Power Spectral Entropy in the ECG of Patients Suffered from Nocturnal Frontal Lobe Epilepsy

ABSTRACT
An explorative study to assess the regularity of nocturnal frontal lobe epilepsy’s sleeping disease patients with power spectral entropy and power spectral entropy variation in different sleep stages is proposed. We analyzed the ECG data from 20 subjects, including 10 patients with nocturnal frontal lobe epilepsy’s sleeping disease and 10 healthy subjects. The ECG data were obtained from the PhysioBank CAP Sleep Database. The first step was to estimate the ECG power spectra. Then, the power spectra were divided into six sub-bands. The final step was to analyze each sub-band power spectral entropy. In comparison with the results obtained from the control group, the power spectral entropy in the patients suffered from nocturnal frontal epilepsy is lower in the frequency bands of 4–8 Hz, 8–16 Hz. Furthermore, the patients’ power spectral entropy in the band of 4–8 Hz is smaller than that in 1.6–4 Hz. The ECG of nocturnal frontal lobe epilepsy’s sleep disease patients has different information entropy. The entropy decrease in nocturnal frontal lobe epilepsy states indicates that the complexity of the heart falls and the normal physiological functions are affected. We can draw a preliminary conclusion that the main frequency band reflecting nocturnal frontal lobe epilepsy is 4–8 Hz.

KEYWORDS nocturnal frontal lobe epilepsy, power spectral entropy, ECG

INTRODUCTION
Epilepsy is the most common neurological disorders. About 5% of the population suffers an epileptic episode during their lifetime, and 1% has epilepsy. Particular attention has been devoted in recent years to those seizures arising from epileptic foci located within the frontal lobe, so-called nocturnal frontal lobe epilepsy (NFLE). Nocturnal frontal lobe epilepsy is an epileptic syndrome primarily characterized by bizarre motor seizures with a semiology suggesting a frontal lobe origin, occurring predominantly during sleep, mostly in stage 2 of non-rapid eye movement (NREM) sleep. The manifestation of epilepsy depends on abnormal discharge in the brain. The changes in emotion, motor activity, sensation, behavior, consciousness or memory are resulted from an abnormal electrical discharge in brain. Epilepsy researches are affected by many factors, such as daytime activities and the changes in emotion. The affection is smaller in the night than in the day, and without frequent band changing. A significant proportion of sleep-related complex motor seizures are difficult to distinguish from NFLE, originate outside the frontal lobe. Moreover, the distinction of NFLE from the non-rapid eye movement arousal parasomnias may be challenging. A correct NFLE diagnosis should be based on a diagnostic methods, including the genetic, morphological, video-polysomnographic and memory aspects.

Electrocardiogram (ECG) signal has been applied for the recording of the biomechanical and bioelectrical activities of the cardiac system. Cardiac system can be influenced by NFLE. The information of NFLE can be gotten by analyzing ECG. It provides useful information about the functional aspects of the cardiovascular system. Mainly, epileptic seizures are associated with several changes in autonomic nervous system, which may lead to gastrointestinal, cardiovascular, respiratory, skin and urinary manifestations. Changes in autonomic nervous system are common in patients with...
epilepsy but not very clearly, probably due to increased motor activity and other factors. Several researchers have proven that heart rate also commonly changes during seizures\textsuperscript{8–10}. Nevertheless, they have not been used in the evaluation of the whole ECG signal in nocturnal frontal lobe epilepsy so far. Heart rate can reveal only part of health information of patients. In addition, EEG data are acquired by placing electrodes on the patient’s scalp. However, acquisition channels may affect people in lots of ways. A multi-channel EEG acquisition system is more complex than the ECG data acquisition system, and therefore the ECG signal is an effective and easier way to obtain from physiological state.

Nonlinear dynamic analysis seems to be a powerful method of revealing the quantitative signal features\textsuperscript{11–14}. Recently, new methods based on nonlinear dynamics and fractal analysis have been developed to quantify complex HR dynamics and to complement conventional spectral measures of HR variability. The entropy refers to regularity, predictability and complex systems in a signal. Power spectral entropy is one of the algorithms to evaluate the entropy. Several studies have shown that power spectrum entropy provides a powerful method of feature extraction for EGG signal\textsuperscript{15–20}. Previously reported that entropy decreases in patients heart rate, reflecting heart decreased complexity and patients at high risk for sudden death\textsuperscript{21,22}. They have already provided clinically useful information on cardiac disease. Therefore, our study obtaining better NFLE information is based on using power spectrum entropy for the whole ECG.

The aim of this study was to assess the regularity of nocturnal frontal lobe epilepsy’s sleeping disease patients with power spectral entropy and power spectral entropy variation in different sleep stages to find the relationship between NFLE and power spectral entropy, and to develop a novel method to estimate the NFLE.

MATERIALS AND METHODS

Subjects

ECG data from PhysioBank Database available at www.physionet.com were used for this study\textsuperscript{23}. PhysioBank database is a large and growing archive of well-characterized digital recording of physiologic signals and related data. PhysioBank currently includes databases of cardiopulmonary, neural and other biomedical signals from healthy subjects and patients with a variety of condition with major public health implications, including sudden cardiac death, congestive heart failure, epilepsy, gait disorders, sleep apnea, and aging\textsuperscript{8}. Among the data, we mainly concerned the database of CAP Sleep in PhysioBank. Two types (nocturnal frontal lobe epilepsy and no pathology) of the ECG were obtained from the CAP Sleep database for our study\textsuperscript{24}.

ECG signals during sleep recorded from 20 subjects (10 males and 10 females) with 23 to 37 years of age without any drugs affecting the central nervous system were studied. Ten normal persons (5 males and 5 females, 23–37 years of age, mean ± SD:32 ± 4.16) were chosen as the control subjects, the other 10 with nocturnal frontal lobe epilepsy (5 males and 5 females, 25–36 years of age, mean ± SD: 29.8 ± 3.85) were the target of this study.

Preprocessing of ECG signals

Since the data in the database were recorded at different sampling rate, so we need to preprocess the raw ECG signals to ensure the data of all the 20 subjects are at the same sampling rate.

Using higher sampling frequency can increase the precision of the signal. But the amount of data stored by the device is defined by the memory size. ECG data were also stored at different sampling rate. This database was recorded at a sampling rate of 128 Hz from 7 subjects and a sampling rate of 512 Hz from 13 subjects. All data must have the same sampling rate, so we need to preprocess necessarily. In this paper ECG signal which sampling rate is 512 Hz should be drawn one sampling point from every four sampling points. Then, all ECG sampling rate was 128 Hz.

Fast Fourier Transform (FFT) plays a very important role in analyzing the frequency components in ECG signal. FFT is a specific kind of Fourier transform used in Fourier analysis, it transforms the time domain function into frequency domain representation. FFT algorithms are commonly employed to compute power spectrum density (PSD) of signals. For a given ECG signal, the collection of magnitude coefficients gives a description of the ECG signal in terms of the intensity of the various underlying frequency components, while the phase of the ECG signal is ignored. The spectral measures have the advantage of relating the power of variation in different frequency bands to different physiological effects.

Power spectra dividing

A typical ECG tracing of the cardiac cycle (heartbeat) comprises a P wave, a T wave, a QRS complex, and a U wave, which is normally not visible in 50–75% of the electrocardiogram because it is hidden by the T wave and upcoming new P wave\textsuperscript{25}. Figure 1 shows the schematic representation of a normal ECG.

The spectral measures have the advantage of relating the power of variation in different frequency bands to different cardiac features. Depending on the features of the heart, power spectra are divided into six sub-bands (Table 1).

Power spectral entropy to get the complexity of cardiac

For an uncertain system, the random variables are $x = (x_1, x_2 \ldots x_n)$, $n \geq 2$, and can be used to indicate
The status of the system. Each \( x_i (i = 1, 2, \ldots n) \) is called an information symbol. The corresponding probabilities are \( P = (P_1, P_2, \ldots P_n) \) \((0 \leq p_i \leq 1; i = 1, 2, \ldots n; \Sigma p_i = 1)\). So the information entropy is expressed as \( S = - \Sigma (p_i \times \ln(p_i)) \). If the sampling rate of the signals is \( f_\mu \), sample point is \( N \), the FFT of the signal is \( F(\omega_i) \). For an angular frequency: \( \omega_i = \frac{2\pi f_\mu}{N} \times i \) \((i = 1, 2, \ldots N/2)\) and signal frequency \( f_i = \left(1, 2, \ldots N/2\right)\). Power spectral entropy is: \( S = - \Sigma (p_i \times \ln(p_i)) \).

Suppose the whole bands \([f_s/N, f_s/2]\) are as a source, and the power spectra are divided into six sub-frequency bands. The total signal components in each sub-frequency band is an information symbol. The power density \( p(\omega) \) is the sum of the power density in each band. \( \Sigma p(\omega) \) is the sum of the whole source. Then \( p_i = \frac{p(\omega)}{\Sigma p(\omega)} \). The power spectral entropy is \( S = - \Sigma (p_i \times \log (p_i)) \), and analyze every sleep stage (S1, S2, S3, S4, REM) of NFLE group and control group of ECG signals using power spectral entropy.

**Power spectral entropy in different sleep stages**

Sleep is essential for human health and well-being. Sleep staging is one of important procedures for clinical diagnosis and treatment of sleep disorder. The R&K model breaks down the sleep progress characteristics into five sleep stages. They are four stages of Non-Rapid Eye Movement Sleep (NREM Stage 1–4) and a Rapid Eye Movement Stage (REM). Understanding of sleep stage is also the focus of recent research. In our study, we will study the power spectral entropy in different sleep stages.

### Results and discussion

As shown in Table 2, sleep stage I, no significant difference was found in the power spectral entropy between control and NFLE patients in all the six sub-band \((P > 0.05)\).

However, in sleep stage II, the power spectral entropy of NFLE patients differs significantly from control in the sub-bands of 0.8–1.6 Hz and 4–8 Hz \((P < 0.01)\). The power spectral entropy in the patients suffered from nocturnal frontal epilepsy is lower in the frequency bands of 4–8 Hz, 8–16 Hz. The NFLE patients’ power spectral entropy in the band of 4–8 Hz is smaller than that in 1.6–4 Hz, as shown in Table 3.

In sleep stage III, the power spectral entropy of NFLE patients differs significantly from the control in the sub-bands of 0.03125–0.8 Hz \((P < 0.05)\) and 4–8 Hz \((P < 0.01)\). The power spectral entropy of the patients suffered from nocturnal frontal epilepsy is lower in the frequency bands of 1.6–4 Hz, 4–8 Hz, 8–16 Hz, and the NFLE patients’ power spectral entropy in the band of 4–8 Hz is smaller than that in 1.6–4 Hz, as shown in Table 4.

In sleep stage IV, the power spectral entropy of NFLE patients differs significantly from controls in the

---

**Table 1** Each sub-frequency band features.

<table>
<thead>
<tr>
<th>Frequency band (Hz)</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/32–0.8</td>
<td>No</td>
</tr>
<tr>
<td>0.8–1.6</td>
<td>RR interval (0.8–1.6)</td>
</tr>
<tr>
<td>1.6–4</td>
<td>QT interval (3.125)</td>
</tr>
<tr>
<td>4–8</td>
<td>PR interval (5–8) T wave (6.25)</td>
</tr>
<tr>
<td>8–16</td>
<td>P wave (12.5) PR segment (8–20)</td>
</tr>
<tr>
<td>16–64</td>
<td>QRS complex (8–12.5) ST segment (8–12.5)</td>
</tr>
</tbody>
</table>

**Table 2** Control group and NFLE group six sub-band power spectral entropy in sleep stage I.

<table>
<thead>
<tr>
<th>Frequency band</th>
<th>Control group</th>
<th>NFLE group</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03125–0.8 Hz</td>
<td>0.2582 ± 0.3771</td>
<td>0.2941 ± 0.3827</td>
<td>0.548</td>
</tr>
<tr>
<td>0.8–1.6 Hz</td>
<td>0.5156 ± 0.2302</td>
<td>0.4944 ± 0.1872</td>
<td>0.521</td>
</tr>
<tr>
<td>1.6–4 Hz</td>
<td>0.7197 ± 0.3337</td>
<td>0.7499 ± 0.2809</td>
<td>0.535</td>
</tr>
<tr>
<td>4–8 Hz</td>
<td>0.8271 ± 0.4230</td>
<td>0.7829 ± 0.2455</td>
<td>0.303</td>
</tr>
<tr>
<td>8–16 Hz</td>
<td>1.1217 ± 0.4230</td>
<td>1.2206 ± 0.3981</td>
<td>0.128</td>
</tr>
<tr>
<td>16–64 Hz</td>
<td>0.8807 ± 0.3531</td>
<td>0.9233 ± 0.3835</td>
<td>0.463</td>
</tr>
</tbody>
</table>

**Table 3** Control group and NFLE group six sub-band power spectral entropy in sleep stage II.

<table>
<thead>
<tr>
<th>Frequency band</th>
<th>Control group</th>
<th>NFLE group</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.03125–0.8 Hz</td>
<td>0.3021 ± 0.4000</td>
<td>0.3737 ± 0.3571</td>
<td>0.548</td>
</tr>
<tr>
<td>0.8–1.6 Hz</td>
<td>0.4603 ± 0.2018</td>
<td>0.5303 ± 0.1849</td>
<td>0.002</td>
</tr>
<tr>
<td>1.6–4 Hz</td>
<td>0.7604 ± 0.2902</td>
<td>0.7611 ± 0.2752</td>
<td>0.983</td>
</tr>
<tr>
<td>4–8 Hz</td>
<td>0.8386 ± 0.3230</td>
<td>0.7309 ± 0.2606</td>
<td>0.002</td>
</tr>
<tr>
<td>8–16 Hz</td>
<td>1.1543 ± 0.4322</td>
<td>1.1268 ± 0.3997</td>
<td>0.572</td>
</tr>
<tr>
<td>16–64 Hz</td>
<td>0.8685 ± 0.3515</td>
<td>0.8852 ± 0.4604</td>
<td>0.726</td>
</tr>
</tbody>
</table>
sub-bands of 0.03125–0.8 Hz (P < 0.001), 4–8 Hz (P < 0.001) and 8–16 Hz (P < 0.05). The power spectral entropy in the patients suffered from nocturnal frontal epilepsy is lower in the frequency bands of 4–8 Hz, 8–16 Hz, 16–64 Hz, and the NFLE patients’ power spectral entropy in the band of 4–8 Hz is smaller than that in 1.6–4 Hz as shown in Table 5.

In sleep REM, the power spectral entropy of NFLE patients differs significantly from controls in sub-bands of 4–8 Hz (P < 0.005). The power spectral entropy in the patients suffered from nocturnal frontal epilepsy is lower in the frequency bands of 4–8 Hz, 8–16 Hz, and the NFLE patients’ power spectral entropy in the band of 4–8 Hz is smaller than that in 1.6–4 Hz (Table 6).

The frequency bandwidth of heart rate is relatively small, so high frequency cannot be analyzed from heart rate. But from whole ECG, cardiac information can be obtained by using power spectral entropy. Therefore, using ECG for analysis can get more information than just using heart rate.

**CONCLUSION**

The main goal of the current study was to assess the regularity of nocturnal frontal lobe epilepsy’s sleeping disease patients with power spectral entropy and power spectral entropy variation in different sleep stages.

This research has shown that the power spectral entropy in the patients suffered from nocturnal frontal epilepsy is lower in the frequency bands of 4–8 Hz, 8–16 Hz than the control group, and the patients’ power spectral entropy in the band of 4–8 Hz is smaller than that in 1.6–4 Hz. The most obvious finding to emerge from this study is that the main frequency band reflecting nocturnal frontal lobe epilepsy is 4–8 Hz in electrocardiogram. The present study provides additional evidence with respect to detection of nocturnal frontal lobe epilepsy from the electrocardiogram. Although the current study is based on a small sample of participants, the findings suggest the ECG of nocturnal frontal lobe epilepsy’s sleep disease patients has different information entropy. The entropy decrease in nocturnal frontal lobe epilepsy states indicates that the complexity of the heart falls and the normal physiological functions are affected. The main weakness of this study was the paucity of clinical trials. Further research in this field would be of great help in distinguishing between patients with epilepsy.

**ACKNOWLEDGEMENT**

This work was supported partly by the Chinese National Natural Science Foundation (No. 31500796) and Guang Dong Provincial Science and Technology Foundation (Nos. 2015B010105006 and 2013B060100011) and Guang Dong Provincial Traditional Chinese Medicine Bureau Science Foundation (20171038) and Guang Zhou City Science and Technology Foundation (2014Y2-00508).

**CONTRIBUTION OF AUTHORS**

Ping Zhou, Zong-Xia M.U., and Chun-Lan H.E. contributed towards data collection and analysis. Ping Zhou, Yao-Xiong Huang, contributed towards reference search, article writing, and proof reading.

**REFERENCES**