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Entropies for detection of epilepsy in EEG

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Summary The electroencephalogram (EEG) is a representative signal containing information about the condition of the brain. The shape of the wave may contain useful information about the state of the brain. However, the human observer cannot directly monitor these subtle details. Besides, since bio-signals are highly subjective, the symptoms may appear at random in the time scale. Therefore, the EEG signal parameters, extracted and analyzed using computers, are highly useful in diagnostics. The aim of this work is to compare the different entropy estimators when applied to EEG data from normal and epileptic subjects. The results obtained indicate that entropy estimators can distinguish normal and epileptic EEG data with more than 95% confidence (using *t*-test). The classification ability of the entropy measures is tested using ANFIS classifier. The results are promising and a classification accuracy of about 90% is achieved.

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1. Introduction

The brain is a highly complex system. Understanding the behavior and dynamics of billions of interconnected neurons from the brain signal requires knowledge of several signal-processing techniques, from the linear and non-linear domains, and its correlation to the physiological events. Many investigators, for example, Duke and Pritchard [1], has proved that complex dynamical evolutions lead to chaotic regimes. In the last 30 years, experimental observations have pointed out that, in fact, chaotic systems are common in nature. A detail of such system is given by Boccaletti et al. [2]. In theoretical modeling of neural systems, emphasis has been put mainly on either stable or cyclic behaviors. Perhaps studying the chaotic behavior at neural level could help in identifying schizophrenia, insomnia, epilepsy and other disorders [3—5].

Non-linear dynamics theory opens new window for understanding the behavior of electroencephalogram (EEG). Until about 1970, EEG interpretation was mainly heuristic and of descriptive nature. Although several papers have discussed quantitative techniques to assist in EEG interpretation [6] in clinical terms the situation remained

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unchanged. Babloyantz et al., have used certain non-linear techniques to study the slow wave sleep signal [7]. Since that time, applications of EEG to several research areas have significantly increased and potential clinical applications have been reported, such as the prediction of epileptic seizures [8,9], characterization of sleep phenomena [10], encephalopathies [11] or Creutzfeldt—Jakob disease [12] and monitoring of anesthesia depth [13,14].

In the analysis of EEG data, different chaotic measures are used in recent literature [15—20]. Jing and Takigawa [15] applied correlation dimensions techniques to analyze EEG at different neurological states. Lehnertz and Elger [16] used correlation dimension technique to test whether a relationship exists between spatio-temporal alterations of neuronal complexity and spatial extent and temporal dynamics of the epileptogenic area. Casdagli et al. [17] showed that the techniques developed for the study of non-linear systems could be used to characterize the epileptogenic regions of the brain during the interictal period. Correlation integral, the measure sensitive to a wide variety of non-linearities, was used for detection. In particular, recordings from epilepsy patients have often attracted researchers' attention and they have used non-linear techniques for analysis [18—20]. Andrzejak et al. [18] have used measures, such as correlation dimension and mean phase coherence to characterize the interictal EEG for prediction of seizures. The effective correlation dimension revealed that values calculated from interictal recordings were significantly lower for the epileptic focus as compared to remote areas of the brain. And also the epileptogenic process during the interictal state is characterized by a pathologically increased level of synchronization as measured by the mean phase coherence.

From studies reported in the literature, EEG signals can be considered to be chaotic. This means that the non-linear dynamics and deterministic chaos theory may supply effective quantitative descriptors of EEG dynamics and underlying chaos in the brain. In this work, we have used various entropy measures, such as Shannon's entropy, Renyi's entropy, Kolmogorov—Sinai entropy and approximate entropy to study and investigate the normal and epileptic EEG signals.

2. Background

Shannon developed the modern concept of 'information' or 'logical' entropy as part of information theory in the late 1940s [21]. Information theory dealt with the nascent science of data communications. Shannon entropy (H) is given by the following equation:

$$H = -\sum p_k \log p_k, \tag{1}$$

where p_k are the probabilities of a datum being in bin k.

It is a measure of the spread of the data. Data with a broad, flat probability distribution will have high entropy. Data with a narrow, peaked, distribution will have low entropy. As applied to EEG, entropy is the statistical descriptor of the variability within the EEG signal. The change in thermodynamic entropy ($\mathrm{d}S$) of a closed system is defined as a quantity that relates temperature (T) to the energy (=heat, $\mathrm{d}Q$) transferred to the molecules via the equation:

$$\mathrm{d}S = \frac{\mathrm{d}Q}{T} \tag{2}$$

Because entropy changes with change of state (e.g., solid to liquid), and because entropy tends to increase with time, it can be considered to be a measure of the degree of 'disorder' of the system. However, 'disorder' is a loosely defined term. Boltzman showed that thermodynamic entropy could be defined precisely as (Boltzman's) proportionality constant (k) multiplied by the logarithm of the number of independent microstates (W) available for the system:

$$S = k \log(W) \tag{3}$$

It is possible to derive the Shannon 'information' entropy (H) from the thermodynamic Boltzman formula (S). Even though there exists a formal analogy between H and S, it does not imply that there is necessarily a material basis for equating H and S in regards to the cortical function. Nevertheless, there does exist tantalizing neurophysiological evidence that the utility of information entropy estimators as measures of cortical function is because — as the cortex becomes unconscious — a true decrease in (the logarithm of) the number of accessible microstates (S) occurs at the neuronal level [22—25]. It indicates that the change in information entropy within the EEG may window a real change in cortical functional organization. Thus, the term 'entropy' may be more than merely a statistical measure of EEG pattern, but in some way truly reflect the intra-cortical information flow. This work evaluates the use of entropy measures for characterizing the normal and epileptic EEG signals.

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