Arrhythmia Detection in Human Electrocardiogram

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Abstract

The Electrocardiogram (ECG), by appropriate mathematical exploration, can be used to detect a majority of heart ailments. As a first step of detection of the disease, the ECG of a medically sound person must be distinguished from that of a diseased person. In this paper, we discuss a method to distinguish a normal sinus rhythm ECG from an arrhythmic ECG. The method involves the study of the shape of beats. Though there are slight alterations, the shape of the beats in an ECG sample largely remains the same. The frequencies that determine the shape of each beat vary; however, only by a small amount with the occurrence of every new beat. Substantial phase coupling among some frequencies present in the beats of an ECG sample might be the cause for such a similarity in the shape of the beats. Though there may be other frequencies that contribute to the shape of the beat, the contribution of the phase-coupled frequencies is significant. Such phase-coupled frequencies of an ECG signal are traced by using the third order spectrum namely the Bispectrum. The bispectral frequencies determine the elemental shape of every beat present in the sample. Having found the bispectral frequencies present in the sample, the Fourier series of the replicated individual beat is studied. By appropriate comparison of the two, the frequency components present in the beat, which determine the shape of beat can be known. The properties of such frequencies can effectively characterize an ECG into rhythmic or arrhythmic.

Keywords

Beat, Bispectrum, Fourier series, Phase-coupling.

INTRODUCTION

The cardiac function is analogous to a feedback system in which output is a non-linear function of the input. Electrocardiogram (ECG) is a graphical representation of the cardiac function, and hence depicts this constant adaptation of the heart.

The shape of beats in an ECG differ from one other though the elemental shape of a beat is preserved in all of them. This elemental shape is determined by a few frequencies that show strong phase coupling over a large dataset. The power spectral analysis can be used to characterize the frequency components present in an ECG sample.

However, it cannot deliver any information regarding their phase coupling since it is phase blind in nature. Consequently, the power spectrum fails to describe the relationship between the different frequency components of the spectrum.

Higher order statistics can estimate the statistical coupling among the frequencies present in a given data [**1**]. In this study, we use bispectrum, which is the third order spectrum, to trace the frequencies that show good correlation and further study their characteristics.

THEORY OF BISPECTRUM AND BICOHERENCE

Higher-order statistics indicate the expectation of more than two values of a stochastic process. The third order statistic, called the third order cumulant, has the following mathematical form :

$$c_3(t_1, t_2) = \Sigma\{ s(t_1)\ s(t_2)\ s(t_1 + t_2)\}$$

Bispectrum is defined as the two dimensional Fourier Transform of the third order cumulant [**2, 4**].

$$C_3(\omega_1, \omega_2) = \sum_{t_1=-\infty}^{+\infty} \sum_{t_2=-\infty}^{+\infty} c_3(t_1, t_2)\ exp\{-j(\omega_1 * t_1 + \omega_2 * t_2)\}$$

$$|\omega_1|, |\omega_2| \leq \pi$$

Thus, the bispectrum is a three dimensional function with the magnitude of bispectrum plotted against the two frequencies ω_1 and ω_2. It measures the correlation between three spectral peaks at the frequencies ω_1, ω_2 and $(\omega_1+\omega_2)$ and thereby estimates the phase coupling between them. As it has twelve regions of symmetry, the knowledge of any one region, for example $\omega_2>0$, $\omega_1>\omega_2$, and $\omega_1+\omega_2<\pi$ is sufficient for its complete description. Strongly coupled frequencies can be effectively traced using the bispectrum. Nevertheless, weakly coupled but strong oscillations would result in the same bispectral value as strongly coupled but low power oscillations. In order to overcome this problem, bicoherence function is used. The bicoherence function is the normalized form of bispectrum with respect to its power spectrum.

$$B(\omega_1, \omega_2) = \frac{C_3(\omega_1, \omega_2)}{|S(\omega_1)\ S(\omega_2)\ S(\omega_1 + \omega_2)|^{1/2}}$$

where $S(\omega)$ is the estimated power spectrum of the signal.

For weak correlation between the three spectral peaks, bicoherence value is low and for strong correlation, it is high [**3**].

METHODOLOGY

Motivation

By visual inspection, we notice that the shape of the beats in an ECG sample is quite similar. However, on closer observation, it can be noted that there are slight distortions in the shape of every beat that make it distinctly different from every other beat of the sample.

In order to study the shape of a single beat in the frequency domain, we have replicated the shape of the beat infinitely in the time domain to form a periodic waveform. The Fourier Series (FS) of such a periodic signal reveals the frequency components present in it. Thus, the unique shape of every beat of the sample can be characterized by its frequency components. However, of all the frequency components that contribute to the shape of the beat, the contribution of the phase-coupled frequencies is significant, with the contribution of the rest being minimal. As the shape of the beat varies by a small amount with the occurrence of a new beat, we expect the phase-coupled frequencies to shift by only a small amount in the frequency domain. However, of all the frequencies present in the FS of a beat, we need to trace only the phase-coupled frequencies. In order to do that, we mathematically define an elemental shape of the beat for a given sample (ESB), with the actual shape of every beat being the result of a small distortion in the ESB. Hence, the frequency components contributing to the shape of the ESB would be the frequencies lying close to the phase-coupled frequencies of every beat in the sample.

The frequency components of ESB can be found out by using the bicoherence function. The bicoherence reveals the strongly coupled frequencies of a given sample. Thus, by computing the bicoherence of an ECG sample, we can obtain the bispectral frequencies (BF) that contribute to the shape of the ESB. The bispectral frequencies are now compared with the FS of a replicated single beat. The frequencies present in the FS of the replicated beat lying close to the BF are expected to predominantly contribute to the shape of the beat. These frequencies are termed as the shape determining frequencies (SDF). The properties of SDF are studied to characterize the ECG.

Frequency Detection (FD) procedure

The block diagram of the FD procedure is depicted in figure 1. The signal is conditioned by DC extraction and amplitude normalization using a high pass filter (5th order Butterworth having cutoff frequency of 3Hz). The bicoherence of data of length 60 – 70 beats is then computed (FFT length = 512 (Hz)). The output is a three dimensional quantity with the magnitude of bicoherence plotted against independent frequency axes ω_1 - ω_2 [Fig.2]. The location of peaks having the maximum amplitude is observed in the form of (ω_1,ω_2). The bicoherence indicates that that the peaks occurring at ω_1, ω_2, and (ω_1+ω_2) are correlated to each other. The extent of correlation is shown by the magnitude of such peaks. The bicoherence is computed over a large data (overlap = 50,FFT length = 512 (Hz)) to get purely phase-coupled frequencies.

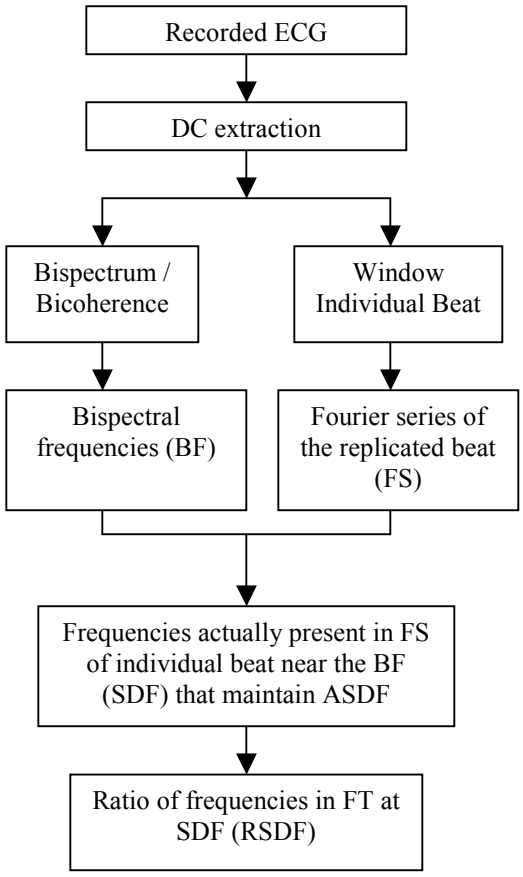

Figure 1. Block diagram of the Frequency Detection procedure

Having obtained the BF, the SDF that show up in an individual beat are found by the following procedure. A single beat is isolated from the ECG by using a rectangular sliding window. The frame size (M) of the sliding window is set in accordance to the sampling frequency f_s, such that the frame size equals the size of a beat. The signal is windowed using a non-overlapping rectangular window of size M samples. The windowed signal is replicated infinitely in the time domain and its FS is computed. The frequencies lying close to BF are separated. The amplitudes of those frequencies are observed over few beats (8 – 10) and amplitudes of the shape-determining frequencies (ASDF) are established. Peaks having magnitudes equal to ASDF and occurring close to BF are separated and termed as the SDF. The process is repeated for all the beats in the sample. The ratio of the magnitudes of SDF (RSDF) is computed and compared.

Implementation

The simulation is done using the Higher-Order Spectral Analysis toolbox of the MATLAB package. Archives from the MIT/BIH Arrhythmia database [**5**] are analyzed, which contain arrhythmic ECG of length 30 min and sampled at a sampling frequency of f_s = 360 (Hz). Normal ECG is obtained from MIT-BIH Normal Sinus Rhythm Database [**5**]. This data is sampled at f_s = 128 (Hz).

RESULTS AND DISCUSSION

The FD procedure is applied to a set of normal and arrhythmic ECG samples shown in Table 1. The bicoherence shows maximum amplitude at several locations in the ω_1-ω_2 plane due to symmetry. However, only one region of symmetry ($\omega_2>0$, $\omega_1>\omega_2$, and $\omega_1+\omega_2<\pi$) is considered to obtain the BF. These frequencies are compared with the FS of the replicated individual beats to establish the ASDF. The bispectrum is also used to detect the bispectral frequencies. It is observed that the bispectrum has the frequencies shown by the bicoherence along with some additional locations of frequencies in ω_1-ω_2 plane. However, we have selected the shape determining frequency components of interest by following the FD procedure that compares the BF with the frequency components of the beats. Those final frequency components obtained using the bispectrum are same as those obtained using bicoherence. The frequencies of additional peaks shown by bispectrum, when compared with the FS of the replicated individual beats, had higher amplitudes than the expected values. Thus, bicoherence seems to be a better option as compared to bispectrum.

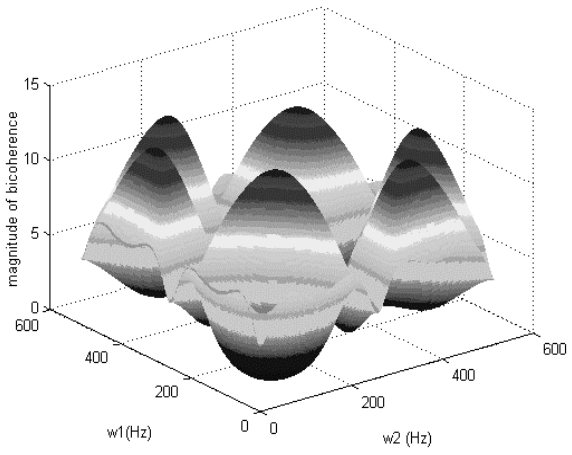

Figure 2. Bicoherence (magnitude vs. ω_1-ω_2 plot) of 16420th sample taken with Nyquist frequency = 300 (Hz)

The bicoherence of the sample 16420 is shown in Fig.2 and the bispectrum of the same sample is shown in Fig.3. In this particular sample, a sample length of 100 beats has been taken. The bicoherence plot of the sample shows several peaks of significant magnitude. But taking symmetry into consideration, we obtain only one significant peak of interest. The bispectral frequencies of that peak are observed to be (563,287). These frequencies are scaled up by a factor of 10, with this factor being consistently maintained over the computation of FS of the replicated individual beats. Figure 4 shows the comparison of the BF with the FS of a replicated single beat of the sample. In order to locate the SDF of this beat, the frequencies present in the FS of the replicated beat lying close to the BF have to be traced. The SDF of this beat are found to be 385 and 561. These are the frequencies at which significant amplitude in the vicinity of the BF occurs.

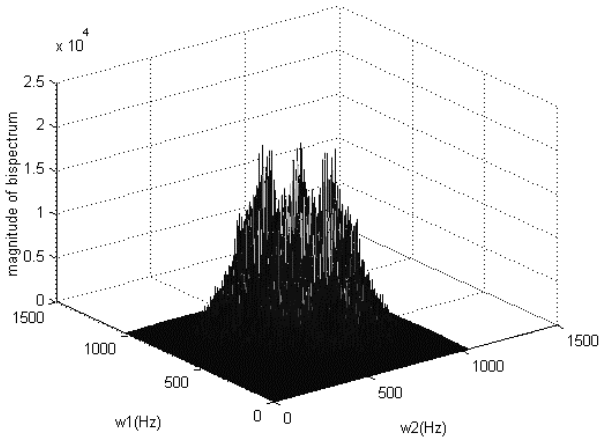

Figure 3. Bispectrum (magnitude vs. ω_1-ω_2 plot) of 16420th sample taken with Nyquist frequency = 512 (Hz)

The amplitudes of the SDF are observed over 8 – 10 beats and ASDF is estimated. Having obtained the ASDF, the FS of the replicated signals of different beats of the sample are calculated. The ratio of the frequencies lying close to the BF maintaining ASDF is also computed.

In the normal database, shape of beats remained consistently similar though there is a slight amount of distortion. The SDF were observed to have the same ratio over all beats of the sample. The ratios are shown in the Table 1. The ASDF could be estimated since the amplitudes of the SDF in the corresponding FS of the replicated beat were found to be nearly equal. On the contrary, the arrhythmic signals showed a distinctly visible variation in shape at specific locations of the signal. In spite of the presence of malady in an arrhythmic ECG, heart tries to get back to the normal condition. In such an attempt, it tries to maintain the shape of beat consistently. But it fails at some locations, where a distinct distortion in shape occurs. A consistent ratio of SDF could not be obtained indicating the abnormality present in every beat of the arrhythmic ECG. However, the approximate value around which the ratio of SDF existed could be estimated, which is shown as ARSDF in the Table 1. While there is a distinctly visible distortion in the shape of beat, the frequencies near BF do not maintain ASDF as expected. The peaks

maintaining ASDF that exist in the FS of replicated beat for the beats prior to the distinctly distorted beat are found to be absent. In the distinctly shape-distorted beat of sample 101, the amplitudes of peaks occurring at SDF are nearly twice the amplitudes of SDF of the sample. The distorted beats in the other samples of arrhythmia database show significantly different amplitudes from ASDF. The ratio of the average of amplitudes of SDF of the distorted beat to that of the sample is shown as RDB in Table 1.

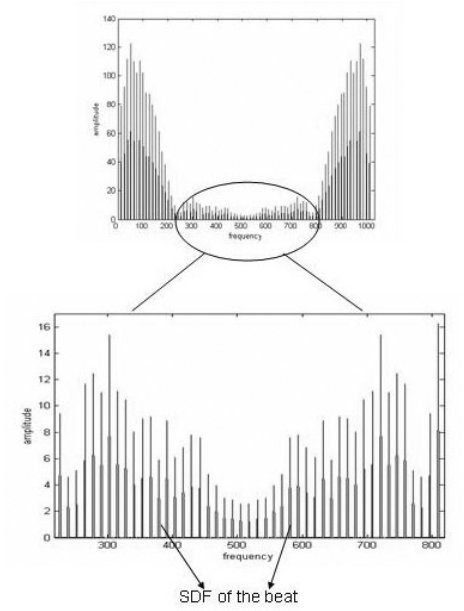

Figure 4. SDF at frequencies 385 and 561 BF (w1, w2) = (563,387)

CONCLUSIONS

Bispectral analysis using the bicoherence reveals the phase-coupled frequencies present in an ECG sample. The comparison of bispectral frequencies with the Fourier series of replicated single beat of the sample reveals the actual frequencies that determine the shape of that particular beat. The ratio of such frequencies remains constant and their amplitudes remain nearly same in the case of normal ECG. In an arrhythmic ECG, the amplitudes of the frequencies vary when the abnormality occurs resulting in the distortion of shape. The peaks maintaining ASDF that exist in the FS of replicated beat for the beats prior to the distinctly distorted beat are found to be absent. The cause for such an absence might be the entry of a foreign frequency that disturb the spectrum. The shift of prior existent peak to some other position and the occupancy of the vacant position by a peak of different magnitude might have led to a change in the shape of the beat. This indicates the presence of disease in an arrhythmic ECG. The frequencies that the bicoherence displayed are present in the bispectrum as well. However, bispectrum shows some extra frequencies that do not contribute to the shape of beat. Hence, bicoherence proves to be a better option than the bispectrum. Thus, the Frequency Detection procedure effectively distinguishes between a normal and an arrhythmic ECG and hence helps in succssfully characterizing an abnormal ECG.

Table 1. Result of the frequency detection procedure when applied on MIT–BIH electrocardiogram database

Normal Sinus Rhythm Database

File Name	M	RSDF
16265.dat	75	1.128
16272.dat	125	1.019
16273.dat	125	1.012
16420.dat	80	1.457

Arrhythmia Database

File Name	M	ARSDF	RDB
101.dat	300	1.004	2.2
102.dat	250	1.056	1.92
103.dat	300	1.061	1.78
104.dat	300	1.041	2.42

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