performance of the morphology system, however, did not change significantly for the two databases.

We also assessed the computational cost of the proposed morphology system on the FSP database. Running our system on MATLAB 2008b (MathWorks Inc.) on a laptop with Intel dual core 1.8 GHz processor, 3 GB RAM, having the 32-bit Microsoft Windows 7 operating system, our system processed 24-h four channel EEG in approximately 30 minutes. Computational performance of the system can be significantly enhanced by developing a standalone version in C++. In addition, running on systems with faster processors with multiple cores can further reduce the computation time. The performance and computational speed suggests that the proposed morphology system can be clinically useful in the review of long-term EEG recordings.

As with other systems, the morphology system generally failed to detect seizure events that occurred with minimal changes in the EEG amplitude. In addition, a large number of false events may be detected by our system in the presence of discharge of sharp wave complexes, spikes, high-amplitude artifacts, and fast EMG artifacts. We anticipate that by including additional artifact removal techniques to handle some of the mentioned artifacts, it would be possible to further improve the specificity, and is considered as part of future work.

5.6 Rapid Review of Prolonged EEG Recordings

5.6.1 Background

In the EMU, the main role of automatic seizure detection method is to aid in a rapid review of the voluminous EEG data. The seizure detection method helps to identify seizures along with false events in the prolonged recordings. The detected events are visually examined by the experts to filter the false events and accurately localize the

epileptogenic sites, which is a tiresome task. Mapping channel-by-channel timeline of seizures and the epileptiform activities can provide visualization of seizure onset and spread (both temporally and spatially), and can be a powerful tool for planning of surgical resection. This type of 2D visualization is generally unavailable for the review of intracranial EEG. Therefore, it becomes very important to develop adjunctive tools that allow quick identification of seizures, provide a view of seizure activity over prolonged durations, seizure recurrence frequency, and the sites involved in the seizure generation for therapeutic interventions and management [5, 38-41].

Rapid identification of epileptogenic sites and evaluation of spatio-temporal dynamics is possible by digital trending tools [38-40]. 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 [38-40]. 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 [38, 40, 42, 190]. CDSA is a modified CSA that allows the display to accommodate a few more channels. Typically, intracranial EEG recording consist of 32 to 256 channels. The large number of channels increases the computational complexity. EEGer experience in the interpretation of such graphical display is yet another limiting factor [38-40]. These factors limit the 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.

5.6.2 Method

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 [38-40]. As previously mentioned in Chapter 4, 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 [5]. It is realized that the sharpness of the EEG waveform can be a robust marker to highlight epileptogenic areas (both temporally and spatially). The sharpness measure to parametrize the EEG waveform morphology proposed in Chapter 4 is utilized to generate the new compressed display.

Easy, reliable and intuitive interpretation is important to maintain patient safety in the EMU, where experienced EEGer may not be 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 a color-intensity plot. To do so, we split the EEG into short segments (epochs) and extract a feature for the graphical display. For compressed display, the 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

$$RSI = \frac{\#\,\text{of}\, m > m_{th}}{\text{Total}\ \#\ \text{of}\ m}, \tag{5.1}$$

where m is a measure of the sharpness of the half-waves in the epoch (see Chapter 4, Section 4.4). The resulting RSI is displayed as a color-intensity plot that allows the compression of several hours of multichannel EEG on a single page display. We randomly selected two patients from the MNI database to illustrate the RSI display to aid in a rapid review of prolonged intracranial EEG recordings.

5.6.3 Results and Discussion

The performance evaluation of the compressed displays is done by examining the display size, interpretation, and computational complexity. To do a comparative assessment of these complexities, we selected CDSA and aEEG displays. Compressed EEG displays using all three techniques (RSI, CDSA and aEEG) were generated for the two patient EEG recordings from the MNI database. Seizure, epileptiform activity, and areas of potential seizure development were visually identified and correlated with the EEG. This evaluation allowed us to decide on the best method among the three techniques.

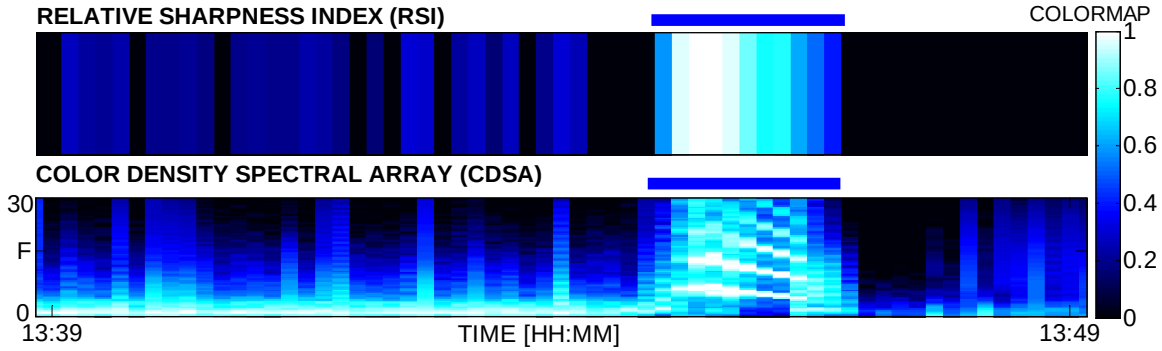

Figure 5.13: Identification of seizure in the compressed EEG display. The example represents 10 min single channel RSI and CDSA displays. Seizure detected by the EEGer is annotated with 'horizontal bar' on both the displays.

First, it is important to describe how compressed displays are interpreted for seizures. Note that compressed display represents EEG activity in a transformed domain as a function of time. The features utilized are the level of sharpness in the RSI display, power at the different frequencies in the CDSA, and the amplitude activity in the aEEG. These features are represented as color-intensity (RSI and CDSA) or trend (aEEG) graphs. An electrographic seizure evolves in both the amplitude and frequency; therefore, the intensity or the magnitude of the feature will be lower during non-seizure and maximum during a seizure. A seizure can be identified by looking for high-intensity segments in the compressed display. An example to illustrate the

interpretation of RSI and CDSA display is shown in Fig. 5.13. 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 with higher color intensity (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. 5.13). Thus, seizures can be identified in the CDSA display by looking for the sections with plateaus.

All displays were scored for seizures using the above mentioned approach. The EEG corresponding to the scored events were visually examined to confirm the detection accuracy. Figure 5.14 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. 5.15A. Referring to Fig. 5.14, 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. 5.14). 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. 5.16). It was found that seizures in this patient were of short duration (30-60 s) with average amplitude below 200 μV. Identification of all the six EEGer-marked seizures

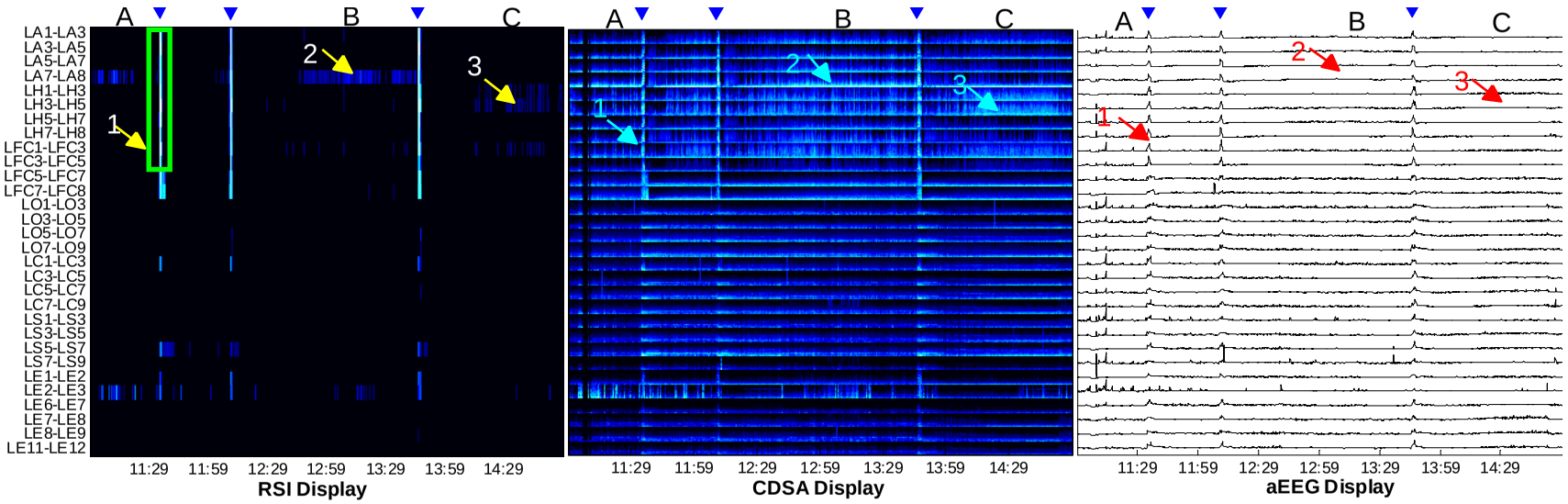

Figure 5.14: Example of multichannel compressed EEG display. The display represents 30 channel 4 h EEG section of Patient 1 for the three schemes (RSI, CDSA and aEEG). The section contains three seizure identified by the EEGer and is annotated by 'downward pointing (blue)' arrows on top of each display. Three events are selected from the RSI display (A, B, and C) with corresponding EEG shown in Fig. 5.15. Location of the selected event is shown by enumerated arrows on the RSI display.

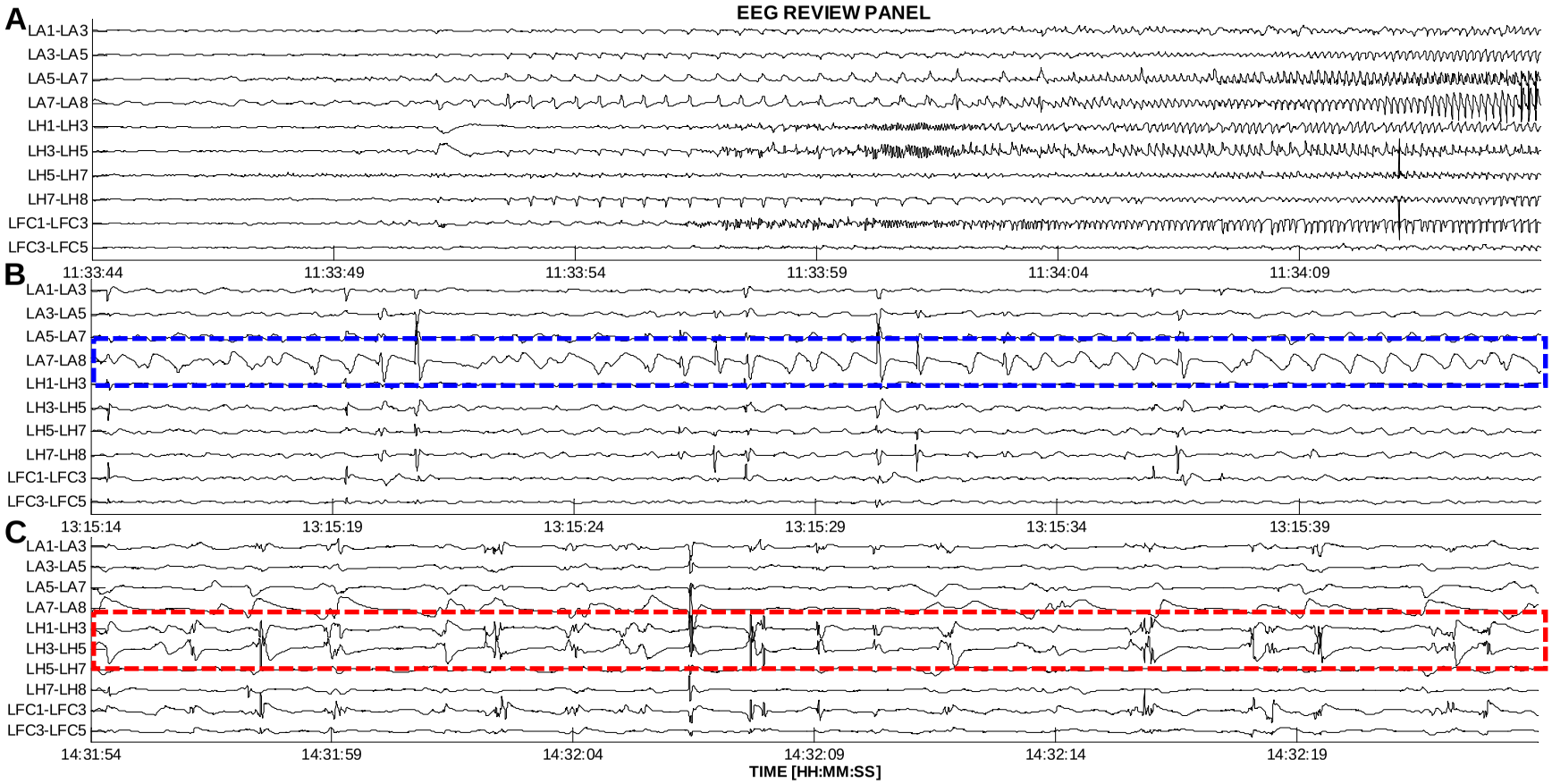

Figure 5.15: EEG corresponding to the events selected from the RSI display in Fig. 5.14. (A) represents a seizure around the time point '1', (B) represents the pre-ictal rhythmic discharge of sharp waves around the time point '2', and (C) represents discharges of sharp wave complexes around the time point '3' in Fig. 5.13, respectively. Each segment represents 30 s of 10 channel EEG.

using CDSA and aEEG was difficult. This 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 [5, 191]. 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 highlight 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 [190]. 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. 5.14) that disappears at the seizure onset. The corresponding raw EEG of such an activity is shown in Fig. 5.15B (obtained around the time instant shown by arrow '2' in Fig. 5.14). In this patient, RSI display also reveals increased sharp activity on other sites as well (channel: LH1-LH3, LH3-LH5 and LH7-LH8). Figure 5.15C depicts an example of such activity (around the time instant shown by arrow '3' in Fig. 5.14). Similarly, in Patient 2, such sharp activity predominantly occurs only on two specific channels (RH1-RH2 and RC1-RC2) as seen in Fig. 5.16 (RSI display). CDSA display also confirmed presence of such activity but not the aEEG display (not shown).

A compressed display is advantageous in the EMUs when timely intervention becomes important on seizure detection to prevent secondary brain damages [5, 38, 39, 192]. The main limiting factor of the compressed display is the display-size complexity [38, 193]. In CDSA and aEEG, the spatio-temporal resolution of the display decreases with an increase in the number of channels and the duration of monitoring, making the interpretation very difficult. On the contrary, an increase in the number of channels minimally affects the RSI display. This effect can be seen on the multichannel

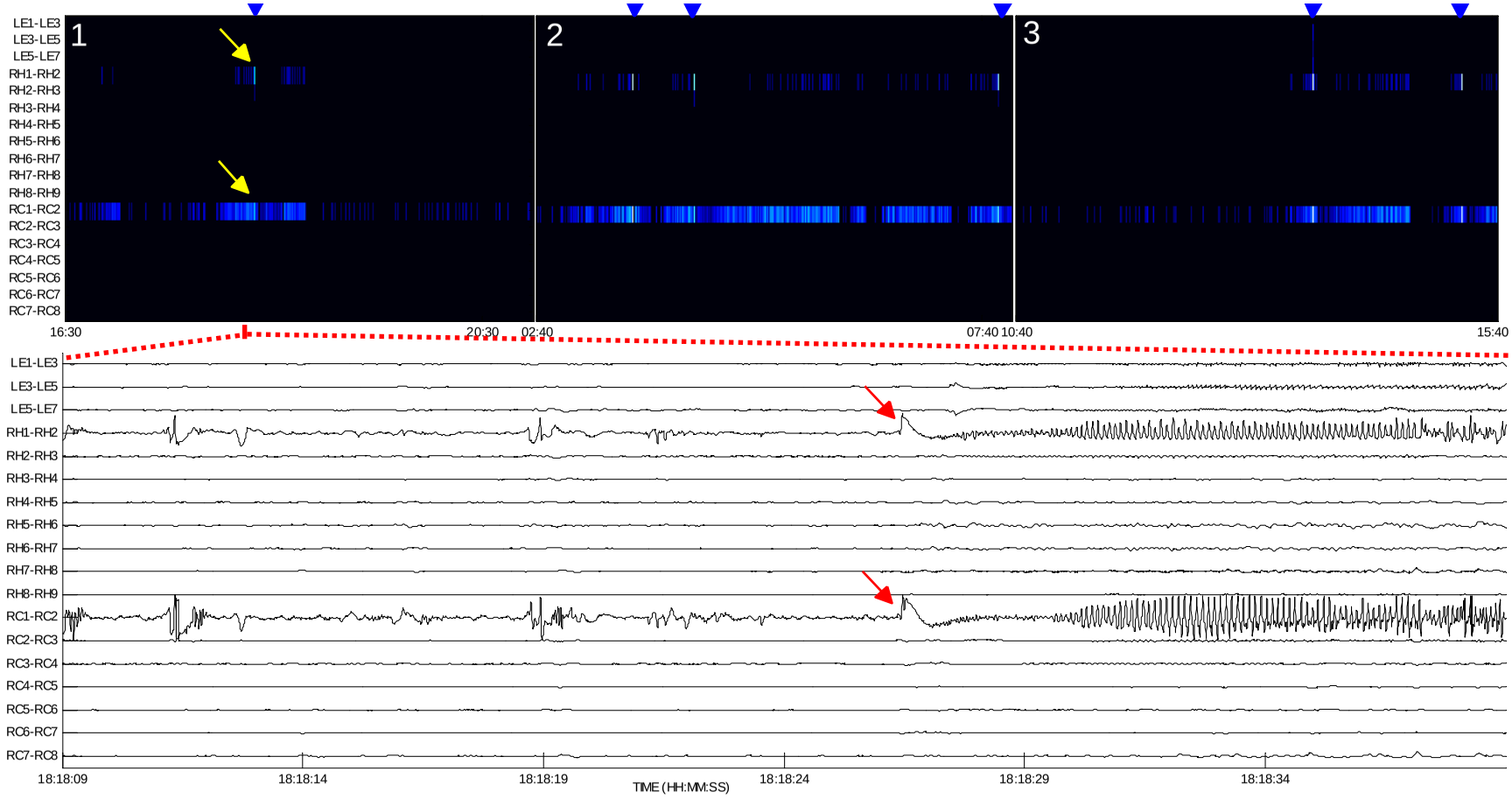

Figure 5.16: Example of 18 channel RSI display for Patient 2. The RSI display represents 16 h of data in three segments (1, 2, and 3), and contains a total of six seizures. Downward pointing 'blue' arrows denote EEGer identified seizures. EEG review panel displays 30 s of an event selected from RSI display for segment #1.

compressed display in Fig. 5.14. An added advantage of the RSI display is that it is easy-to-interpret, and hence can be used by experienced as well as inexperienced staff to monitor and flag ongoing or ensuing abnormalities.

5.7 Summary

In this chapter, we have evaluated the performance of three new NPS systems proposed in Chapter 4 and compared against the three popular NPS systems from the literature on the MNI test dataset. We have selected one of the new NPS systems and one of the comparison NPS systems to make a head-to-head comparison on a completely blind test data.

Among the new NPS systems, the morphology and eSD systems both outperformed the comparison NPS systems in terms of sensitivity as well as specificity on the seven patients single-channel MNI test dataset. Furthermore, the morphology system and the Grewal-Gotman system were selected for further performance assessment on a completely blind test data (FSP database). The FSP database consists of 21 patient intracranial EEG recordings that were recorded using a different EEG system with a different sampling rate and included varied types of electrodes (depth, grid and strip electrode). The morphology system does not require any *a priori* knowledge of patient-specific seizures. It is based on quantifying the morphology of the EEG waveform. The method does not require a background EEG in computing the 'sharpness' feature, which improves the overall computational cost, and the results do indeed show an improvement in the sensitivity and specificity on the FSP database. The performance suggests that the morphology system can be clinically useful in the review of long-term depth EEG recordings.

The chapter also described a clinical tool for the EMU, aimed to rapidly review prolonged recordings, and to identify epileptogenic sites by a novel multichannel

compressed (RSI) display. The new RSI display is compared for computational, interpretation and display complexities against two popular digital trending tools from the literature. The RSI display has been shown to be easy-to-interpret compared to the compressed EEG displays for multichannel prolonged intracranial EEG recordings.