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Reduced electrode arrays for the automated detection of rhythmic and periodic patterns in the intensive care unit: Frequently tried, frequently failed?

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HIGHLIGHTS

- First study that systematically evaluates the effect of automated electrode reduction on pattern detection.
- Effect of electrode reduction on pattern detection sensitivity was evaluated by a computer algorithm.
- Guidance which reduced EEG array may offer the highest detection results in specific situations.

ABSTRACT

Objective: To investigate the effect of systematic electrode reduction from a common 10-20 EEG system on pattern detection sensitivity (SEN).
Methods: Two reviewers rated 17130 one-minute segments of 83 prospectively recorded cEEGs according to the ACNS standardized critical care EEG terminology (CCET), including burst suppression patterns (BS) and unequivocal electrographic seizures. Consensus annotations between reviewers were used as a gold standard to determine pattern detection SEN and specificity (SPE) of a computational algorithm (baseline, 19 electrodes). Electrodes were than reduced one by one in four different variations. SENs and SPEs were calculated to determine the most beneficial assembly with respect to the number and location of electrodes.
Results: High automated baseline SENs (84.99–93.39%) and SPEs (90.05–95.6%) were achieved for all patterns. Best overall results in detecting BS and CCET patterns were found using the "hairline + vertex" montage. While the "forehead + behind ear" montage showed an advantage in detecting ictal patterns, reaching a 15% drop of SEN with 10 electrodes, all montages could detect BS sufficiently if at least nine electrodes were available.
Conclusion: For the first time an automated approach was used to systematically evaluate the effect of electrode reduction on pattern detection SEN in cEEG.
Significance: Prediction of the expected detection SEN of specific EEG patterns with reduced EEG montages in ICU patients.

Abbreviations: ACNS, American clinical neurophysiology society; BAM, "Banana" montage; BS, burst suppression patterns; CCET, American clinical neurophysiology society standardized critical care EEG terminology; cEEG, continuous electroencephalography; CRM, "Crown" montage; D15, drop of detection sensitivity of more than 15%; EEG, electroencephalography; FOM, "Forehead + behind ear" montage; HAM, "Hairline + vertex" montage; ICU,, intensive care unit; NCS,, nonconvulsive seizures; NOPAT, no pattern; PD, periodic discharge; RAA, rhythmic alpha activity; RDA, rhythmic delta activity; RTA, rhythmic theta activity; SEN, sensitivity; SPE, specificity.

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1. Introduction

Continuous EEG (cEEG) allows noninvasive monitoring of brain function with a high temporal resolution. Especially in the intensive care unit (ICU) it can add important information where conclusions from clinical examination may often be limited. For many applications, such as the detection of nonconvulsive seizures (NCS), the guidance of seizure treatment and the management of pharmacological induced coma, cEEG is considered the primary diagnostic tool (Jordan, 1999; Friedman et al., 2009). But even with an increased awareness of seizures in the ICU and huge advancements in computer technology, the use of EEG remains limited in everyday clinical practice. This is mainly due to the significant efforts associated with EEG. Besides the negligible costs of the recording device, personnel resources represent the major limiting factor. On the one hand, specially trained, 24-h available physicians are needed to review several hours of EEG. On the other hand, EEG technician must attach and maintain the electrode setup. In an ICU setting a trained EEG technician needs about 30–45 min to setup 19 cup electrodes. But collodion will dry out within the first six hours and needs accurate maintenance (Young et al., 2006). To increase availability and simplify the EEG setup, several studies assessed the possibility to work with a reduced number of electrodes (Bridgers and Ebersole, 1988; Foldvary et al., 2000; Tekgul et al., 2005; Kolls and Husain, 2007; Shellhaas and Clancy, 2007; Wusthoff et al., 2009; Young et al., 2009; Karakis et al., 2010; Nitzschke et al., 2011; Rubin et al., 2014; Tanner et al., 2014; Brenner et al., 2015; Lepola et al., 2015; Muraja-Murro et al., 2015).

A reduced electrode setup may have more potential benefits than just time saving. It can come in handy for patients where proper lead placement due to head wounds or drains is not possible. Furthermore, it may encourage physicians to use cEEG more frequently and consolidate acceptance among nursing staff. Previous studies reported frequent delays in the diagnosis of NCS (Dunne et al., 1987). Since mortality increases with seizure duration (Young et al., 1996) a reduced and easy applicable electrode setup should facilitate prompt diagnosis of NCS and benefit critical care patients.

Until now various approaches of electrode reduction have been published, that can be roughly summarized into three groups. Group-one tried to use a single-channel EEG (e.g. C3, C4). This was mainly used in neonates where most of seizures originate from the central midline (Schultz et al., 1992; Shellhaas and Clancy, 2007; Wusthoff et al., 2009). Group-two tried to cover as much of the scalp as possible, maintaining the 10–20 system based locations of electrodes (e.g. F3, F4, T7, Cz, T8, O1, O2) (Foldvary et al., 2000; Tekgul et al., 2005; Kolls and Husain, 2007; Karakis et al., 2010; Rubin et al., 2014; Lepola et al., 2015). Group-three's main interest was to develop an electrode setup which was easy to use and fast to apply in emergency cases (Bridgers and Ebersole, 1988; Young et al., 2009; Brenner et al., 2015; Muraja-Murro et al., 2015). In this setting it should be possible to place electrodes, without the help of an EEG technician, under the hairline on the forehead and behind the ear (e.g. Fp2, Fp1, F8, F7, Sp1, Sp2, T9, T10). Concerning seizure detection, nearly all major studies showed a tendency towards poor sensitivity (SEN). The common denominator of all these studies was to predefine a reduced electrode setup and compare its seizure detection rates with that of a standard 10–20 system.

In the present study, we reduced the electrodes of the International 10–20 EEG system systematically one by one, which to the best of our knowledge has never been done before. A computational algorithm assessed each reduction step. Four different variations of final electrode arrays, mainly derived from previously published reduced EEG montages were evaluated. Detection sensitivities (SEN) and specificities (SPE) for unequivocal electrographic seizures (spike-wave > 3 Hz, evolving discharges > 4 Hz), patterns defined by the ACNS Standardized Critical Care EEG Terminology (CCET) and burst suppression patterns (BS) were calculated (Hirsch et al., 2013). The aim of the study was to observe and illustrate the change in detection SEN and SPE for every reduced electrode and pattern of interest, to allow an individual assessment in cases where reduced setups are needed.

2. Methods

2.1. Dataset

A dataset of 92 prospectively recorded cEEGs in a neurological and a neurosurgical ICU (Neurological Center Rosenhuegel, General Hospital Vienna) was used. EEGs were recorded with a Micromed EEG recording system (SystemPLUS Evolution 1.04.95, Micromed S.p.A., Veneto, Italy) using the International 10–20 electrode system with a sampling rate of 256 Hz. Inclusion criteria for this study were 1) recordings longer than 24 h and 2) artefact-free recordings from a full set of 19 electrodes for more than 90% of the overall recording time. 7 EEGs were recorded with less than 19 electrodes. Another 2 patients had a recording time under 24 h. This left 83 patients for the study (6733 h, mean individual recording duration 73 h). Two types of electrodes were used for recordings: gold cup electrodes (Genuine Grass Gold Disc electrodes) and conductive plastic cup electrodes (Ives EEG Solutions). Research was prior approved by the institutional ethics committee.

2.2. NeuroTrend

NeuroTrend is a computational method that facilitates screening of long-term EEGs. It automatically detects rhythmic and periodic patterns in surface EEG and displays their localization and frequency in a graphical user interface. Results are visualized with a focus on data and time compression. Therefore, hours of cEEG can be compressed and displayed on a single screen. The definition of rhythmic and periodic EEG patterns follows the guidelines of CCET adding unequivocal electrographic seizures including generalized spike-wave discharges at 3 Hz or faster as well as evolving discharges that reach frequencies of more than 4 Hz and BS (Hirsch et al., 2013). Fürbass et al. (Fürbass et al., 2015) described the technical background of the algorithm, while Herta et al. (Herta et al., 2015) recently performed a validation of NeuroTrend. For this study a newer version of the algorithm was used. Especially RDA, which showed a high rate of false positive detections due to general slowing in the past, improved in terms of detection SEN and SPE as seen in Table 1. NeuroTrend is part of the encevis software package, in this work version V1.3 of encevis was used (http://www.encevis.com).

2.3. Data processing and statistical methods

The first minute of each hour of the raw cEEG recordings were identified and reviewed by two clinical neurophysiologists. In these segments the reviewers could assign one of four possible labels (1) periodic discharge (PD), (2) rhythmic delta activity (RDA), (3) ictal group (4) burst suppression patterns (BS). In each one-minute EEG segment multiple annotations could be made if they occurred consecutively. If no annotation was made the specific segment was labeled no pattern (NOPAT). Periodic and rhythmic delta patterns were rated according to the CCET guidelines. The ictal group included unequivocal electrographic seizures including generalized spike-and-wave discharges at 3 Hz or faster as well as evolving discharges that reach frequencies of more than 4 Hz.

Table 1
Detection performance of NeuroTrend. Two reviewers rated multiple segments of cEEG. Interrater agreement between the reviewers was calculated by Cohen's kappa (κ) statistics. Agreements were used as consensus annotations and compared to the detection results of the computer algorithm "NeuroTrend". Corresponding interrater agreement between the algorithm and the reviewers as well as detection sensitivity and specificity of the algorithm are shown. As a baseline calculation, a standardized 10-20 EEG system with 19 electrodes was used.

Category	n Annotation Segments	Segment length [sec]	n Agreements between both Reviewers	Sensitivity [%]	Specificity [%]	κ between Reviewers	κ between Reviewers & NeuroTrend
PD	17130	20	1305	87.36	90.05		
RDA	17130	20	121	93.39	91.87		
Ictal Group SW (n = 20) RTA* (n = 125) RAA* (n = 7)	17130	20	152	90.07	95.60	0.75	0.67
BS	5710	60	653	84.99	91.52	0.71	0.64

BS, burst suppression; κ, Cohens Kappa; PD, periodic discharges; RAA, rhythmic alpha activity; RDA, rhythmic delta activity; RTA, rhythmic delta activity; SW, spike-wave.
[a]Confirmed electrographic seizure activity in theta or alpha range.

Because BS typically lasted for longer periods, the whole one-minute segment was annotated either as a segment with or without BS. All other patterns could only be present for a few seconds. Therefore, annotations of these patterns were split into three non-overlapping 20-s segments.

Cohen's kappa statistic was used to calculate an interrater agreement. All segments that showed agreement between the two reviewers were considered as consensus annotations and used for further analysis. 10–20 system based cEEGs with 19 electrodes (excluding reference and ground electrode) were analyzed by the computer algorithm NeuroTrend. Consensus annotations were compared with the results of NeuroTrend. Detection performance of NeuroTrend was assessed by assigning one of four possible results to each annotation: True positive, false positive, true negative and false negative. A pattern was counted as true positive if one of the patterns detected by NeuroTrend in the annotation segment matched the consensus annotations of the reviewers. A consensus annotation without a matching NeuroTrend detection in the annotation minute was counted as false negative. An annotation segment with one or several NeuroTrend detections that did not match the consensus annotations was counted as false positive. An annotation segment without consensus annotation and without any detected pattern by NeuroTrend was counted as true negative. SEN and SPE were calculated according to the following formulas:

$$SEN\ [\%] = \frac{True\ Positive}{True\ Positive + False\ Negative} * 100$$

$$SPE\ [\%] = \frac{True\ Negative}{True\ Negative + False\ Positive} * 100$$

2.4. Electrode reduction

After having established an automated baseline for SEN and SPE using all 19 leads according to the International 10-20 EEG system (Fp1, F3, C3, P3, O1, Fp2, F4, C4, P4, O2, F7, T7, P7, F8, T8, P8, Fz, Cz, Pz), electrodes were reduced in a stepwise fashion. SEN, SPE and their confidence intervals were calculated separately for each electrode eliminated from the setup. Four variations of electrode reductions, depending on their local distribution, were used and labeled "forehead + behind ear montage" (FOM), "hairline + vertex montage" (HAM), "banana montage" (BAM) and "crown montage" (CRM). 12 to 13 reduction steps were calculated leaving six or seven electrodes for final calculations. Below, the steps of electrode reduction are shown as superscript numbers. The final EEG montages are shown in bold (Fig. 1):

Forehead + behind ear montage (FOM, Fig. 1A):

O1^{1}-O2^{2}-P3^{3}-P4^{4}-Pz^{5}-T7^{6}-T8^{7}-C3^{8}-C4^{9}-Cz^{10}-F3^{11}-F4^{12} - **Fp1-Fp2-F7-Fz-F8-P7-P8^{13}**

Hairline + vertex montage (HAM, Fig. 1B):

P7^{1}-P8^{2}-F7^{3}-F8^{4}-P3^{5}-P4^{6}-F3^{7}-F4^{8}-Fz^{9}-Pz^{10}-C3^{11}-C4^{12} - **Fp1-Fp2-T7-Cz-T8-O1-O2^{13}**

Banana (= Longitudinal) montage (BAM, Fig. 1C):

Cz^{1}-Pz^{2}-Fz^{3}-P7^{4}-P8^{5}-F7^{6}-F8^{7}-T7^{8}-T8^{9}-P3^{10}-P4^{11}-F3^{12}-F4^{13} - **Fp1-Fp2-C3-C4-O1-O2^{14}**

Crown (= Transversal) montage (CRM, Fig. 1D):

Cz^{1}-O1^{2}-O2^{3}-Fp1^{4}-Fp2^{5}-C3^{6}-C4^{7}-T7^{8}-T8^{9}-P3^{10}-P4^{11}-F3^{12}-F4^{13} - **F7-Fz-F8-P7-Pz-P8^{14}**

The detection results based on the EEGs of each reduction step were compared to the consensus annotations of the reviewers. SEN and SPE were quantified and the number of electrodes for which detection SEN dropped more than 15% (D15) was determined.

2.5. Validation of computational results

To validate the computational NeuroTrend results a single reduced EEG dataset was annotated a second time by the two reviewers. For reevaluation, we chose the montage that achieved a D15 with the least number of electrodes for every evaluated pattern. Furthermore, the number of electrodes was reduced to the half (reduction step 10, 9 electrodes). For this reduced montage 50 EEG segments from each of the four pattern groups and 50 EEG segments without patterns were randomly selected resulting in 250 EEG segments.

The same reviewers who established the primary consensus annotations annotated the 250 segments again. They were blinded to the distribution of patterns. The reduced montages were presented to the reviewers as short 20-s EEG segments. Switching between longitudinal, transversal and referential montages was allowed during the review process.

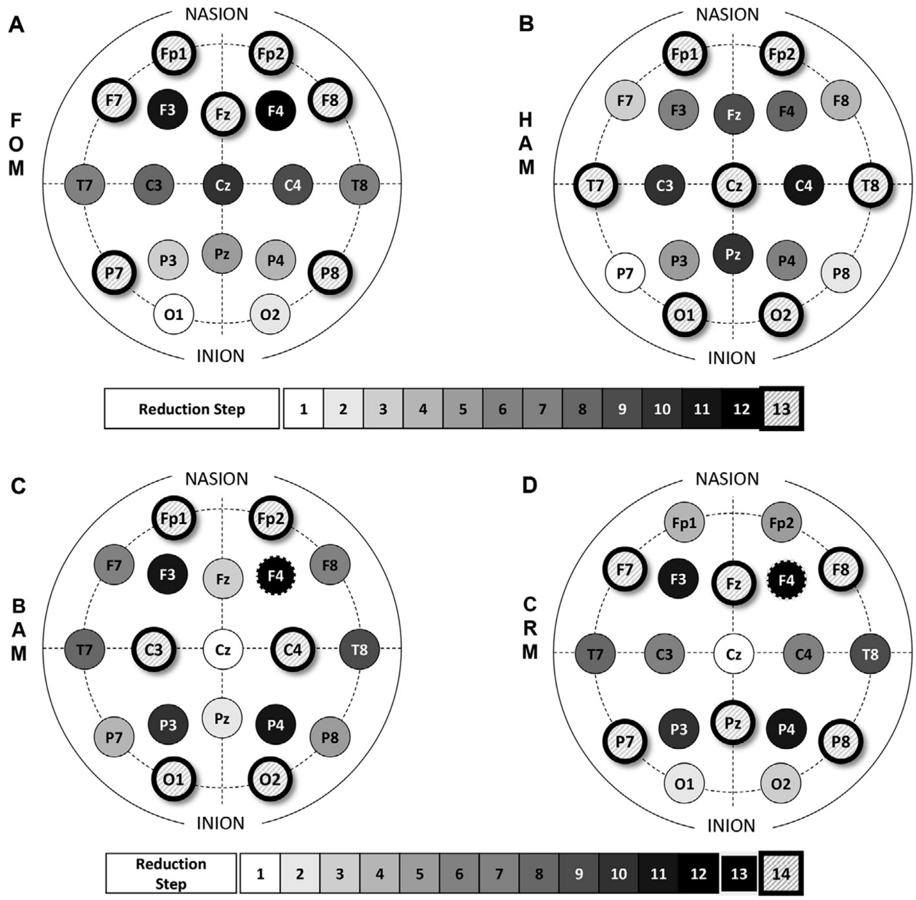

Fig. 1. Four different variations of electrode reductions from a common 10-20 EEG montage are shown. The different shades of gray (Reduction Step) numbers the succession of lead reduction starting with 'step 1' in white. The final electrode array is shown striped and boldly encircled ('step 13' or 'step 14'), labeling the different final montages. (A) A "forehead + behind ear" EEG montage (FOM), also known as "subhairline" montage, is shown. Because it is quickly installed and easy to use, it is commonly used in the emergency department. (B) The "hairline + vertex" montage (HAM) tries to cover the whole scalp but leads to double distances between electrodes in the final reduced montage. (C, D) A longitudinal "banana" montage (BAM) as well as a transversal "crown" montage (CRM) is shown. They were thought to be advantageous in detecting patterns with different local distributions.

The review results of the 250 EEG samples with the reduced 9 electrodes were compared to the primary consensus annotations with the full electrode setup to determine if samples were annotated equally. SEN of these annotations was calculated for each reviewer to quantify the loss of SEN and agreement.

Then consensus annotations between the two reviewers based on the reduced nine electrodes EEG samples were determined and classified as correct or incorrect by using the primary consensus annotations. The computational result was evaluated on the same samples to define correct or incorrect detections. The number of samples with correct annotations and incorrect computer result are defined as c. The number of samples with incorrect annotations and correct computer result are defined as b. To prove that no statistically significant difference between human and computational annotations exist the McNemar test with the test statistic $\chi^2 = \frac{(|b-c|-1)^2}{b+c}$ and a critical value of 3.841 for $\alpha = 0.95$ was used on this paired nominal data.

3. Results

3.1. Detection performance of NeuroTrend

17,130 20-s annotations showed agreement between the two reviewers and were considered as consensus annotations. In these 17,130 segments 1578 rhythmic and periodic EEG patterns were found and compared with the detection results of the computer algorithm. Baseline detection SENs and SPEs of NeuroTrend were calculated with a full set of 19 electrodes. Table 1 illustrates the consensus annotations found for different pattern groups as well as the detection performance of NeuroTrend. For BS 5710 60-s annotations showed agreement between the reviewers. 653 BS were found and compared to the computer algorithm (Table 1).

3.2. Electrode reduction

For most pattern categories and reduction montages, a reduction of electrodes caused a continuous decline in SEN, while SPE increased as illustrated in Fig. 2. Table 2 shows the number of electrodes used for which a D15 occurred in different pattern types and corresponding montages.

3.2.1. Periodic discharge (PD)

We detected a stable decrease in SEN for PD, no matter which electrode reduction montage was used (Fig. 2B). PDs occurred with 58.52% disproportionately often considering the distribution of all pattern groups. D15 was encountered in the HAM (SEN: 76.32%, SPE: 92.61%) with 13 electrodes, which was the best result compared to all other montages. A stable decline in SEN occurred until the 9th electrode was removed (10 electrodes remaining), a rapid decrease was observed thereafter. After the final reduction step, very poor SENs were observed, ranging from 42.76% to 53.26%.

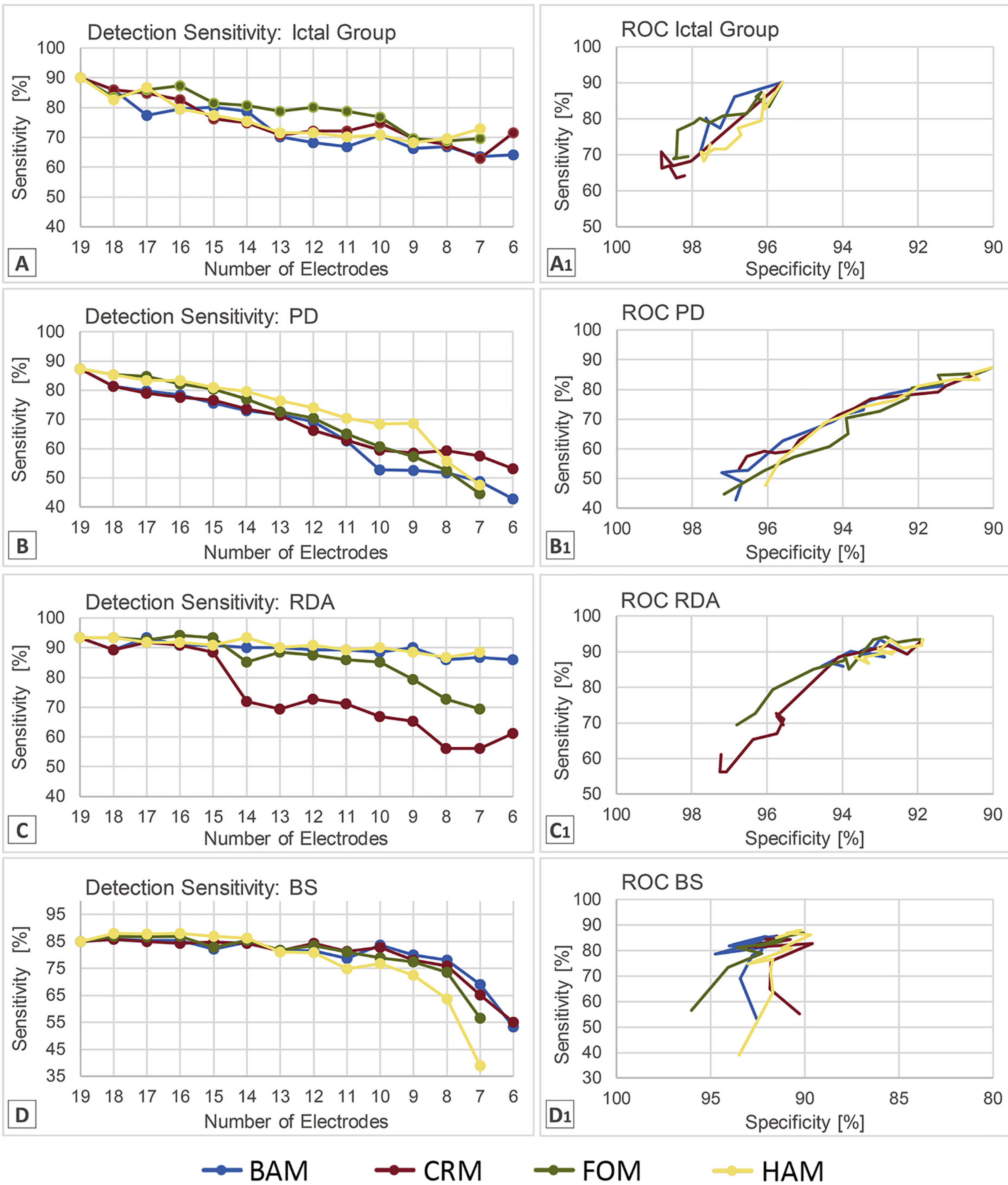

Fig. 2. Changes in detection sensitivity (left) and specificity (right) of NeuroTrend with a decreasing number of electrodes are illustrated for different pattern types and different reduction montages. BAM, banana montage; CRM, crown montage; FOM, forehead + behind ear montage; HAM, headband + vertex montage; PD, periodic discharge; RDA, rhythmic delta activity; Ictal group, spike-wave >3 Hz or evolving discharges >4 Hz; BS, burst suppression.

3.2.2. Ictal group (RTA, RAA, SW)

In the ictal group the overall best performing reduction montage was FOM with a D15 at 10 remaining electrodes (SEN: 76.82%, SPE: 98.38%). Further reduction of electrodes caused a slight but not explainable detection increase in some montages with final SENs between 64.24% and 72.85% (Fig. 2A).

3.2.3. Rhythmic delta activity (RDA)

RDA was the only group where different reduction montages diverged strongly. HAM and BAM nearly showed no decrease of SEN and even did not reach a D15 with the last reduction step. With the final array, HAM showed the best detection SEN of 88.43% (SPE: 93.67%). On the contrary FOM reached a D15 with 10 remaining electrodes and CRM with 15, respectively. Low SENs of 69.42% and 61.16% made these two montages unsuitable for the detection of RDA with only 6 to 7 leads (Fig. 2C).

3.2.4. Burst suppression patterns (BS)

In all reduction montages BS showed a uniform decline after a D15 with eight to nine electrodes remaining. The best montage

Table 2
Number of electrodes for which detection sensitivity dropped more than 15%.

Category	Item	"Banana" montage (BAM)	"Crown" montage (CRM)	"Forehead + behind ear" montage (FOM)	"Hairline + vertex" montage (HAM)
PD (periodic discharge)	Number of electrodes	15	15	14	13
	SEN (%)	75.56	76.70	77.01	76.32
	SPE (%)	93.40	93.26	92.28	92.61
Ictal Group (electrographic seizures)	Number of electrodes	15	16	10	15
	SEN (%)	80.13	82.78	76.82	77.48
	SPE (%)	97.63	97.45	98.38	96.78
RDA (rhythmic delta activity)	Number of electrodes	6	15	10	6
	SEN (%)	85.95	88.43	85.12	88.43
	SPE (%)	93.97	94.10	94.76	93.67
BS (burst suppression)	Number of electrodes	8	8	8	9
	SEN (%)	78.10	75.96	73.51	72.43
	SPE (%)	92.79	91.79	94.09	91.82

SEN, sensitivity; SPE, specificity.

at D15 was BAM with a SEN of 78.10% and a SPE of 92.27% with 8 leads after which an exponential decline occurred (Fig. 2D). The final array with BAM showed a SEN of 53.29% and a SPE of 92.55%, which was slightly inferior to the final array of FOM, which revealed a SEN of 56.51% and a SPE of 96.03%.

3.3. Validation of computational results

The overall most sensitive montage at reduction step 10 (nine remaining electrodes) was HAM with a SEN of 76.12% and a SPE of 87.58%. At this reduction step, the computer algorithm calculated a SEN of 68.21% for the ictal group, 88.43% for RDA, 68.74% for PD and 72.44% for BS. Corresponding SPE were high with 97.76 for the ictal group, 92.62 for RDA, 94.52 for PD and 91.69 for BS. Results with confidence intervals are shown in Fig. 3 (NeuroTrend; 9 electrodes). With the same reduced set of nine electrodes, 250 EEG segments were reevaluated by the two reviewers to validate the calculations of the computer algorithm.

In the ictal group the two reviewers reached detection SENs of 82% (SPE 94%) and 78% (SPE 98%), respectively. RDA could be detected with SENs of 84% (SPE 90% & 100%) each. Lower agreements were seen for PD with SENs of 82% (SPE 100%) and 64% (SPE 100%) as well as BS with SENs of 80% (SPE 94%) and 56% (SPE 98%). The detection SEN of NT calculated with nine electrodes compared to 19 electrodes declined between a range of 5–22% for different pattern groups. For the reviewers, comparing annotations with 9 electrodes with the consensus annotations, a decline between 16–44% was found.

The elimination of EEG segments without consensus annotations from the two reviewers resulted in overall $n = 156$ EEG segments that were used for the test statistic. The initial 50 samples of each pattern group reduced to $n_{PD} = 38$, $n_{RDA} = 42$, $n_{ictal\ group} = 38$, $n_{BS} = 38$ samples. The hypothesis that no statistically significant difference between the consensus annotations of two reviewers and the computational results existed could not be rejected for all four subgroups ($\chi^2_{PD} = 0.57$, $\chi^2_{RDA} = 0.5$, $\chi^2_{ictal\ group} = 3.2$, $\chi^2_{BS} = 1.2$) and for the combined 156 samples ($\chi^2 = 0.41$). This shows that the average detection SEN based on computational and human review has to be considered as equal.

4. Discussion

The present study aims to investigate the effect of electrode reductions from a standard 10-20 EEG system. Unlike previous studies this was done automatically by a computer algorithm, making it feasible (1) to determine detection SENs for every single electrode that was removed (2) to observe the effect of different sequences in which electrodes were removed. This automated and technical approach of analyzing the effect of decremental electrode reduction on pattern detection, distinguishes the study from others. The vast majority of previous studies used more clinically orientated approaches to determine if a certain number of predefined electrodes were sufficient to detect seizures (Bridgers and Ebersole, 1988; Foldvary et al., 2000; Tekgul et al., 2005; Kolls and Husain, 2007; Shellhaas and Clancy, 2007; Wusthoff et al., 2009; Young et al., 2009; Karakis et al., 2010; Nitzschke et al., 2011; Rubin et al., 2014; Tanner et al., 2014; Brenner et al., 2015; Lepola et al., 2015; Muraja-Murro et al., 2015). These studies only gave a brief insight into a small selection of existing possibilities because they missed the flexibility to change montages or add and remove electrodes. Furthermore, their main goal was to detect seizures, while the effect of electrode reduction on other patterns was not investigated. Our study on the other hand should be seen as a proof of concept. We tried to demonstrate that automation is a feasible and reasonable method to asses reduced electrode arrays, taking also patterns defined by CCET into account. The results may be expected but have never been accurately illustrated. Most of the previously published studies used between four to ten electrodes. According to our data a clear decline in pattern detection begins after the 10th electrode is removed. Therefore, our results form a foundation for further, more clinically oriented studies.

HAM outperformed all other reduction montages by reaching a D15 with the lowest number of electrodes. Best results could be achieved with six electrodes for ictal group patterns and RDA as well as nine electrodes for PD. HAM is easy and fast to apply because anatomic landmarks can be used to estimate correct electrode placement. Important drawback of the montage is the poor performance in detecting BS, which could be used to monitor treatment effects and estimate sedation depth in the ICU. Detection rates (SEN 72.85%, SPE 97.51%) of HAM match previous studies that used similar reduced arrays. Rubin et al. reviewed 50 ictal and 50 non-ictal EEG records for the presence or absence of seizures (Rubin et al., 2014). They used the electrodes F3, F4, T7, Cz, T8, O1, O2 and reviewed the EEG with transverse, longitudinal and referential to Cz montages. A detection SEN of 70% and SPE of 96% for seizures was found. They concluded that this was an unacceptable poor SEN for seizure detection. The same was suggested by Kolls and Hussain after the review of 120 preselected "clear" pattern clips by five epileptologists (Kolls and Husain, 2007). A six-channel montage including the electrodes Fp1, Fp2, F7, F8, T3, T4, T5, T6 (longitudinal bipolar, referential to ipsilateral ear, referential to contralateral ear) was used. Reviews were compared to medical records and showed SEN rates of 72% for seizures and 54% for PDs. Higher detection rates were shown by Karakis et al. (Karakis et al., 2010). They reviewed 38 preselected EEG samples, including only

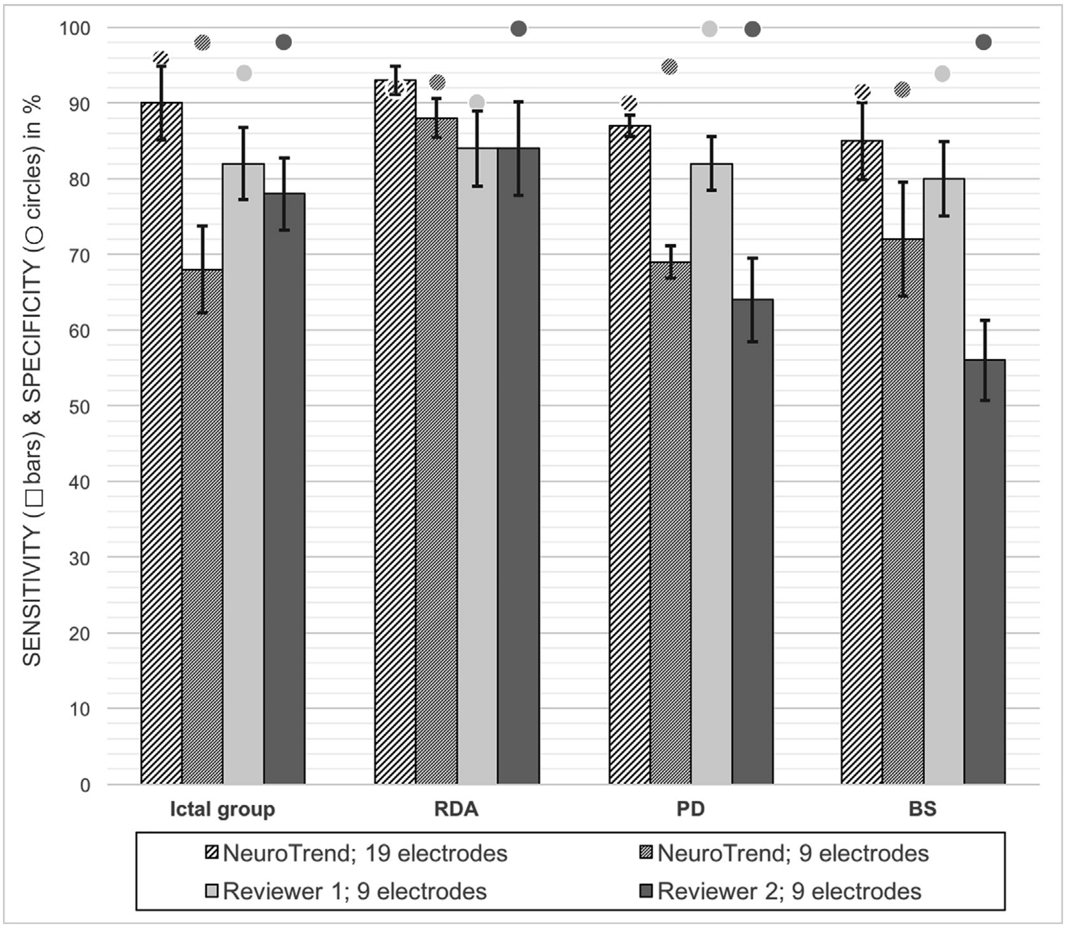

Fig. 3. Detection sensitivities (SEN, bars) and specificities (SPE, circles) for different pattern groups are shown. Bars & circles with oblique stripes illustrate SENs/SPEs of the computer algorithm (NeuroTrend) for 19 and 9 electrodes, respectively. Filled bars and circles illustrate SENs/SPEs of two different reviewers for 9 electrodes. PD, periodic discharge; RDA, rhythmic delta activity; Ictal group, spike-wave >3 Hz or evolving discharges >4 Hz; BS, burst suppression.

10 samples with seizures. A seizure detection rate of 85% was found with a six-channel EEG (Fp1, Fp2, T3, T4, O1, O2, Cz; double diamond, circumferential, referential to Cz) compared to 92.5% for the 10-20 EEG. The difference in the detection SEN of approximately 10–15% compared to our data could be explained by the general lower detection rate of the computer algorithm compared to consensus annotations in our study.

FOM has found application in the emergency department and predefined electrode bands that adhere to the skin of the forehead and behind the ear are already available (Myllymaa et al., 2013; Muraja-Murro et al., 2015). In our study P7 and P8 had to replace the electrodes behind the ear. The overall performance of FOM was mediocre with a D15 ranging between 8 to 14 electrodes depending on the pattern type observed. Nevertheless, there may be a potential use for the FOM in the emergency department as detection SEN was high in the ictal group before reducing the 10th electrode (SEN of 76.82%). Similar detection rates were shown by Young et al. (Young et al., 2009). Two epileptologists reviewed 70 cEEGs of 24 h with a standard 10–20 system as well as with a reduced array of four frontal channels. 31 patients suffered from seizures which were detected in 68% of all cases by the reduced montage. PDs showed lower rates of 39%, which can be confirmed by our observation (44.67%). A lower SEN was found by Tanner et al. (Tanner et al., 2014) who retrospectively reviewed 170 patients of which 8% had seizures. They found a seizure detection rate of 54% with a reduced setup of seven to eight leads. Contradictory findings were presented by Bridgers and Ebersole (Bridgers and Ebersole, 1988). They performed an interrater agreement assessing 25 patients with epileptiform abnormalities. One epileptologist reviewed 16 channel EEG data while the other epileptologist had only seven channels available. 91% of all epileptiform complexes were detected by reviewing seven channels with a false positive rate of 10% and a false negative rate of 8%. Other studies that investigated the influence of FOM on detection rates were affected by small numbers of evaluated patients or a low incidence of seizures (Brenner et al., 2015; Lepola et al., 2015; Muraja-Murro et al., 2015).

CRM and BAM were not previously described as reduced montages in literature. They were thought to offer advantages in detecting strictly localized patterns such as PD. This hypothesis was not met as both arrays showed a poor performance for PDs and were mediocre in detecting patters of the ictal group. Interestingly both montages scored highest in detecting BS while diverging in the detection of RDA. CRM showed a steep decline in SEN after frontopolar and occipital electrodes were removed. This may be explained by over-interpretation of RDA in the consensus annotations if generalized frontal slowing occurred. When interpreting the raw EEG, double distances between electrodes must be considered as they strongly influence the EEG curve. The used computer algorithm could handle these double distances by calculating results with a common average of remaining electrodes even though it is based on visual detection of EEG data.

Validation of NeuroTrend results showed that the computer algorithm scored a little worse than the reviewers except for RDA but no significant discrepancies could be observed. This time, no consensus annotations between the reviewers were established, as this would have biased the validation by leaving only clear and easy to recognize patterns. On the one hand, persistent low detection rates of the algorithm in comparison to the reviewers would have implied an unusable poor algorithm. On the other hand, persistent high detection rates compared to the reviewers might have indicated an implausible result since the algorithm is based on visual analyzes. Results between the two reviewers varied a lot for PDs and BS indicating difficulties in annotating these patterns with a reduced number of electrodes.

The strength of the study, to keep the focus on clinical relevant, non-selected data comprises some limitations. Because of the huge amount of work in annotating hours of cEEG to establish consensus annotations, a limited number of patients (n = 83) was enrolled. "Real-world" conditions immanent are numerous EEG segments with no specific patterns and an unequal distribution of patterns (Table 1).

The study lacks information about pattern localization because the algorithm showed a low performance in distinguishing lateralized from generalized patterns in a previous study (Herta et al., 2015). This limits the statement about the advantages and disadvantages of the individual assemblies. Furthermore, it must be stressed that all observed patterns frequently occur together during cEEG in the ICU. It would be misguided to assume that in a given patient a certain montage may be superior to another montage for clinical monitoring purposes based upon these results. For example, if seizure detection is the primary goal, not only ictal group patterns but also PD and RDA may classify as seizures and in the further course of treatment the detection of BS may become of interest.

The ACNS does not recommend the use of less than 19 electrodes as well as deviations of the International 10-20 system placement but recognizes the need of a smaller number of electrodes in some situations (ACNS, 1994). Hence it is very difficult to give recommendations for the use of a reduced EEG array, as seizures may not be detected at all if standard EEG is not available or not applicable as argued by Young et al. (Young et al., 2009).

Our aim was to demonstrate a new approach of testing the usability of reduced EEG montages. Clear advantages of an automated assessment comprise the possibility of rapidly processing huge amounts of data, clear visualization, exact determination of frequencies and amplitudes as well as identification of pattern localization. Abilities that may not only find application in research and science but also in clinical practice.

5. Conclusion

For the first time a computer algorithm was successfully used to evaluate the effect of decremental electrode reduction from the international 10-20 EEG system. The findings roughly reflect which reduced assembly may be the most appropriate in specific situations where a full 10-20 EEG system cannot be applied. However, studies on how the reduced montages perform in individual patients still have to be carried out. In the future, we expect more detailed and specific analyzes by our algorithm taking new variables as for example pattern localization into account.

Disclosure

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We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

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