CHAPTER 4

QRS COMPLEX DETECTION

4.1. INTRODUCTION

ECG signal analysis is widely used for diagnosing many cardiac diseases. Since most of the useful clinical information in the ECG signal is found in the intervals and amplitudes defined by its significant points (characteristic wave peaks and boundaries), Wavelets have been applied to several problems in electro cardiology including detection of ECG characteristic points and in the analysis of ventricular late potential. Previous approaches reported for R peak (QRS complex) detection include non linear filtering followed by non linear transformation with threshold, matched filters, second order derivatives, slope criteria, adaptive filtering, wavelet transform, and artificial neural network. Many of the methods available in the literature use a common approach to detect QRS complex, consume less time and are easy to implement but the main drawback of these methods are that the frequency variation in QRS complexes affect their performance. The frequency band of QRS complexes generally overlaps the frequency band of noise resulting in both false positive and false negative. Methods using artificial neural networks are time consuming due to the use of grammar and inference rules whereas wavelet based methods are found to be a promising tool for good estimation of time and frequency localization. Some of the algorithms presented in these methods can only be used to obtain a subset of the ECG characteristic points. The development of accurate and robust algorithm for automatic detection of significant points is the subject of major importance.
Analysis of the signal at various resolutions is accomplished by decomposing the signal into elementary functions that are well localized both in time and frequency domain. Dyadic DDWT is used to decompose the pre-processed ECG signal. Second levels approximation coefficients are used to reconstruct the signal. Squaring and threshold the reconstructed signal is used to detect the R peaks. The correction procedure is followed to detect the correct R peaks and to remove the pseudo R peaks. Then QRS complexes are detected by using window or slope criteria. Fifty two records from the MIT-BIH arrhythmia data base are used to evaluate the performance of the proposed method.

The main objectives of this QRS complex detection are as follows:

- Detect the correct R peaks
- Remove the pseudo R peaks
- Extract of QRS complex along with their onset and off set without distorting the P and T waves and smooth transition of the ST-T segment.

This chapter explains the DDWT based R peak (QRS complex) detection, heart rate calculation and Poincaré plot. Peaks of the R waves in the ECG signals have the largest amplitude among other waves. In order to detect the R peaks, specific approximation of the signal is selected. The performance of the proposed QRS complex extraction is evaluated by using the parameters such as Sensitivity (Se (%)) and Positive Prediction (PP (%)).
4.2. QRS COMPLEX DETECTION

Fig. 4.1 shows the block diagram of the proposed QRS complex detection method. The pre-processed ECG signal is used as an input signal. Two-level forward dyadic DDWT is applied to decompose the input signal. The reconstruction of the signal is obtained by using the second level approximation coefficients and applying IDDWT. To make the R peak significant, the reconstructed signal is squared. To separate the R peaks, threshold is applied and a local maxima is obtained with the respective position. Then from the location of the R peaks the RR interval is calculated. The correct R peaks are extracted and pseudo R peaks are removed. From the location of the correct R peaks, the correct RR interval is calculated and QRS complex is extracted.

**Fig. 4.1 Block diagram of the proposed QRS complex detection method**

4.2.1. R Peak Detection

ECG signal has most of its energy contained in its low frequencies. The energy of the QRS complex lies between 3Hz to 40Hz. Wavelet transform provides multi resolution
analysis of the original signal. Multi resolution analysis is designed to give good time resolution and poor frequency resolution at high frequencies and good frequency resolution and poor time resolution at low frequencies. This approach makes sense especially when the signal at hand has high frequency components for short duration and low frequency components for long duration. Energy spectrum of the wavelet functions is concentrated in low frequencies as it is in the case of ECG signal.

Peaks of the R waves in the ECG signal have the largest amplitude among other waves. In order to detect the R peaks, specific approximation of the signal is selected. The procedure for the R peak detection is as follows:

1. Apply two-level forward dyadic DDWT to decompose the pre-processed ECG signal.
2. Retain the second level wavelet approximation coefficients and discard all the wavelet detail coefficients.
3. Apply IDDWT for step 2 to reconstruct the ECG signal.
4. Square the reconstructed signal.
5. Obtain the maximum value of the squared signal.
6. If sample value \( (i) \geq 0.133 \) times of the maximum value and sample value \( (i) > \) sample value \( (i+1) \), retain the sample value \( (i) \) and its position else retain the sample value \( (i+1) \) and its position (for R peak detection).
7. Obtain the RR interval time series.
8. If successive R peak < threshold, retain the R peak with maximum value and its position and discard the other else retain the R peak as it is (for correct R peak detection). This threshold value is signal dependent.

Detection of R peaks is very important because they define the cardiac beats and the exactness of all forthcoming detections.

4.2.2. Q and S Waves Detection

Q and S peaks occur about the R peak within 0.12 second. In order to make the peaks noticeable, the signal reconstructed using the approximation coefficients of level two \(2^2\) is used. Then a window of size 60ms is set before the R peak and minimum of the signal is searched. This point / position denotes the Q wave or the onset of the QRS complex. Similarly a window of the same size follows the R peak and the position of the minimum of the windowed portion denotes the S wave or the offset of the QRS complex. If the minimum value is less than the previous value and the next value, then the QRS complex with are extracted from the onset and offset of the QRS complex, otherwise it is extracted using the slope detection procedure. A normal QRS complex indicates that the electrical impulse has progressed normally from the bundle of His to the Purkinje network through the right and left bundle branches and that normal depolarization of the right and left ventricles has occurred.

The procedure for Q and S waves' detection is as follows:

1. Use the reconstructed signal used for R peak detection

2. Keep the position of the R peak
3. Set a window of size 60ms before the R peak and obtain minimum of the signal and its position (i.e.: sample (i))
4. If the minimum that is the sample (i) < sample (i+1) and sample (i-1), then register the position as the onset of the QRS complex (Q wave) else go to step 7
5. Set a window of size 60ms after the R peak and obtain minimum of the signal and its position (i.e.: sample (i))
6. If the minimum that is the sample (i) < sample (i+1) and sample (i-1), then register the position as the offset of the QRS complex (S wave) go to step 9 else go to step 8.
7. Apply slope detection before the R peak to detect the Q wave or the onset of the QRS complex
8. Apply slope detection after the R peak to detect the S wave or the offset of the QRS complex. (For wider QRS complex)
9. QRS width is calculated from the onset and the offset of the QRS complex. It is defined as the difference between the Q and the S wave positions.

The normal value of QRS width ranges from 60 milliseconds to 120 milliseconds.

4.2.3. Heart Rate Calculation

Heart rate is a term used to describe the frequency of the cardiac cycle. It is calculated as the number of contractions (heart beats) of the heart in one minute and expressed as Beats per Minute. The heart rate is calculated using the formula

\[
\text{Heart Rate} = \frac{60}{RR_{int}}
\]  

(4.1)

Where \( RR_{int} \) is the difference between successive R peaks in seconds.
Resting Heart Rate (RHR) is a term used to describe a person’s heart rate when he/she is not performing any activities. It is best measured in the morning, before even getting out of bed. A person's resting heart rate typically rises with age. Fit people generally have lower RHR, so it is often used as a measure of fitness. Elite endurance athletes have resting heart rate less than 30 bpm. Measuring RHR every day is a good way of detecting possible illness, as the RHR will be elevated by 8-10 beats if the immune system is attempting to fight something. When resting, the adult human heart beats at about 70 bpm for males and 75 bpm for females. This rate varies from subject to subject. Resting heart rate can be significantly lowered in athletes, and significantly higher in obese. The body can increase the heart rate in response to a wide variety of conditions in order to increase the cardiac output (the amount of blood ejected by the heart per unit time). Exercise, environmental or psychological stress can cause the heart rate to increase above the resting rate.

Maximum Heart Rate (MHR) is the heart rate that a person can achieve during maximal physical exertion. Research indicates that it is most closely linked to a person's age; a person's MHR will decline as they age. Some research indicates the speed at which it declines over time is related to fitness. More fit a person is, the slower it declines as they age. However, the reference range is nominally between 60 bpm to 100 bpm.

4.2.4. Heart Rate Variability

Heart rate variability (HRV) is the variation of beat-to-beat intervals (RR intervals). A healthy heart has a large HRV, while decreased or absent variability may indicate cardiac disease. HRV also decreases with exercise-induced tachycardia. One
aspect of heart rate variability is used as a measurement of fitness, specifically the speed at which one's heart rate drops upon termination of vigorous exercise. The speed at which a person's heart rate returns to resting is faster for a fit person than an unfit person. A drop of 20 bpm is typical for a healthy person [132-136].

Heart rate variability is concerned with the analysis of the intervals between heart beats. An emerging analysis technique is the Poincaré plot, which takes a sequence of intervals and plots each interval against the following interval. The geometry of this plot has been shown to distinguish between healthy and unhealthy subjects in clinical settings. The Poincaré plot is a valuable HRV analysis technique due to its ability to display nonlinear aspects of the interval sequence. Poincaré plot provides summary information as well as detailed beat-to-beat information on the behavior of the heart. Poincaré plot is becoming a popular technique due to its simple visual interpretation and its proven clinical ability as a predictor of disease and cardiac dysfunction.

Statistically, the plot displays the correlation between consecutive intervals in a graphical manner. Nonlinear dynamics consider the Poincaré plot as the two-dimensional (2-D) reconstructed RR interval phase-space, which is a projection of the reconstructed attractor describing the dynamics of the cardiac system.

The RR interval Poincaré plot typically appears as an elongated cloud of points oriented along the line-of-identity. The dispersion of points' perpendicular to the line-of-identity reflects the level of short-term variability. The dispersion of points along the line-
of-identity reflects the level of long-term variability. The Poincaré plot is analyzed quantitatively by calculating the standard deviations of the distance of the $RR_{int}$ to the $y = x$ line and $y = -x+2*RR_m$ line where $RR_{int}$ is the RR interval and $RR_m$ is the mean of all $RR_{int}$ and the Standard Deviation (SD) is referred to as SD1 and SD2, respectively. SD1 is related to the fast beat-to-beat variability or short-term variability and SD2 described longer-term variability of $RR_{int}$. The ratio (SD1/SD2) is computed to describe the relationship between these components. For normal subject this ratio is less than one and for abnormal subject this ratio is greater than one.

4.3. PERFORMANCE MEASURES

Sensitivity and Positive Prediction are used as performance measures. These two parameters are calculated using the following equations

- Sensitivity $Se(\%) = \frac{TP}{(TP+FN)} \times 100$ (4.2)
- Positive Prediction $PP(\%) = \frac{TP}{(TP+FP)} \times 100$ (4.3)

Where TP is number of true positive (correct) detection, FP is number of false positive (wrong) detection and FN is number of false negative (missed) detection.

4.4. EXPERIMENT RESULTS AND DISCUSSIONS

Fifty two records from MIT-BIH arrhythmia database are used to evaluate the proposed method. All records are sampled at 360 Hz with 11-bit resolution. In the pre-processing stage, the ECG signal is de-noised and the base line wandering is removed as discussed in the previous chapter. The pre-processed signal is used as an input signal. Peaks of the R waves in the pre-processed ECG signal have the largest amplitude among
other waves. The R peak is predominant in the second level approximation since the energy of the QRS complex lies between 3Hz to 40Hz. Using the proposed method, the correct R peaks are detected and the pseudo R peaks are removed / discarded. The RR interval time series is generated. Using equation (4.1) the heart rate of the ECG signal is calculated.

Fig. 4.2. Performance of the proposed method for Record 100
(a) Pre-processed ECG Signal – Record 100
(b) Reconstructed ECG Signal - R peak Detection – Record 100
(c) Squared the Reconstructed ECG Signal - R peak Detection – Record 100
(d) Heart Rate Variation – Record 100

Then the Q and S waves are detected using the proposed method. The reconstructed signal used for Q and S wave detection is same as that of R peak detection.
QRS width is calculated from the onset and the offset of the QRS complex. It is defined as the difference between the Q and the S wave positions. For a normal person the value of the QRS width ranges from 60 milliseconds to 120 milliseconds.

Fig.4.2, Fig.4.3 and Fig.4.4 show the performance of the proposed method for three different records 100, 117 and 213 respectively for duration of 45.51 second. In all the three figures, the first one (Fig.4.2 (a), Fig.4.3 (a) and Fig.4.4 (a)) shows the pre-processed ECG signal. After pre-processing the ECG signal must have the region other than P wave, QRS complex and T wave in the base line. This is clearly verified for all records. The second one (Fig.4.2 (b), Fig.4.3 (b) and Fig.4.4 (b)) shows the reconstructed signal for R peak / QRS complex detection as per the proposed method and the third one (Fig.4.2 (c), Fig.4.3 (c) and Fig.4.4 (c)) shows the squared signal for perfect R peak detection. From the R peaks, the correct R peaks are extracted.

From the correct R peaks the RR interval time series is generated by using the difference between the successive RR intervals. The heart rate variation is plotted as the fourth one (Fig.4.2 (d), Fig.4.3 (d) and Fig.4.4 (d)). From, the plots it is clear that for record 100, there is one abnormality (around 5 seconds) out of fifty six peaks and the e first peak is more abnormal out of eighty four peaks and heart rate is above the normal rate. For the same time interval all the three records have different number of RR intervals.
Fig. 4.3. Performance of the proposed method for Record 117

(a) Pre-processed ECG Signal – Record 117
(b) Reconstructed ECG Signal - R peak Detection – Record 117
(c) Squared the Reconstructed ECG Signal - R peak Detection – Record 117
(d) Heart Rate Variation – Record 117

The sensitivity and positive prediction are used as performance measures. These two parameters are calculated by using the equation (4.2) and equation (4.3) respectively. This method detects the R peak with 100% Sensitivity and 99.5% Positive Prediction.
Fig. 4.4. Performance of the proposed method for Record 213

(a) Pre-processed ECG Signal – Record 213
(b) Reconstructed ECG Signal - R peak Detection – Record 213
(c) Squared the Reconstructed ECG Signal - R peak Detection – Record 213
(d) Heart Rate Variation – Record 213

Fig. 4.5. Poincaré plot (Normal Subject)
Heart rate/ heart rate variability is used to classify the abnormal subject from the normal subject. It is a graphical presentation of the correlation between consecutive RR intervals. The standard deviation of the points' perpendicular to the line-of-identity denoted by SD1 describes short-term variability. The standard deviation along the line-of-identity denoted by SD2 describes long-term variability. Heart rate variability is analyzed by using the Poincaré plot. Fig.4.5 and Fig.4.6 show the Poincaré plot for a normal subject and abnormal subject respectively. The ratio SD1/SD2 for normal subject is typically 0.65 and it varies from 0.36 to 0.94.

4.5. PERFORMANCE COMPARISON

Table 4.1 gives the number of R peaks / QRS complex detected out of annotated peaks in the MIT-BIH arrhythmia data base. The sensitivity and positive prediction are used as performance measures. This table also gives the performance comparison of this method with other methods exists in the literature.
Table 4.1 Performance Comparison of QRS Complex Detection

<table>
<thead>
<tr>
<th>S.No</th>
<th>QRS Detector</th>
<th>Annotations</th>
<th>TP</th>
<th>FP</th>
<th>FN</th>
<th>Se in %</th>
<th>PP in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Proposed Method</td>
<td>107925</td>
<td>107925</td>
<td>53</td>
<td>Nil</td>
<td>100</td>
<td>99.95</td>
</tr>
<tr>
<td>2.</td>
<td>Bahoura et al (WT)</td>
<td>109635</td>
<td>109819</td>
<td>135</td>
<td>184</td>
<td>99.83</td>
<td>99.88</td>
</tr>
<tr>
<td>3.</td>
<td>Li et al (WT)</td>
<td>104070</td>
<td>104182</td>
<td>65</td>
<td>112</td>
<td>99.89</td>
<td>99.94</td>
</tr>
<tr>
<td>4.</td>
<td>Afonso et al</td>
<td>90535</td>
<td>90909</td>
<td>406</td>
<td>374</td>
<td>99.59</td>
<td>99.56</td>
</tr>
<tr>
<td>5.</td>
<td>Pan et al</td>
<td>109532</td>
<td>109809</td>
<td>507</td>
<td>277</td>
<td>99.75</td>
<td>99.54</td>
</tr>
</tbody>
</table>

Pan et al reported the sensitivity as 99.75% and positive prediction as 99.54%, Afonoso et al reported the sensitivity as 99.59% and positive prediction as 99.56%, Li et al reported the sensitivity as 99.89% and positive prediction as 99.94% and Bahoura et al reported the sensitivity as 99.83% and positive prediction as 99.88%. Totally 107925 R peaks are used from 52 records and the proposed method detects 107978 R peaks, out of these 107925 are correct R peaks (True Positive) and 53 are wrong R peaks (False Positive). This proposed method did not miss any R peaks or False Negative is zero. This method detects the R peak with 100% Sensitivity and 99.95% Positive Prediction. Since sensitivity and positive prediction are improved in the proposed method, this method is more suitable to detect the R peak / QRS complex as compared to other methods exist in the literature.

4.6. CONCLUSION

The proposed method is very efficient in detecting the R peaks of ECG signal. Forward dyadic DDWT is used to decompose the pre-processed ECG signals. The R peak
is predominant in the second level approximation since the energy of the QRS complex lies between 3 Hz to 40 Hz which needs low level of decomposition for faster implementation of the wavelet filters. The absence of very low (< 2 Hz) and very high (> 40 Hz) frequency components of the ECG signal helps to detect the correct R peaks. Keeping the second level approximation ($2^2$) for reconstruction and making the square of the reconstructed signal lead to a better detection of R peaks. That is the original shape of the signal especially the sharp Q, R and S peaks, without distorting the P and T waves is preserved. The proposed method achieves good R peak / QRS complex detection performance (100% Sensitivity and 99.95% Positive Prediction) for the MIT – BIH arrhythmia database as compared to other methods exist in the literature. These features make the proposed method an attractive choice to detect R peak / QRS complex from the ECG signal automatically. This can also help to classify the abnormal person from normal person using the heart rate / Poincaré plot of the ECG signal.