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Selection of optimal AR spectral estimation method for EEG signals using Cramer–Rao bound

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Abstract

Electroencephalography is an essential clinical tool for the evaluation and treatment of neurophysiologic disorders related to epilepsy. Careful analyses of the electroencephalograph (EEG) records can provide valuable insight and improved understanding of the mechanisms causing epileptic disorders. The detection of epileptiform discharges in the EEG is an important element in the diagnosis of epilepsy. In this study, EEG signals recorded from 30 subjects were processed using autoregressive (AR) method and EEG power spectra were obtained. The parameters of autoregressive method were estimated by different methods such as Yule-Walker, covariance, modified covariance, Burg, least squares, and maximum likelihood estimation (MLE). EEG spectra were then used to analyze and characterize epileptiform discharges in the form of 3-Hz spike and wave complexes in patients with absence seizures. The variations in the shape of the EEG power spectra were examined in order to obtain medical information. These power spectra were then used to compare the applied methods in terms of their frequency resolution and determination of epileptic seizure. The Cramer–Rao bounds (CRB) were derived for the estimated AR parameters of the EEG signals and the performance evaluation of the estimation methods was performed using the CRB values. Finally, the optimal AR spectral estimation method for the EEG signals was selected according to the computed CRB values. According to the computed CRB values, the performance characteristics of the MLE AR method was found extremely valuable in EEG signal analysis.

Keywords: Electroencephalograph; Epileptic seizure; AR spectral estimation method; Power spectral density; Cramer–Rao bound

1. Introduction

About 1% of the people in the world suffer from epilepsy and 30% of epileptics are not helped by medication [1]. Research is needed for better understanding of the mechanisms causing epileptic disorders. Careful analyses of the electroencephalograph (EEG) records can provide valuable insight into this widespread brain disorder. The detection of epileptiform discharges occurring in the EEG between seizures is an important component in the diagnosis of epilepsy. In this work, autoregressive (AR) methods were used to analyze epileptiform discharges in recorded brain waves (EEG) from patient with absence seizures (petit mal). Absence seizure is one of the main types of generalized seizures and the underlying pathophysiology is not completely understood. Neurologists make an absence seizure epileptic diagnosis primarily through visual identification of a 3-Hz spike and wave complex [1–3].

An EEG contains a wide range of frequency components. However, the range of clinical and physiological interests is between 0.5 and 30 Hz. This range is divided into a number of frequency bands as follows [4]:

Delta (0.5–4 Hz): Delta rhythms are slow brain activities preponderant only in deep sleep stages of normal adults. Otherwise, they suggest disease.

Theta (4–8 Hz): This EEG frequency band exists in normal infants and children as well as during drowsiness and sleep in adults. Only a small amount of theta rhythms appears in the normal waking adult. Presence of high theta activity in awake adults suggests pathological conditions.

Alpha (8–13 Hz): Alpha rhythms exist in normal adults during relaxed and mentally inactive awakeness. The amplitude is mostly less than 50 μV and appears most prominent in the

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occipital area. Alpha rhythms are blocked by opening the eyes (visual attention) and other mental efforts such as thinking.

Beta (13–30 Hz): Beta activity is mostly marked in fronto-central region with less amplitude than alpha rhythms. It is enhanced by expectancy states and tension.

Since there is no single criterion evaluated by the experts, visual analysis of EEG signals in time domain may be insufficient. Therefore, some automation and computer techniques have been used for this aim. Since the early days of automatic EEG processing, representations based on a Fourier transform have been most commonly applied. This approach is based on earlier observations that the EEG spectrum contains some characteristic waveforms. A number of spectral estimation method have recently been developed and compared to the more standard fast Fourier transform (FFT) method have been studied in the literature [5–9]. AR spectra can be computed by different algorithms such as the Burg method and Yule-Walker method [5–12].

A number of spectral estimation techniques have been developed recently for EEG signal processing. The AR method is the most frequently used among model-based (parametric) methods, since the estimation of the parameters in the AR signal models is a well-established topic and the estimates are found by solving linear equations of the system. The parameters of the AR method can be estimated by using different estimation methods such as Yule-Walker, covariance, modified covariance, Burg, least squares, and maximum likelihood estimation (MLE) [5–12].

In this study, EEG signals were obtained from 30 subjects, 5 with epilepsy and 25 controls. The rest of them had been healthy subjects, were examined by taking into consideration of their power spectral densities (PSDs). The PSDs of the EEG signals were obtained by different parametric methods. The AR parameters were estimated by Yule-Walker, covariance, modified covariance, Burg, least squares, and MLE methods. We provided detailed analysis of the EEG signals; hence spectral distributions of these signals were visualized. These parametric estimation methods were compared in terms of their frequency resolution and the effects in epileptic seizure detection. The Cramer–Rao bounds (CRBs) were derived for the estimated AR parameters and the performance evaluation was performed by using CRB values. According to the computed CRB values, the optimal AR spectral estimation method was selected for the EEG signals.

2. Materials and methods

2.1. EEG data acquisition and representation

Scalp EEG signals are synchronous discharges from cerebral neurons detected by electrodes attached to the scalp. Epileptic seizure is an abnormality in EEG recordings and characterized by brief and episodic neuronal synchronous discharges with dramatically increased amplitude. This anomalous synchrony may occur in the brain locally (partial seizures) which is seen only in a few channels of the EEG signal, or involving the whole brain (generalized seizures) which is seen in every channel of the EEG signal. Four channels of EEG (F7-C3, F8-C4, T5-O1 and T6-O2) recorded from a healthy subject is shown in Fig. 1 and a patient with absence seizure epileptic discharge is shown in Fig. 2.

Currently, analysis of the recorded EEG data is performed primarily by neurologists through visual inspection. Most studies on the characteristics of the 3-Hz spike and slow wave complex have been based on simple visual inspection of data recorded for different channels. EEG signals for both healthy and unhealthy cases were recorded from subjects under relaxation, with their eyes closed. The recording conditions followed Guideline 7 of the American EEG Society and electrodes were placed according to the International 10–20 system. The signals were digitized and transferred to the PC using 12-bit AD converter, storage-sampling rate at 200 Hz.

Two neurologists with experience in the clinical analysis of EEG signals separately inspected every recording included in this study to score epileptic and normal signals. Each event was filed on the computer memory and linked to the tracing with its start and duration. These were then revised by the two experts jointly to solve disagreements and set up the training set for the program, consenting to the choice of threshold for the epileptic seizure detection. The agreement between the two experts was evaluated as the rate between the numbers of epileptic seizures detected by both experts. When revising this unified event set, the human experts, by mutual consent, marked each state as epileptic or normal. They also reviewed each recording entirely for epileptic seizures that had been overlooked by all during the first pass and marked them as definite or possible. Nevertheless, a preliminary analysis was carried out solely on events in the whole set, as each stage in these sets had a definite start and duration.

2.2. Cramer–Rao bound

Since the parameter estimates which are obtained by the estimators having lower variance will be close to the actual values, the parameter estimation method having the lowest variance should be selected for parameter estimation. Cramer–Rao bound can be defined as selection of the estimation method having the lowest variance. Since all information is in material form in the observed data and the underlying probability density function (PDF) for the data, the estimator accuracy depends directly on the PDF. In determination of CRB, PDF of the observed data is defined as the function of the unknown parameter and is referred to as likelihood function: $p(x;\theta)$, where θ denotes the vector of unknown parameters ($\theta=[\theta_1 \;\; \theta_2 \;\; \cdots \;\; \theta_p]^{\mathrm{T}}$). Then the log-likelihood function is determined. To obtain the CRB, the well-known formula which states that the elements of the Fisher information matrix is used,

$$[I(\theta)]_{ij} = -E\left[\frac{\partial^2 \ln p(x;\theta)}{\partial\theta_i \partial\theta_j}\right], \quad i = 1, 2, \ldots, p, \quad j = 1, 2, \ldots, p, \tag{1}$$