Power spectral analysis of ECG signals during obstructive sleep apnoea hypopnoea epochs

#Chandan K. Karmakar, Ahsan H. Khandoker, Marimuthu Palaniswami
Department of Electrical and Electronic Engineering, The University of Melbourne
Melbourne, VIC 3010, Australia. E-mail: {c.karmakar, a.khandoker, swami}@ee.unimelb.edu.au.

Abstract

Based on the evidence that sympathovagal balance around apnoeas/hypopnoeas are altered in sleep apnoea patients, we utilize power spectral density (PSD) analysis to better understand the impact of obstructive sleep apnoea (OSA) and hypopnoea on RR intervals and QRS amplitudes of ECG signals. In addition, receiver operating characteristics (ROC) analysis was performed in order to test the performance the PSD features of ECG signals to recognize OSA, hypopneas and normal breathing events. Maximum area under ROC curve was found to be 0.83 for OSA-normal group in the frequency range of 0.000-0.094 cycles/interval. For OSA-hypopnoea epochs classification, PSD of QRS amplitudes was performed better than that of RR intervals. The results of the study will be useful in designing an automated classifier to recognize apnoeas/hypopnoeas/normal epochs using PSD features of ECG signals.

1. INTRODUCTION

Sleep apnoea has been recognized as a highly prevalent disease that remains under diagnosed [1]. It has been estimated that 9% of women and 24% of men in the United States of America suffer from the condition [2]. It has a strong link with cardiovascular diseases, poor cognitive performance, and increased risk of motor vehicle and workplace accidents due to reduction in sleep quality [3]. Obstructive sleep apnoea (OSA) is usually known as sleep apnoea and more common than central sleep apnoea (CSA). It is a cardio-respiratory disorder characterized by brief interruptions of breathing during sleep. OSA results from complete collapse of a narrowed pharynx whereas partial collapse is responsible for hypopnoea. The standard definition of hypopnoea is 50% reduction in thoracoabdominal amplitude than the presence of normal continued airflow, lasting for 10 seconds or more. However, a reduction of more than 95% in thoracoabdominal amplitude is considered as the full apnoea event [4]. The definitive measurement of sleep apnoea is apnoea/hypopnoea index, which is calculated by averaging the number of apnoea and hypopnoea events per hour [5].

The standard technique for diagnosing full OSA or hypopnoea is polysomnomgraphy, which is an inconvenient, expensive and time consuming procedure involves multi-channel recording. On the other hand, OSA diagnosis using Electrocardiogram ECG is an inexpensive, less invasive and more convenient approach for patients. The surface ECG is a robust and non invasive data acquisition procedure that contains concealed information about central automatic control of cardiovascular function, respiration and the electric activity of heart. As a result OSA detection with ECG signal is a popular research topic for last few years. The challenge organized by physionet and computer in cardiology in 2000 also stimulated the introduction of a wide variety of techniques for detecting OSA and scoring level of apnoea by counting number of apnoea minutes for a subject. The best result of the challenge was 100% accuracy in detecting the OSA+ /OSA-subject and 90% accuracy in minute-by-minute classification [6].

The power spectral analysis of heart rate variability (HRV) [i.e., RR intervals of ECG signals] signal is an important method for monitoring the autonomic nervous system control function. The variation of density of power at different frequency range may be able to identify the imbalances of autonomic nervous system. In earlier studies [6-8], power spectral analysis was used to recognize OSA events using HRV and ECG derived respiratory (EDR) signals. The study hypothesis was that apnoeas/hypopnoeas are associated with changes of HRV and EDR characteristics. Hence this study investigates spectral oscillations of nocturnal HRV and EDR signals during apnoeas/hypopnoeas/normal breathing events.

2. METHOD

A. ECG and apnoea/hypopnoea scoring

Digitized ECG signals recorded from 9 patients were obtained from Compumedics Pty Ltd for this study. The average length of recording was around 10.5 hours. The apnoeas/hypopnoeas epochs were manually scored according to standard criteria by the sleep specialist of Compumedics. The result of the scoring was markings for the beginning and the end of episodes of disordered breathing. To determine the class of each 1-minute epoch, the markings were mapped to time with a resolution of one second. Each epoch contains apnoeas or hypopnoeas or both. The minute epochs were then classified according to the dominant type of event in the minute. Duration of 10 seconds or more were taken as threshold for deciding apnoea/hypopnoea class. The final result of the
scoring was labelled as either “Normal” (-1), “Hypopnoea” (1) or “Apnoea” (2).

B. Calculation HRV and EDR signal

Initially the ECG signal was divided into minute epochs. Total 5834 epochs were obtained from nocturnal ECGs of 9 patients. QRS complex detection times and amplitudes were determined with 1 ms precision for all recordings using an algorithm described in another study [9]. Amplitude of each QRS complex (EDR signal) and interval between successive R waves (HRV signal) of QRS complex were calculated. To remove any false intervals, missed and/or ectopic beats we considered RR intervals within the range of 0.5s-1.5s. The corresponding QRS amplitudes were also removed from the EDR signal.

C. Power spectral analysis

The power spectrum density (PSD) is the estimation of distribution of power contained in a signal over frequency. The PSD of a stationary random process $x_n$ can be expressed by the following equation [10]:

$$P_x(f) = \frac{1}{f_s} \sum_{m=-\infty}^{\infty} R_x(m) e^{-2\pi imf/f_s}$$

Where, $f_s$ is the sampling frequency and $R_x(m)$ is the autocorrelation function of the signal. The power of the signal in a given frequency band can be calculated by integrating over positive and negative frequencies:

$$P(f_1, f_2) = \int_{f_1}^{f_2} P_x(f) df + \int_{-f_2}^{-f_1} P_x(f) df$$

HRV signal were a sequence of RR-intervals associated with each 1-minute segment. Any epoch containing less than 30 data points were excluded for feature extraction. After exclusion total 5476 (out of 5834) epochs were analyzed. The index of the signal was beat number. In order to eliminate the bias of mean and variance of the signal on feature extraction, all signals were normalized by calculating their $z$-score (i.e., $(x-\mu)/\sigma$, where $\mu$ is the mean and $\sigma$ is the standard deviation for the signal). The sequence was then zero padded to length 128.

In this study we have used the MATLAB R2006b implementation of Welch’s method for calculating power spectrum density (PSD). In this method the data is zero-padded to length of the FFT and divided into overlapping segments. Then PSD of each segment is computed and the PSD estimates are averaged out, which is the result of the power spectral analysis. This averaging decreases the variance of the estimate relative to a single periodogram estimate of the entire data record [11]. We have used FFT length of 128 data points which is divided into eight segments with 50% overlap between them. The resultant PSD vector length is 65 which also represent the number of frequency bin. The resolution of each bin is $1/128$ (i.e.$0.0078$ cycles/interval).

D. Statistics and ROC analysis

MATLAB statistics toolbox was used to perform a multivariate repeated measures ANOVA (within three groups namely OSA, Hypopnoea and Normal) to test the influence of OSA and hypopnoea on PSD. To test for differences between group means after an ANOVA was significant, we used bonferroni post hoc test. In order to provide the relative importance of features, receiver-operating curve (ROC) analysis was used [12], with the areas under the curves for each feature represented by the ROCarea. A ROCarea value of 0.5 means that, the distributions of the features are similar in two groups with no discriminatory power. Conversely, a ROCarea value of 1.0 would mean that the distributions of the features of the two groups do not overlap at all. ROC plots are used to gauge the predictive ability of a classifier over a wide range of threshold values. A threshold value was applied such that a value below the threshold was assigned into one category whereas a value equal to or above the threshold was assigned into another category. ROC curves were plotted using results to examine qualitatively the effect of threshold variation on the classification performance. The area under ROC curve was approximated numerically using the trapezoidal rules [12] where the larger the ROC area the better the discriminatory performance. The frequency ranges were selected depending on the ROC area values of different groups at each frequency bin. The ROC area of 0.70 is used as threshold for selecting any frequency bin as significant feature.

![Fig. 1: Median PSD derived from the HRV signal of the OSA, Hypopnoea and Normal 1-min segments from 9 sets of ECG recordings. Along the y-axis, a log scale is used and the median and interquartile (25%-75%) range of the power is shown for each frequency bin.](image-url)

3. RESULTS AND DISCUSSION

Figure 1 represents the median and interquartile, IQR (25%-75%) values of power of HRV signal for three groups. The median value of OSA and hypopnoea are very similar, except for the frequency range 0.17-0.0273 (cycles/interval). In this range, there is more power in the PSD of hypopnoea epochs than in the PSD of OSA epochs. This probably corresponds to the frequency range associated with respiratory sinus arrhythmia. The median PSD values of OSA and normal epochs of all frequencies are different, except for the
frequency range 0.086-0.141 (cycles/interval). In the frequency range 0.000-0.063 and 0.172-0.273 (cycles/interval) the difference in median PSD values was comparatively higher than other frequency ranges. For hypopnoea and normal epochs the maximum difference was found in the frequency range 0.000-0.0623 (cycles/interval).

The median and interquartile (25%-75%) values of power of EDR signal for three groups are shown in Figure 2. The frequency range of OSA and normal epochs are different in all frequency range. The difference is highest in the frequency range 0.000-0.094, 0.165-0.266 and 0.360-0.453 (cycles/interval). In the first range, there is more power in the PSD of OSA epochs than in the PSD of normal epochs. However in other two ranges PSD of OSA epochs have less power than PSD of normal epochs. For hypopnoea and normal epochs, the median values are very similar and a small difference in median values exists in the frequency range 0.360-0.453 (cycles/interval). In case of OSA and hypopnoea the median values differs mostly at frequency range 0.000-0.094 and 0.165-0.266 (cycles/interval). In the findings in earlier studies [6]. In this frequency range the median power of hypopnoea is close to median power of OSA in PSD of HRV that indicates both OSA and hypopnoea has similar effect on HRV signal. But in PSD of EDR it is close to the median value of normal group in PSD of EDR. This is probably due to the partial cessation or partial reduction in airflow which in turn affects the respiratory response insignificantly.

The maximum difference in the median power found between hypopnoea and normal groups in the PSD of EDR. Interesting result found in the frequency range 0.165-0.266, where the difference of OSA-normal group is lower than the difference of OSA-hypopnoea group. Further study will be required to identify the reason of such behaviour.

ANOVA analysis was performed for each frequency band along with the bonferroni post hoc test. From the p value it was found that the PSD features for OSA, hypopnoea and normal groups were significantly different (p<0.001) for all frequency band shown in Table 1. Bonferroni post hoc test results revealed significant differences (p<0.01) exist among all groups at each frequency bands.

The highest ROC area between OSA-Normal, Hypopnoea- Normal and OSA-Hypopnoea groups are respectively 0.83, 0.72 and 0.78 as shown in Table 2. The sensitivity and specificity for each threshold for these frequency bands are shown in Figure 3. The accuracy, sensitivity and specificity for each ROC curve was {76%, 70%, 79%}, {70%, 60%, 72%} and {74%, 60%, 79%} respectively.

The limitations of this study include small sample size of apnoeas/hypopnoeas epochs and apnoeas with arousals were not taken into consideration.
Fig. 3: ROC (receiver operating characteristics) curves showing sensitivity (true positive) and 1-specificity (false positive) for various thresholds for OSA-Normal, Hypopnoea-Normal and OSA-Hypopnoea groups. For each group the frequency band with highest ROC area is shown.

4. Conclusion

From the results of this study, it can be concluded that effect of OSA and hypopnoea events on PSD of RR interval was similar, but different on QRS amplitudes. To distinguish OSA epochs from hypopnoeas, PSD features of QRS amplitude are better choice. On the other hand, OSA epochs can easily be distinguished from normal epochs using both types of PSD features, however, hypopnoea and normal epochs are only distinguishable using the frequency range 0.000-0.063 (cycles/interval) of PSD of RR intervals. These results show that the impact of OSA and hypopnoea on ECG is different in terms of PSD features. Hence it is a better option to model a classifier with treating OSA and hypopnoea as different class using PSD feature. Results found from this study could be useful in extracting features for developing an automated machine learning model to recognize apnoeas/hypopnoeas/normal breathing events.

Acknowledgement

This study was supported by an Australian Research Council (ARC) linkage project with Compumedics Pty Ltd (LP0454378). The authors like to thank Dr E. Zilberg of Compumedics for providing the sleep studies for this study.

References