures without overt clinical signs (i.e., nonconvulsive status epilepticus [NCSE])[1,2] are of particular concern, given the demonstrated correlation between the delays in diagnosis and treatment of these seizures and increased mortality.[3–5] In obtunded or comatose patients, the development of subtle motor signs, including myoclonus and nystagmus, can aid the diagnosis of nonconvulsive seizures[2]; however, the ultimate confirmation with EEG is always necessary.

Emergent EEG has exceptional value in detecting NCSE in patients undergoing evaluation for acute encephalopathy.[6–8] In patients presenting to the emergency department with altered mental status, emergent EEG leads to the diagnosis of nonconvulsive seizures in 3% to 8% of cases.[9] Furthermore, in patients who arrived comatose or developed coma without overt seizures during their hospitalization, EEG revealed NCSE in 8% of cases.[10] In resource poor settings, access to immediate EEG outside of regular business hours is often restricted by a shortage of neurodiagnostic technologists,[11] the unattainable cost of equipment,[10] and a lack of broadband infrastructure allowing rapid transmission and interpretation of recordings.[12] To overcome these barriers, limited-montage EEG recorded with conventional EEG equipment or a portable receiver has been introduced for rapid identification of seizures and triaging patients with suspected NCSE.[13,14] Limited-montage EEG obtained by hospital staff other than neurodiagnostic technologists generated signals with quality equal to that recorded by trained EEG technologists.[15]

The commercially available devices supporting limited montage EEG include fully prefabricated headbands[16] and reusable and disposable EEG caps.[17,18] These devices with limited montage arrays are being offered by several companies, but the positive predictive value of limited-montage EEG in detecting electrographic seizures remains unclear. Furthermore, there is no consensus on a minimum number of electrodes

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The findings from this study were presented in various formats at the Annual Meeting of the American Epilepsy Society (Baltimore, MD, December 2019) and the 2nd International Congress on Mobile Devices and Seizure Detection in Epilepsy (Lausanne, Switzerland, September 2019). The manuscript itself was not presented at any conference.

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Address correspondence and reprint requests to Olga Taraschenko, MD, PhD, Comprehensive Epilepsy Program, Department of Neurological Sciences, University of Nebraska Medical Center, 988435 Nebraska Medical Center, Omaha, NE 68198-8435, U.S.A.; e-mail: olha.taraschenko@unmc.edu.

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sufficient to generate high-quality recordings. In this study, we assessed the sensitivity, specificity, and predictive values for seizures of two electronically configured limited-montage EEG electrode configurations. One iteration of these configurations is built into several commercially available devices. In addition, we determined if the information derived from these recordings allowed the interpreting physician to make an appropriate clinical decision in the immediate management of patients with nonconvulsive seizures. The overarching goal of the study was to determine whether the currently available prefabricated limited-montage arrays can be used for the rapid detection of nonconvulsive seizures at the facilities with no EEG support.

METHODS

EEG Sampling

This retrospective study was conducted with the approval of the Institutional Review Board at the University of Nebraska Medical Center, a level 4 comprehensive epilepsy center. EEG acquisition was performed using the XLTEC 7.1.1 video-EEG system (Natus, Oakville, ON, Canada) with standard 21 electrode 10 to 20 arrays. EEG laboratory logs were reviewed to identify adult patients who underwent routine or continuous EEG monitoring at the University of Nebraska Medical Center between January 2012 and March 2017 and were diagnosed with NCSE. Thirty patients with NCSE were identified via review of procedure notes. Epochs containing single focal and generalized nonconvulsive seizures were identified in 17 and 13 patients, respectively. Using the same EEG catalog, we identified an additional 30 patients with rhythmic or polymorphic generalized or focal background slowing and 30 patients with normal EEG (Fig. 1). The raw EEG tracings of these recordings and the corresponding videos were reviewed by a board-certified epileptologist for confirmation, and ninety 60 to 180 seconds long representative segments containing the patterns of interest were selected; all previous annotations were removed. The epochs containing seizures included ictal onset, evolution, and offset, whereas the duration of other nonseizure epochs was arbitrary. Seizure was defined as rhythmic sharp activity or spike and wave discharges with evolution in frequency, location, or morphology.[19] Patterns with pseudo-periodic discharges at 2.5 Hz along the ictal-interictal continuum[20] were excluded.

Reconfiguration of EEG Montages

Thirty representative EEG tracings containing a single electrographic seizure, 30 epochs with focal or generalized slowing, and 30 epochs containing normal, awake, or asleep EEG background were recorded at fixed speed in three reconfigured montages: a bipolar "double banana" configuration (i.e., full montage, Fig. 2A), a nine-electrode double-distance configuration (i.e., neonatal, Fig. 2B), and a circumferential 10-electrode montage (i.e., hatband, Fig. 2C). The 270 segments (90 epochs in three different montages) were assembled into an electronic survey (see **Video**, **Supplemental Digital Content 1**, http://links.lww.com/JCNP/A114). The full montage was arranged in the following configuration: Fp1-F7; F7-T3; T3-T5; T5-O1; Fp1-F3, F3-C3; C3-P3; P3-O1; Fp2- F8, F8-T4; T4-T6; T6-O2; Fp2-F4; F4-C4; C4-P4; P4-O2; Fz-Cz; Cz-Pz (Fig. 2A). The neonatal montage was constructed in the following bipolar configuration: Fp1-T3; T3-O1; Fp1-C3;

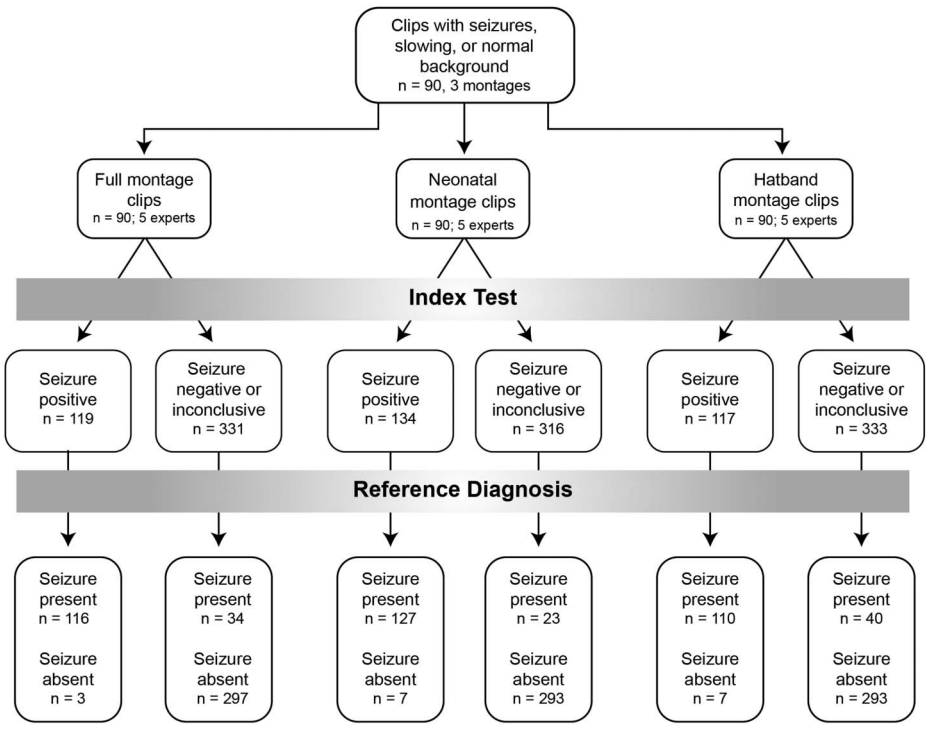

FIG. 1. Standards for reporting diagnostic accuracy flow diagram of the study design.

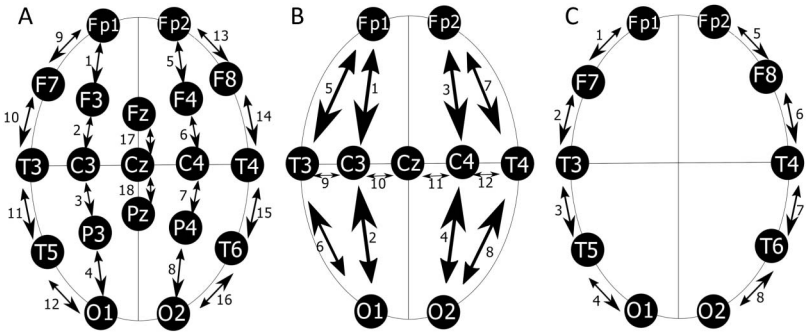

FIG. 2. EEG electrode configuration maps for the full montage (**A**), or neonatal (**B**), and hatband (**C**) reduced montages.

C3-O1; Fp2-T4; T4-O2; Fp2-C4; C4-O2; T3-C3; C3-Cz; Cz-C4; C4-T4 (Fig. 2B). The hatband montage was configured as follows: Fp1-F7; F7-T3; T3-T5; T5-O1; Fp2-F8; F8-T4; T4-T6; T6-O2 (Fig. 2C).

Board-certified epileptologists or clinical neurophysiologists with at least 2 years of uninterrupted experience in reading EEGs were asked to determine whether seizure or slowing were present on each segment. The experts were considered to fail to identify seizures if they selected either "no evidence of seizure" or "unable to tell." In addition, experts were asked whether the diagnostic information derived from the review of the EEG segment was sufficient to initiate patient treatment or pursue an additional EEG in a full montage configuration. Escalation of care was defined as ordering full montage EEG, administering anticonvulsants, or requesting both interventions. The responses were regarded as "appropriately escalated care" if any of these actions were chosen for seizures. The decision not to order additional EEG and not to administer antiepileptic drugs was categorized as choosing not to escalate care. The responses were regarded as "appropriately nonescalated care" if they did not choose any of these actions for nonictal patterns. The study data were collected and managed using the Research Electronic Data Capture (REDCap) electronic data capture tools hosted at the University of Nebraska Medical Center.[21]

Experts reviewed videos of the segments (approximately 12 seconds per screen) containing the pattern of interest with the time scale and the electrode labels appearing similar to conventional EEGs. Segments were recorded at 1.0 playback speed. The videos could be restarted multiple times, and the entire survey could be paused and resumed as needed. The responses were compared with the individual interpretation of the corresponding full montage segment in the same survey and an official read of the clinical EEG (by a nonparticipating expert). The clinical data were not provided in the survey.

Statistical Analyses

Seventeen clips containing patterns with slowing were obtained from the patients who also contributed segments with seizures; however, the responses to all of the clips were regarded as statistically independent variables. Sensitivity, specificity, and predictive values of each montage for seizures were determined with respect to the individual responses to the corresponding electronically configured full montage and the official EEG interpretation (by a nonparticipating expert). Interrater reliability was estimated for each measure within each segment type using Fleiss Kappa statistic, which allows for more than two raters.[22,23] To determine participant performance while detecting seizures using limited-montage EEG, we applied logistic regression analysis to calculate the area under the receiver operating characteristic curve (ROC) along with associated 95% confidence intervals. The seizure or nonseizure pattern on the full montage segment (and the official EEG interpretation) was the outcome, and the same pattern on the limited-montage EEG was the predictor.[24] SAS software version 9.4 was used for most data analyses (SAS Institute Inc, Cary, NC). Interrater reliability was calculated using R software[25] and an interrater reliability package.[26]

RESULTS

Seizure Detection in Reference to Full Montage EEG

To account for the lack of clinical information during the review of the limited montage segments, we compared participant responses to limited montage segments with their own interpretation of the corresponding electronically reconfigured full montage EEG segments. Combined for five experts, the sensitivities of the neonatal and hatband montages for seizure diagnosis using this approach were 0.96 (confidence interval [CI] = 0.90–0.99) and 0.84 (CI = 0.76–0.90), respectively. The specificities of these limited montages for seizure were 0.94 (CI = 0.91–0.96) and 0.98 (CI = 0.95–0.99), respectively. The positive predictive value for the hatband montage was higher than that of the neonatal montage, whereas the negative predictive value of the neonatal montage was higher than that of the hatband montage (Table 1).

Clinical Management Decisions in Reference to Full Montage EEG

To examine the yield of EEG in streamlining the clinical care of patients with seizures, the raters were asked whether the information obtained from the examination of full montage or limited montage EEG segments would trigger an escalation of care. The experts who chose to escalate care for seizures during the review of the full montage segments also opted to escalate care while assessing neonatal montage segments 96% of the time and while assessing hatband montage segments 92% of the time (Fig. 3).

TABLE 1 Diagnostic Test Characteristics for the Detection of Seizures Using the Full, Neonatal, and Hatband Montages

Standard for Comparison	Montage	Test Characteristics*			
		Sensitivity	Specificity	PPV	NPV
Corresponding full montage	Neonatal	0.96 (0.90–0.99)	0.94 (0.91–0.96)	0.85 (0.78–0.91)	0.98 (0.96–0.99)
	Hatband	0.84 (0.76–0.90)	0.98 (0.95–0.99)	0.93 (0.86–0.97)	0.94 (0.91–0.97)
Official EEG interpretation	Full	0.77 (0.70–0.84)	0.99 (0.97–1.00)	0.97 (0.93–0.99)	0.90 (0.86–0.93)
	Neonatal	0.85 (0.78–0.90)	0.98 (0.95–0.99)	0.95 (0.90–0.98)	0.93 (0.89–0.95)
	Hatband	0.69 (0.61–0.77)	0.99 (0.97–1.00)	0.96 (0.91–0.99)	0.87 (0.82–0.90)

*Range represents 95% CI.
NPV, negative predictive value; PPV, positive predictive value.

Overall Accuracy to Detect Seizures in Reference to Full Montage EEG

To assess the overall accuracy of limited-montage EEG to discern seizure from nonseizure patterns, we computed the area under an ROC curve. With respect to participant performance on distinguishing seizure and nonseizure patterns while working with the neonatal and hatband montages, the area under the ROC curves were 0.95 (CI = 0.93–0.97) and 0.91 (CI = 0.87–0.94), respectively. These areas correspond to the excellent diagnostic accuracy of applying the neonatal and hatband configurations to distinguish ictal from nonictal patterns.

When comparing participant management between the two limited montages with full montage, the areas under the ROC curves were 0.87 (CI = 0.84–0.90) and 0.81 (CI = 0.78–0.84), respectively, which corresponds to the good abilities of both methods to allow the examiner to accurately triage patients.

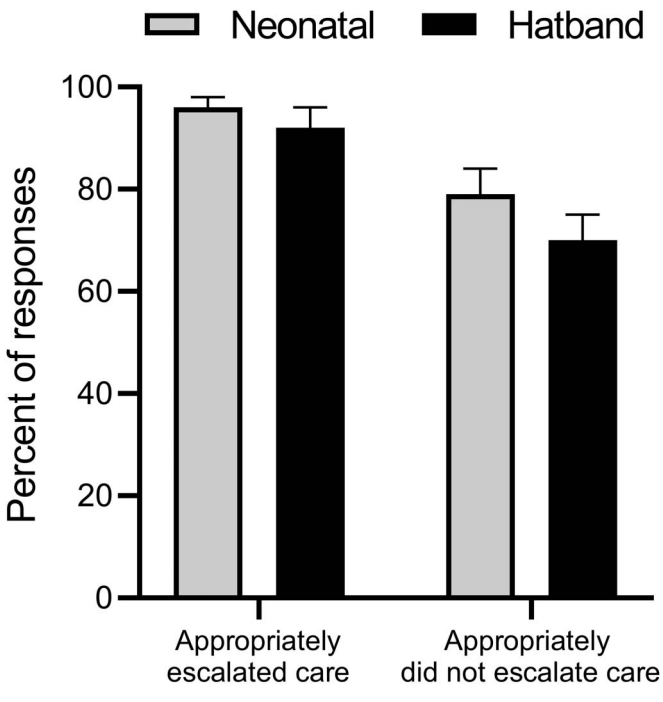

FIG. 3. Clinical management of patients with ictal and nonictal patterns during the assessment of the neonatal and hatband montage EEGs in reference to full montage EEG.

Seizure Detection in Reference to Official EEG Interpretation

Because we were interested in evaluating the quality of the limited montage methods for the clinical use, we also performed the analysis in comparison to the official EEG read on a standard 21-electrode clinical EEG. Combined for five experts, sensitivity and specificity for seizure patterns using the full montage were 0.77 (CI = 0.70–0.84) and 0.99 (CI = 0.97–1.00), respectively.

Experts detected seizure patterns using the neonatal and hatband montages with sensitivities 0.85 (CI = 0.78–0.90) and 0.69 (CI = 0.61–0.77), respectively. The specificities of these montages for seizure detection were 0.98 (CI = 0.95–0.99) and 0.99 (CI = 0.97–1.00), respectively. The positive predictive value was the highest for the full montage (0.97), whereas the negative predictive value was highest for the neonatal montage (0.93) (Table 1).

For seizure patterns in the full montage, five clips were misclassified as nonseizures by ≥ 3 experts, and one clip was mislabeled by all five experts. For seizure patterns in the neonatal montage, two segments were misclassified as nonseizure by ≥ 3 experts. In the hatband montage, eight clips were misclassified by ≥ 3 experts and four clips were mislabeled by all five experts. There were no clips with slowing or normal background in any montage that were inappropriately misclassified as seizures by ≥ 3 experts.

Clinical Management Decisions in Reference to Official EEG Interpretation

While reviewing the segments containing seizures in full montage, experts chose to appropriately escalate care in 96% of occurrences. On the other hand, reviewers choose to appropriately escalate care in all cases of seizures for neonatal montage and in 95% of occurrences in hatband montage. For the segments without seizure patterns, experts appropriately chose to not escalate care 78% of the time, 66% of the time, and 58% of the time for full, neonatal, and hatband montages, respectively (Table 2).

The analysis of the specific clinical decisions in response to seizure patterns revealed that both interventions (i.e., anticonvulsants

TABLE 2. Clinical Management of Seizures and Non-ictal Patterns Using the Full, Neonatal and Hatband Montages

Montage	Pattern	No Intervention	AED Alone	EEG Alone	Both Interventions	Any Appropriate Intervention
Full	Ictal	4	0	10	86	96
	Non-ictal	78	0	20.3	1.7	78
Neonatal	Ictal	0	0.7	9.3	90	99.3
	Non-ictal	66	0	31.3	2.7	66
Hatband	Ictal	5.3	0	18	76.7	94.7
	Non-ictal	58.3	0	40	1.7	58.3

Proportions of responses expressed as percentages of all responses to each pattern and montage combination.
AED, antiepileptic drug.

and extended EEG) were favored by most experts while reviewing all three montages (Table 2 and Fig. 4).

Overall Accuracy to Detect Seizures in Reference to Official EEG Interpretation

When working with a full montage, the area under the ROC curve was 0.88 (CI = 0.85–0.92), suggesting that this method was good at separating seizures from nonseizure patterns. When working with the neonatal and hatband montages, the areas under the ROC curves were 0.91 (CI = 0.88–0.94) and 0.84 (CI = 0.80–0.88), suggesting that these methods were excellent and good, respectively, in distinguishing seizures from nonseizure patterns.

To establish the accuracy of the two limited montage EEG methods in discerning between appropriate and inappropriate escalation/management of care, we determined that the ROC area under an ROC curves for the full, neonatal, and hatband montages were 0.87 (CI = 0.84–0.90), 0.83 (CI = 0.80–0.86), and 0.77 (CI = 0.73–0.80), respectively.

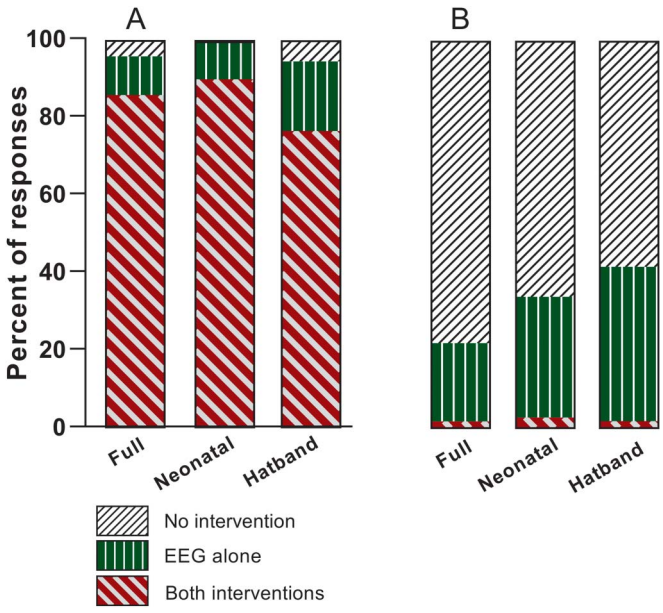

FIG. 4. Specific categories of clinical management for ictal (**A**) and nonictal (**B**) patterns in reference to official EEG interpretation.

Interrater Reliability

The interrater reliability for seizure detection combined for all five experts was 0.74 for the full montage. Similarly, interrater reliabilities for the neonatal montage and the hatband montage were 0.75 and 0.74, respectively. The interrater reliabilities for clinical management based on each segment were 0.58 and 0.39 for the neonatal and hatband montages, respectively. Interrater reliability for clinical management using the full montage EEG was 0.66.

DISCUSSION

In this study, we systematically assessed the accuracy of two limited montage EEGs in the diagnosis of acute nonconvulsive seizures. In addition, this study is the first to examine the utility of the data derived from the limited montage EEGs for the clinical management of patients with nonconvulsive seizures.

Diagnostic Utility

We found that neonatal and hatband montage EEGs for had sensitivities of 0.96 and 0.84 to detect nonconvulsive focal or generalized seizures in reference to the full montage in bipolar electrode configuration. The sensitivities were substantially lower (0.85 and 0.69, respectively) when the comparisons were made about the official EEG interpretations. Although we ultimately were interested in determining how these limited montage arrays built into commercially available devices would perform in respect to the official EEG interpretations and we performed this analysis, comparison with the full montage recordings is more appropriate because it takes into account the lack of access to clinical data during the survey. Ultimately, the combination of both approaches helped to estimate true clinical utility and account for the limitations inherent to the survey design (e.g., inability to switch montages or the requirement to make a conclusion based on the review of a single tracing).

According to the guidelines of the American Clinical Neurophysiology Society, at least 16 channels (or 21 electrodes) should be used concurrently during the acquisition of clinical EEGs in adults; a larger number of electrodes is encouraged.[27] In

a study by Herta et al.,[28] the sensitivity of limited montage EEG to detect rhythmic, periodic, and ictal patterns was found to decline stepwise with every consecutive lead electronically removed from the array. Furthermore, the accuracy of the recording in detecting seizures decreased dramatically after the removal of the tenth electrode.[28] In contrast to this premise, we found that the overall sensitivity of the nine-electrode neonatal montage for seizures was superior to that of the 10-electrode hatband montage (0.96 and 0.84, respectively). This is likely because our neonatal montage was comprised of a greater number of channels (i.e., 12) than our hatband montage (i.e., 8), thereby providing more electrographic information. Our findings also support the notion that hatband montage is less sensitive for detection of seizures,[29] whereas similar configurations with midline electrodes have higher accuracy for ictal patterns.[28,30,31]

The sensitivity of the neonatal montage in our study exceeds the upper limit of the range reported in another recent study (0.69–0.81).[32] The higher estimate was based on the electronically configured limited montage in adult patients with seizures,[32] and the lower estimate used patients with status epilepticus; the assessments were made during a review of 2-hour-long segments.[32] Our determinations were made based on 1-to-3-minute-long EEG segments containing a single seizure or other pattern of interest. It is encouraging that seizures could be detected rather quickly on much shorter recordings and with high accuracy using our neonatal EEG lead configuration. The sensitivity of our montage to detect seizures was also higher than that reported by Herta et al. (i.e., 0.76) in an electronically configured nine-electrode "hairline plus vertex" double distance montage[28]; however, our segment selection and analysis process differed from that used in the former study.

In previous studies, the sensitivities of a four-channel subhairline hatband montage for epileptiform activity were 0.54[33] and 0.68.[34] By contrast, sensitivities of the six-channel montage applied at the hairline level were much higher (0.72–0.92).[14,29,30] Despite higher accuracy of the hairline montage compared with the subhairline approach, Kolls and Husain[29] found that nearly 30% of seizures were missed when interpreting the hairline montage and concluded that this method has a prohibitively high false-positive rate. Our hatband montage, which mimicked the hairline montage, had sensitivity of 0.84, which is in the range of previously reported values. In the study by Vanherpe et al.,[14] where the authors found a higher sensitivity of the hairline montage (0.92), the patterns of interest were primarily comprised of the generalized seizures. By contrast, our study contained both focal and generalized patterns, and the former may have been more challenging to detect.

We found that both limited montage configurations in our study yielded high specificity for seizures. Notably, the specificity of the neonatal montage in our study (0.94) approximated that demonstrated in another study (0.92–0.97).[32] Similarly, the specificity of 0.98 of our hatband montage was comparable with other studies (0.94–1.0).[14,29–31,33] This was further supported by the findings from logistic regression analyses, which showed that the neonatal and hatband montage were excellent and good, respectively, in separating seizure and nonseizure patterns. In the consensus analyses, full montage and both limited montages had comparably high interrater reliability. Taken collectively, these findings suggest that 9 and 10 electrode montages in the current configurations provide sufficiently good accuracy for detection of nonconvulsive seizures.

Clinical Management

We determined whether the data available within a limited montage EEG was sufficient to facilitate the key decisions made by clinicians after the interpretation of ictal EEGs. In this pursuit, we assumed that physicians would order full montage EEG when there was doubt in the interpretation of a pattern on the limited montage recording or when a prolonged recording would be necessary to guide treatment. Furthermore, we assumed that experts would administer anticonvulsants if an ictal pattern was identified. We learned that the EEG findings identified on limited montage EEG allowed clinicians to appropriately escalate care in most occurrences of electrographic seizures.

When reviewing specific management choices made in response to ictal patterns presented in each montage, we noted that an overwhelming majority of management decisions favored to obtain EEG along with ordering anticonvulsants, and this uniform response was particularly apparent for neonatal montage. When reviewing specific management choices made in response to nonictal patterns presented in each montage, we noted more variability in expert response (Table 2).

In summary, based on consistent agreement among several experts, we found that neonatal and hatband configurations were excellent and good, respectively, in separating seizure from normal and slow background and that both montage configurations had high sensitivity to detect seizures. In most of our simulated scenarios, conclusions regarding the presence or absence of seizures reached during the interpretation of the limited montages lead participants to decide to appropriately escalate care for seizures. Taken collectively, these findings are promising to suggest that in some patients with suspected nonconvulsive seizures, ictal patterns can be distinguished from normal background or nonrhythmic slowing using a limited array of EEG electrodes.

Limitations

This study has several limitations. First, the participants who were experienced in visual interpretation of full montage EEGs may have less experience interpreting limited-montage EEGs. Although the comparisons were made in reference to the digital full montage segments, the visualization of the electrographic seizure patterns (even on the reconfigured full montage) may not fully reflect the features of clinical EEG. Furthermore, the short duration of segments included in our survey could have allowed readers to identify seizures more readily. A clinical EEG spans a much greater length of time, and readers do not specifically anticipate finding seizures. These differences may have biased expert responses and caused an overestimation of the sensitivity of each montage for seizures in the comparisons to the official EEG interpretation. Thus, our conclusions may not be fully generalizable to conventional clinical EEG. Second, all isolated seizures included in this study were nonconvulsive and were extracted from recordings of patients with NCSE. This limits

generalizability of our findings to other patient populations and seizure scenarios. The responses for focal and generalized nonconvulsive seizures were not disaggregated, given the small sample size. It is therefore uncertain whether the utility of the limited montage differs for focal and generalized nonconvulsive seizures. In addition, we excluded the patterns with pseudoperiodic discharges at 2.5 Hz that lie on the ictal-interictal continuum that are notoriously challenging to definitively classify as seizures even using conventional EEG. This could lead to overestimation of the performance of limited montage EEG.

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