MONITORING THE BRAIN IN THE ADULT ICU

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1 Introduction

The electroencephalogram (EEG) is well-suited for continuous brain monitoring in neurological patients in the ICU, since the EEG is very sensitive for potential risks like ischemia and (non-convulsive) seizures [1]. However, to allow real-time computer assisted interpretation of the EEG, quantitative EEG (qEEG) and an adequate presentation of the data are required. This paper describes the implementation and initial evaluation of a system for real-time classification of EEG patterns based on a combination of qEEG features. The system must be able to classify the most common EEG patterns that are observed in adult neurological patients in the ICU: normal EEGs, iso-electric EEGs, low voltage EEGs, burst suppression patterns, hypofunctional EEGs (with focal or diffuse slowing), EEGs with generalized periodic discharges (GPDs) and EEGs with seizure activity. Creating such a system is a first step towards real-time, computer-assisted detection of seizure activity and ischemia in critically ill patients.

2 Methods

Several qEEG features are implemented and combined into a single classifier. This classifier consists of a decision tree, which is constructed based on prior physiological and pathophysiological knowledge and subsequently improved by using two training sets. The features that are used in this decision tree are:

- The mean amplitude: The mean amplitude is mainly used to classify iso-electric EEGs and low voltage EEGs.

- The alpha to delta ratio (ADR) [2,3] and spectral edge frequency (SEF_x): These features are used for detecting hypofunctional EEG patterns. Both features can be extracted from the power spectrum. The ADR is the ratio between the power in the alpha (8-13) and delta band (0-4 Hz), while the SEF_x is the frequency below which a certain percentage (denoted by x) of the total power is located. In this study the SEF_{90} is used.

- A high frequency ratio: To detect high frequency artifacts, i.e. caused by muscle contractions, we introduced a high frequency ratio. This is defined as the ratio between the power of the frequency band from 0.5 Hz to 25 Hz, and the power of the frequency band from 25 Hz to 30 Hz.

- The nearest neighbour synchronization [4]: This is the coherence between a specific electrode and its surrounding electrodes or nearest neighbours. It is thereby a measure for short distance synchronization. During seizure activity the level of synchronization is often increased.

- A measure for periodicity based on the autocorrelation: An increased periodicity is oftentimes observed during seizure activity. To detect epochs with an increased periodicity, a similar method to the one proposed by Deburchgraeve et al. [5] is used. First, the autocorrelation functions are calculated for each window of 5 seconds with an overlap of 4 seconds. This is done for all channels. Secondly, the zerocrossings in these autocorrelation functions are detected. The ratios between the different zerocrossing intervals are calculated. The mean value of these ratios is used as a measure for the periodicity. This value approaches 1 for signals with a high periodicity and is higher or lower than 1 for signals without periodicity.

- A burst-suppression index: To detect burst suppression patterns and GPDs, we implemented a burst and suppression detector. First, the signal is preprocessed with the non-linear energy operator (NLEO) defined by:

$$\phi(n) = (x_{n-1} \cdot x_{n-2}) - (x_n \cdot x_{n-3}),$$

with x_n denoting the current sample of signal x, x_{n-1} the first sample before sample n etc. [5]. This preprocessed signal shows which parts of the EEG have a high local energy (high amplitude and/or high frequency). Then, a moving threshold is used to detect increases in this signal. This running threshold is set as four times the mean plus four times the standard deviation of the last 0.5 seconds of the signal, with a minimum of 10 μV^2. After the detection of a burst the next 0.5 seconds will be skipped to prevent that a single burst is detected more than once. This step is done for all nineteen channels. A burst has to be detected in more than 10 channels at the same time (within a window of 0.2 seconds) to be classified as a true burst. In a comparable way, suppressions are detected in the EEG. The same NLEO is applied to the EEG, but the threshold for the detection of suppression is fixed to 5 μV^2. If the amplitude of the signal is below this value during more than 1.5 seconds in 10 or more EEG channels at the same time, this will be interpreted as a suppression. Ten seconds of EEG will be interpreted as a burst suppression pattern, if there is at least one burst and at least one suppression detected. In an EEG pattern with GPDs, a rapid increase in high-energy also occurs. Generally, these GPDs occur multiple times in a 10 seconds recording, and the EEG signal of that period does not contain any periods of suppression. Therefore, 10 seconds of EEG with 3 or more bursts and without any suppressions will be interpreted as GPDs.

- The brain symmetry index (BSI) [6]: For the detection of asymmetries a pairwise derived variant of the BSI is used, which can be calculated by:

$$BSI(t) = \frac{1}{MK}\sum_{ch=1}^{M}\sum_{n=1}^{K}\left|\frac{R_{n,ch}(t) - L_{n,ch}(t)}{R_{n,ch}(t) + L_{n,ch}(t)}\right|,$$

with $R_{n,ch}(t) = a_{n,ch}^{2}(t)$ for the channels in the right hemisphere and by a similar expression for the channels in the left hemisphere. Here, K is the number of Fourier coefficients and M is the number of channel pairs, while $a_{n,ch}(t)$ is the Fourier coefficient with index n of channel ch, evaluated at time t, corresponding to a particular epoch $[t - T, t]$ with duration T. A period of 10 seconds is used for T and the BSI is calculated in the frequency range from 0.5 to 25 Hz, with a spectral bandwidth of 0.5 Hz. The possible range of the BSI is from zero (perfect symmetry for all channels) to 1 (maximum asymmetry). A pairwise variant of the BSI was used instead of the original BSI to increase the sensitivity for abnormalities that affect different regions in both hemispheres (i.e. in patients with traumatic brain injury). A similar variant of the BSI was recently also used by Sheoraypandaj et al. [7]. All routines are implemented in Matlab (The Mathworks Inc.).

The two training sets contain a representative set of EEG patterns obtained from patients in our ICU. The complete training set consists of 41 EEG epochs. An independent test set of 20 EEG epochs is used for the evaluation. All EEG epochs consist of 5 minute 19-channel registrations and are evaluated offline. Both test and training sets contained all of the most common types of EEG measured in ICU patients as mentioned in the introduction. Artifact rejection is performed by visual inspection of the EEGs. An output of the decision tree is obtained for every ten seconds of EEG. In addition, a pilot measurement for real-time analysis is performed in the ICU, after implementation of the complete classifier in a dedicated EEG monitor (Neurocenter EEG, Clinical Science Systems, Netherlands).

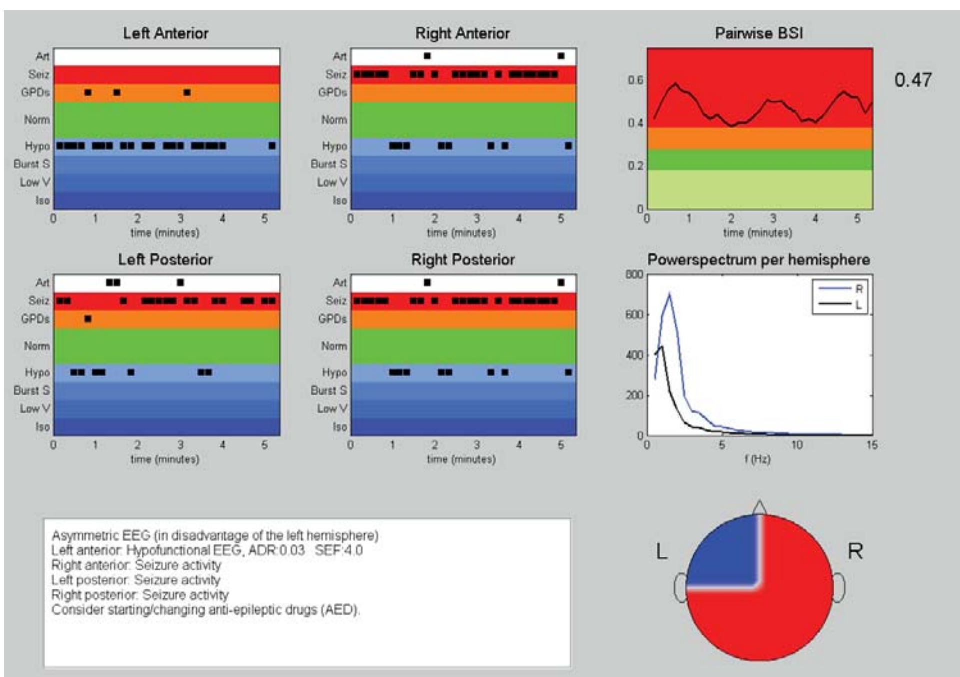

Figure 1: Example of the user interface in a patient with a focal status epilepticus from the right hemisphere spreading to the left posterior regions. Results are displayed as trend curves and in written language (lower left panel). (ART=artifact, Seiz=seizure activity, GPDs=generalized peridodic discharges, Norm=normal, Hypo=hypofunctional, Burst S=burst suppression, Low V=low voltage, Iso=iso-electric and BSI=brain symmetry index).

Instead of using Matlab routines, the analysis in this monitor system is performed using GNU Octave. The user-interface is shown in figure 1. The upper left part of the interface consists of four plots, one for each “brain part”, with the output of the decision tree as a function of the page number. In the two upper figures at the right the trend of the BSI and the power spectrum per hemisphere are shown. The BSI is calculated over the complete brain, therefore this feature cannot be used in the decision tree per specific brain part and is displayed separately. At the bottom of the interface the conclusion is given. This description is based on the last 5 minutes of EEG. Finally, this interpretation is transferred to a color coded head at the bottom right. In this figure a brain part can be colored red (for seizure activity or GPDs), gray (for normal EEGs), blue (for hypofunctional, burst suppression or low voltage EEGs) or black (for iso-electric EEGs). The conclusion in words and the color coded head in the bottom planes are displayed to allow a quick and unmistakable interpretation by non-experts, while the other figures in the interface can help to give more detailed information to the neurologist. The dynamics of longer EEG registrations can be seen at a single glance in the four plots showing the output of the decision tree. Hereby, not only time-related information can be obtained but also information about localization. In this example the results of a patient with bursts of seizure activity is shown. This seizure activity is primarily located in the right hemisphere. The bursts of seizure activity are alternating with shorter periods of hypofunctional EEG. This is clearly displayed in the interface. The trend of the BSI shows the dynamical character of this EEG as well.

3 Results

It was found that 36 EEG epochs (88%) of the training sets and 17 EEG epochs (85%) of the test set were classified correctly. Even though great care has been taken in selecting representative and artefact-free EEG epochs of the training and test sets, various EEG registrations still contained some artifacts. Most misclassifications of both test and training sets are caused by the presence of these artifacts or by missing low amplitude bursts or GPDs.

Finally, the real-time implementation is evaluated in one ICU patient who suffered from a non-convulsive status epilepticus. During this four hour measurement the system performed well and the dynamic behavior (from a hypofunctional pattern to GPDs and finally to bursts of seizure activity) in this patient was clearly detected and displayed.

4 Discussion

An EEG classification system is presented for monitoring in the ICU. The proposed system satisfies the requirement to interpret most common EEG patterns that are observed in adult neurological patients in the ICU: normal EEGs, iso-electric EEGs, low voltage EEGs, burst suppression patterns, hypofunctional EEGs (with focal or diffuse slowing), EEGs with generalized periodic discharges (GPDs) and EEGs with seizure activity. This can be done with a reasonable accuracy of 85%. Further improvement for the detection of low amplitude bursts or GPDs and artifacts is required to further improve the performance. At present, additional evaluation of the system is performed in our general ICU. In conclusion, the proposed system, based on various qEEG features, is suitable for real-time classification of EEG patterns. This is a first important step in the development of a system for real-time monitoring of the brain in ICU patients.

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