33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Rapid Identification of Epileptogenic Sites in the Intracranial EEG

R. Yadav, *Student Member, IEEE*, M. N. S. Swamy, *Fellow, IEEE,* and R. Agarwal, *Member, IEEE*

***Abstract*—The paper presents a novel computationally simple, easy-to-interpret compressed EEG display for multichannel intracranial EEG recordings. The compressed display is based on the level of sharp activity (relative sharpness index (RSI)) in the EEG, which profoundly increases during paroxysmal activities. RSI is graphically presented as a color-intensity plot that allows compressing several hours of EEG into a single display page. RSI display is a bird's-eye-view of the EEG that may reveal seizure evolution ('build-up'), seizure precursors, or sites associated with the seizures. We present examples from two patients to illustrate the method's ability to identify epileptogenic sites that may be difficult to observe in the conventional review process. RSI is compared with the color density spectral array (CDSA) and amplitude integrated EEG (aEEG) display. Examples demonstrate the RSI display to be simple, easy to interpret, computationally light and fast enough for online application.**

***Index Terms*—EEG, seizure detection, compressed EEG display, CDSA, aEEG**

I. Introduction

EPILEPSY surgery is a potential therapeutic option for medically refractive epilepsy patients who have failed to achieve seizure control with medication. The burden of uncontrolled seizures include increased mortality, greater adverse side effects of medication, potential cognitive decline, and impairment of psychosocial functioning [1]. Prolonged intracranial EEG recording is performed prior to epilepsy surgery in the epilepsy monitoring unit (EMU). The goals of presurgical evaluation are to identify and localize epileptogenic zones for surgical resection, and also to determine whether a resection can be performed without undue morbidity [1], [2]. These information are gleaned from careful review of the intracranial EEG. However, visual review of voluminous EEG is very challenging, tiresome, and expensive.

Automatic seizure detection techniques have received intense attention in the recent past. Such methods are used in the epilepsy monitoring unit (EMU) and neuro-intensive care unit (NICU) as a seizure warning systems. These methods often have very high sensitivity to maintain patient safety, but at the cost of a large number of false detections. In spite of high sensitivity, several non-convulsive electrographic seizures go undetected. Continuous round-the-clock visual review of the EEG by an EEG expert, is one way to identify all seizures but not a practical solution. In many EMUs/NICUs, patients are monitored by nursing staff during the night and extended hours and not by the EEG experts. Therefore, an easy-to-interpret EEG display is needed for the EMU/NICU that also permits real-time viewing of several hours of EEG.

In the EMU, the main role of automatic seizure detectors is to aid the rapid review of the voluminous EEG [3]. The review allows in the accurate localization of the epileptogenic sites, however, is still a tiresome task. Mapping channel-by-channel timeline of seizures and epileptiform activities can provide visualization of seizure onset and spread (both temporally and spatially), which can be a powerful tool for planning of surgical resection. This type of 2D visualization is generally unavailable for review of intracranial EEG. Therefore, it becomes very important to develop adjunctive methods that allow quick identification of seizures, provide a view of seizure activity over prolonged durations, seizure recurrence frequency, and sites involved in the seizure generation for therapeutic interventions and management [1], [2], [4]-[6].

Rapid identification of epileptogenic sites and evaluation of spatio-temporal dynamics is possible by digital trending tools [4]-[6]. Tools such as amplitude integrated EEG (aEEG), envelope trend (ET), compressed spectral array (CSA), color density spectral array (CDSA), and compressed EEG pattern analysis (CEPA) allow graphical display of the EEG trends [4], [5]. The process typically involves splitting EEG data into small epochs, and extracting features for graphical display. For example, CSA displays time, frequency, and power in a three-dimensional graphical view. However, CSA display has a practical limitation of a few channels [2], [5]-[7]. CDSA is a modified CSA that allows the display to accommodate a few more channels. Typically, intracranial EEG recordings consist of 32 to 256 channels. Large number of channels increases the computational complexity. EEGer experience in the interpretation of such graphical display is yet another limiting factor [2], [6], [8]. These factors limit utility of the compressed EEG display in the EMU. Computationally simple and easy-to-interpret compressed EEG display, specially designed to review multichannel intracranial EEG for paroxysmal or seizure activity is much needed.

This paper presents a novel computationally simple, easy-to-interpret compressed EEG display for multichannel intracranial EEG recording. The method is based on quantifying EEG waveform sharpness in epochs [3]. Each epoch is graphically displayed (color-intensity plot) based on the level of sharp activity in the epoch. This allows compressing several hours of the EEG on a single page display. With examples from two patients, we demonstrate the utility of the novel compressed

Manuscript received April 14, 2011. This work was partially supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada under grant # A-7739.

R. Yadav, M. N. S. Swamy, and R. Agarwal are with Center for Signal Processing and Communications (CENSIPCOM), Department of Electrical and Computer Engineering, Concordia University, 1455 de Maisonneuve Blvd. West, Montreal, QC, H3G 1M8, Canada. Email: r_yadav@encs.concordia.ca, swamy@encs.concordia.ca, and ragarwal@leapmedical.ca

978-1-4244-4122-8/11/$26.00 ©2011 IEEE

display for rapid review and identification of epileptogenic sites. CDSA and aEEG are used for comparative assessment.

II. Method

We use data from two patient's intracranial EEG from an existing database [3]. Each patient had five EEG sections that are utilized in the assessment of the compressed EEG display.

Note that the seizure onset zone is the single most definitive localizing feature of the epileptogenic region. For this reason, it is important to identify all channels (electrodes) in the seizure onset, and their recurrence frequency for anatomical localization [1]. An electrographic seizure is a discharge of sharp wave complexes evolving in frequency and amplitude, including repetitive spikes. Furthermore, discharge of sharp waves (sharp transients, spikes, and epileptiform discharges) occur more frequently than seizure and can be linked to the brain regions involved in the epileptogenesis [1]. Therefore, sharpness of the EEG waveform can be a robust marker to highlight epileptogenic areas (both temporally and spatially). To do so, the EEG waveform is partitioned into half-waves and modeled by the best-fit straight line [3]. The sharpness θ is the angle or slope of the best-fit straight line for each half-wave, which is highly sensitive to amplitude and frequency changes in the EEG. More detailed information on the sharpness feature θ and threshold θ_{th} can be found in [3]. In this paper, the threshold θ_{th} is fixed (not tunable) and remained same both patients.

Easy, reliable and intuitive interpretation is important to maintain patient safety in the EMU/NICU where experienced EEGer may not be always available round-the-clock. Color-intensity plots are intuitive, easy-to-interpret and require minimal training. Therefore, we quantify the level of sharp activity in the EEG and graphically display it as color-intensity plot. To do so, we split EEG into short segments (epochs) and extract feature for graphical display. EEG is processed in 10 s non-overlapping epochs. The feature for graphical display is the level of sharp activity in an epoch referred to as relative sharpness index (RSI), and is given by

$$RSI = \frac{\#\text{ of } \theta > \theta_{th}}{\text{Total \# of } \theta}. \quad (1)$$

RSI index is a relative measure, and therefore, minimally influenced by a change in the epoch length. The resulting RSI is displayed as color-intensity plot that allows the compression of several hours of multichannel EEG on a single page display. Resulting display is compared to the more popular CDSA and aEEG displays [2], [6]. Display size, interpretation and computational complexity are compared for the three methods.

III. Results/Discussion

Compressed EEG displays using all three techniques (RSI, CDSA and aEEG) were generated for the two patient EEG recordings. Seizure, epileptiform activity, and areas of potential seizure development were visually identified and correlated with the EEG. This evaluation allowed us to decide the best method among the three techniques.

First, it is important to describe how compressed displays are interpreted for seizures. Note that compressed display

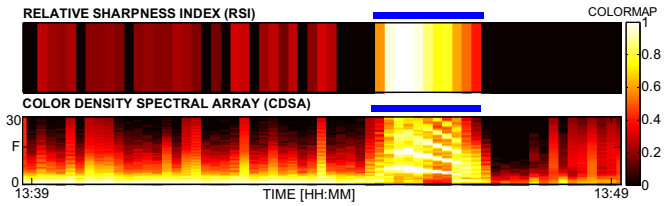

Figure 1. Identification of seizure in the compressed display. The example represents 10 min single channel RSI and CDSA display. Seizure detected by the EEGer is annotated with 'horizontal bar' on both the displays. (see text for description)

represents EEG activity in a transformed domain as a function of time. The feature utilized in the RSI display is the level of sharpness, power at the different frequencies in the CDSA, and amplitude activity in the aEEG. These features are represented as color-intensity (RSI and CDSA) or trend (aEEG) graphs. An electrographic seizure evolves in the amplitude and frequency, therefore, the intensity or the magnitude of the feature will be lower during non-seizure and higher during the seizure. A seizure can be identified by looking for high-intensity segments in the compressed display. An example to illustrate interpretation of RSI and CDSA display is shown in Fig. 1. The example represents 10 min single channel EEG that contains a seizure (horizontal bar above the graph). Each vertical block in the RSI display represents RSI in a 10 s epoch. The RSI reaches maximum (= 1) during the early part of the seizure and slowly decreases as seizure evolves and eventually terminates. In our experimentation, we found that the RSI is minimal (< 0.2) during normal background activity, between 0.2 and 0.5 in the presence of paroxysmal discharges and above 0.5 during the seizure. We believe seizures can be identified by looking for instances of color intensities corresponding to RSI > 0.5 in the display. Similarly, high power at several frequencies is observed in the CDSA display during the seizure, resulting in a plateau formation (see Fig. 1). Identifying such a plateau's in the CDSA and in the aEEG display can imply seizure presence. Next, we describe the analysis of the compressed displays.

All displays were scored for seizures using the above approach. The EEG corresponding to the scored events were visually examined to confirm the detection accuracy. Figure 2 depicts an example of 30 channel 4 h compressed display using the three techniques for Patient #1. The EEGer marked seizure events are annotated on top of each display by downward pointing 'blue' arrow. All seizures of this patient were longer than 60 s with an average amplitude above 200 μV. It was easy to identify seizure for all three methods. An example of the seizure obtained around the time instant '1' is shown in Fig. 3A. Refering to Fig. 2, seizures do not occur on all the channels according to RSI and CDSA display. However, seizure occurs on most channels according to the aEEG display (Fig. 2). EEG review confirmed that seizures actually occur only on specific channels, and RSI mapping of seizure channels were more accurate and precise than the CDSA mapping.

Similarly, identification of seizure was easier using RSI display in Patient #2 (see Fig. 4). It was found that seizures in this patient were short duration (30-60 s) with average amplitude below 200 μV. Identification of all six EEGer marked seizures using CDSA and aEEG was difficult. This

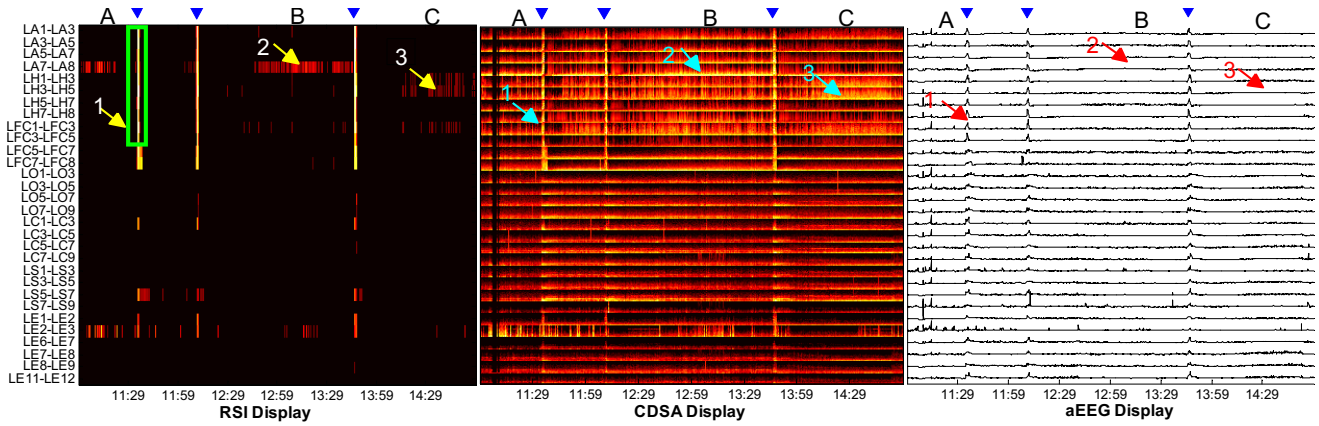

Figure 2. Example of multichannel compressed display. The display represents 30 channel 4 h EEG section of Patient #1 for the three schemes (RSI, CDSA and aEEG). The section contains three seizure identified by the EEGer and is annotated by 'downward pointing (blue)' arrow on top of each display. Three events are selected from the RSI display (A, B, C) and reviewed in the EEG review panel (shown in Fig. 3). Location of the selected event is shown by enumerated arrows on the RSI display.

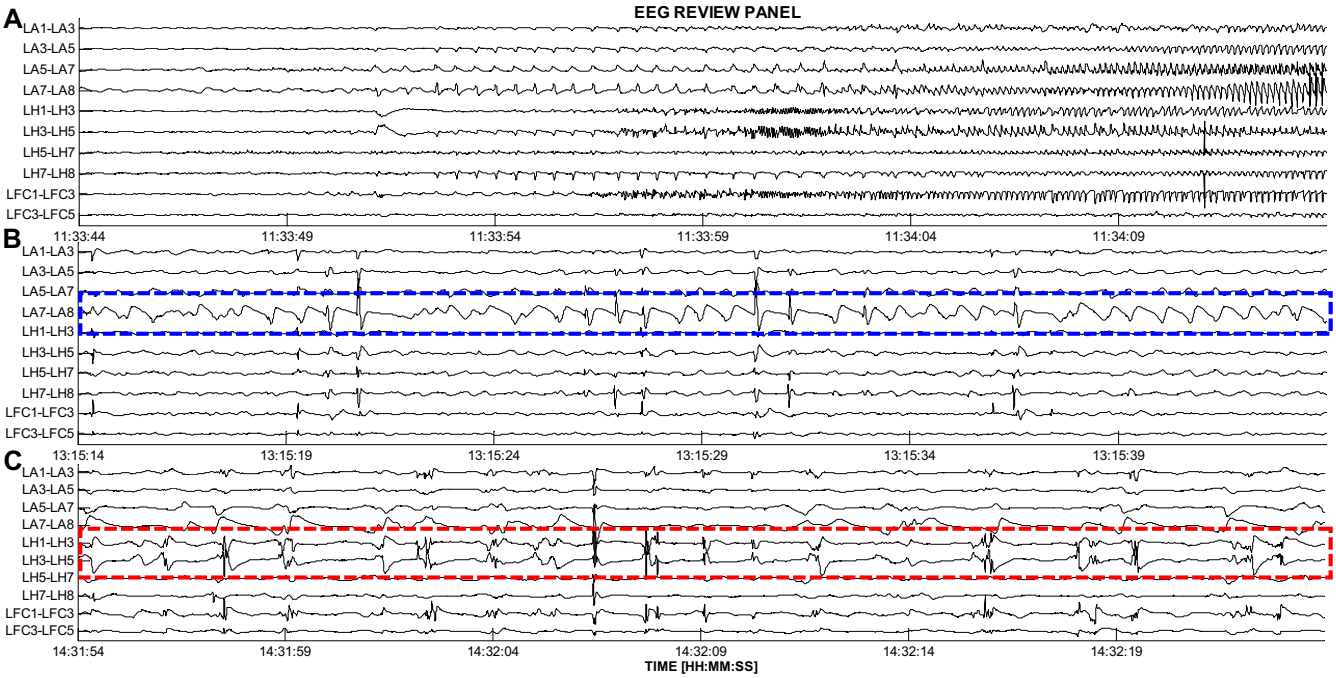

Figure 3. EEG corresponding to the event selected from the RSI display in Fig. 1. (A) represents a seizure around the time point '1', (B) represents the pre-ictal rhythmic discharge of sharp waves around the time point '2', and (C) represents discharges of sharp wave complexes around the time point '3' in Fig. 1, respectively. Each segment represents 30 s of 10 channel EEG.

is probably due to the fact that seizures in this patient were focal and low amplitude (channel: RH1-RH2 and RC1-RC2). This is consistent with the observations in [2], [6]. As with the CDSA and aEEG, detection of seizures with no or minimal change in the EEG amplitude (< 20 μV) is also challenging for the RSI display. However, RSI is still able to clearly and accurately highlights the epileptogenic sites, i.e., channels with profoundly increased sharp activity (confirmed by the EEG review) than the comparison displays. Increased sharp activities are often associated with regions involved in the seizure generation [1, 7]. Therefore, this information may be clinically vital in the identification of neuronal areas involved in the seizure generation. In Patient #1, we observed such activity to be present, predominantly and consistently in all seizure EEG sections on the channels LA7-LA8, LFC1-LFC3 and LE2-LE3 (see Fig. 2) that disappears at the seizure onset. The corresponding raw EEG of such activity is shown in Fig. 3B (obtained around the time instant shown by arrow '2' in Fig. 2). In this patient, RSI display also reveals increased sharp activity on other sites as well (channel: LH1-LH3, LH3-LH5 and LH7-LH8). Figure 3C depicts an example of this activity (around the time instant shown by arrow '3' in Fig. 2). Similarly, in Patient #2, such sharp activity predominantly occurs only on two specific channels (RH1-RH2 and RC1-RC2) as seen in Fig. 4 (RSI display). CDSA display also confirmed presence of this activity but not the aEEG display (not shown).

Presurgical evaluation for anatomical localization of epileptogenic sites involves identification of seizures, sites involved in the seizure generation, frequency of seizure recurrence, and time-lag between successive seizures, including sites involved

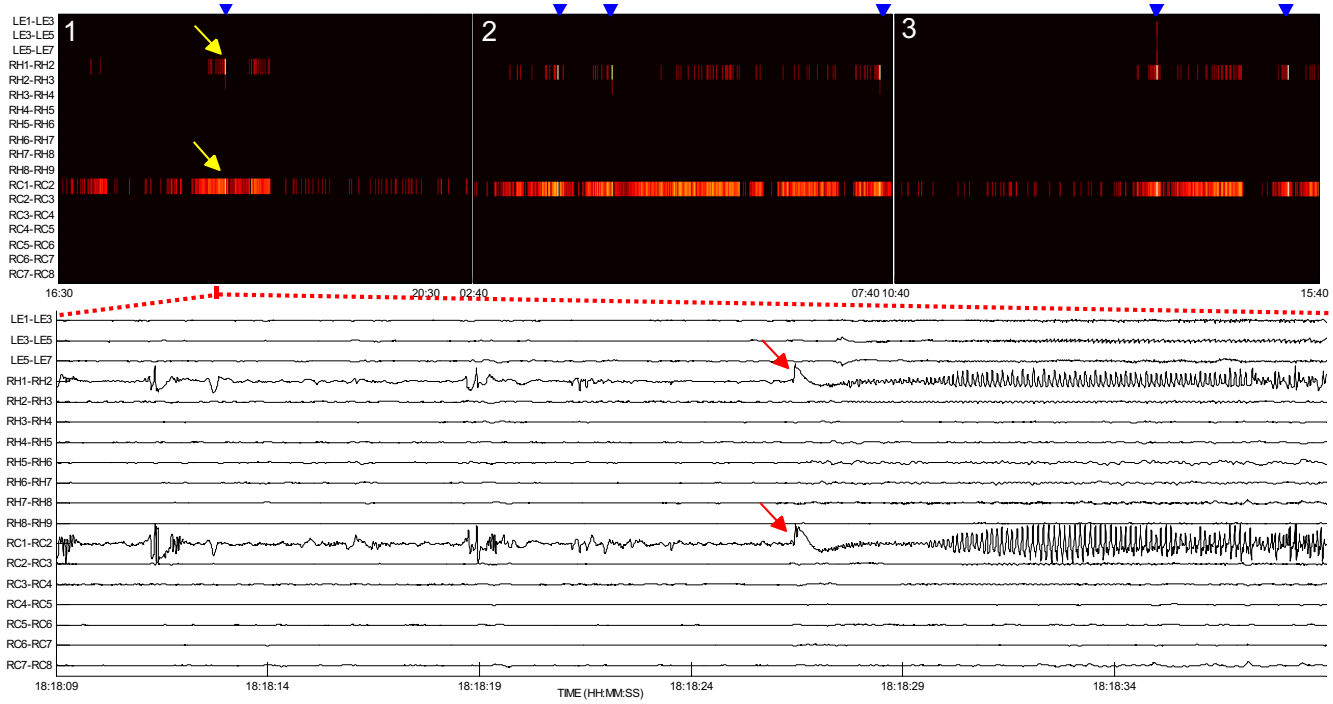

Figure 4. Example of 18 channel EEG RSI display for Patient #2. The 3 RSI display represents 16 h of data that contains a total of six seizures. Downward pointing 'blue' arrows denote EEGer identified seizures. EEG review panel displays 30 s of a event selected from RSI display #1.

with epileptiform discharges [1, 7]. These informations were clearly highlighted in the RSI display among the three techniques described.

Compressed display are advantageous in the EMUs/NICUs when timely intervention becomes important on seizure detection to prevent secondary brain damages [2], [6], [7]. Two main factors that limit the utility of the compressed display in the EMU/NICU are the ease in the interpretation and display size [2]. Spatio-temporal resolution of the display decreases with an increase in the number of channels and the duration of monitoring, which makes interpretation very difficult. CDSA and aEEG require a magnitude interpretation while RSI does not. Therefore, with increase in the number of channels, CDSA and aEEG appear very compressed where the actual magnitudes cannot be easily interpreted. On the contrary, increase in the number of channel minimally affects RSI display. This effect can be seen on the multichannel compressed display in Fig. 2. RSI display overcomes these two main limiting factors. Therefore, it can be used in the EMU/NICU by experienced as well as inexperienced staff to monitor and flag ongoing or ensuing abnormalities.

IV. CONCLUSIONS

We have introduced a new simple compressed EEG display to identify seizures in the intracranial EEG recording. The method analyzes the EEG waveform sharpness to highlight seizures and epileptiform discharges. The results are presented as a compressed display chart based on the relative sharpness index (RSI). The RSI display is minimally influenced by the display size, is easier to interpret, and allows rapid identification of seizures compared to the CDSA and aEEG display. Using the EEG of two patients, we have demonstrated the feasibility and utility of the method as a decision support tool for online application in the EMU and NICU. The method requires an extensive evaluation on a larger dataset for clinical application and will be a part of the future work.

ACKNOWLEDGMENTS

The author's would like to thank Stellate Systems, Montreal, Canada for providing the intracranial EEG data used in the present study.

REFERENCES

[1] E. Niedermeyer and F. H. Lopes da Silva, *Electroencephalography: basic principles, clinical applications, and related fields*. Lippincott Williams & Wilkins, 5th ed., 2005.

[2] C. I. Akman, V. Micic, A. Thompson, and J. J. Riviello, "Seizure detection using digital trend analysis: Factors affecting utility," *Epilepsy research*, vol. 93, no. 1, pp. 66–72, 2011.

[3] R. Yadav, R. Agarwal, and M. N. S. Swamy, "A novel morphology-based classifier for automatic detection of epileptic seizures," *Annual International Conference of the IEEE Engineering in Medicine and Biology Society.*, vol. 2010, pp. 5545–8, 2010.

[4] R. Agarwal, J. Gotman, D. Flanagan, and B. Rosenblatt, "Automatic eeg analysis during long-term monitoring in the icu," *Electroencephalography and clinical neurophysiology*, vol. 107, no. 1, pp. 44–58, 1998.

[5] A. K. Shah, R. Agarwal, J. R. Carhuapoma, and J. A. Loeb, "Compressed eeg pattern analysis for critically ill neurological-neurosurgical patients," *Neurocritical care*, vol. 5, no. 2, pp. 124–33, 2006.

[6] C. P. Stewart, H. Otsubo, A. Ochi, R. Sharma, J. S. Hutchison, and C. D. Hahn, "Seizure identification in the icu using quantitative eeg displays," *Neurology*, vol. 75, no. 17, pp. 1501–8, 2010.

[7] P. W. Kaplan and F. W. Drislane, *Nonconvulsive Status Epilepticus*. Demos Medical Publishing, New York, USA, 2008.

[8] V. Gnatkovsky, S. Francione, F. Cardinale, R. Mai, L. Tassi, G. L. Russo, and M. de Curtis, "Identification of reproducible ictal patterns based on quantified frequency analysis of intracranial eeg signals.," *Epilepsia*, vol. 52, pp. 477–488, Mar 2011.