Review of Heart Rate Variability Analysis and its Measurement

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Abstract

Electrocardiogram (ECG) illustrates the electrical activity in the heart, and is the most important physiological parameter that gives the correct assessment regarding the functioning of the heart. The QRS complex is a prominent waveform in an ECG that gives the basis for analyzing heart rate variability (HRV). HRV is referred as the beat-to-beat alterations in heart rate. Commercial devices these days provide preset computerized measurement of HRV, thus providing the cardiologist a simple tool for both research and clinical learning. For obtaining meaningful data from the ECG, a noise free inter-beat interval (IBI) time series is required to be extracted. This is realized by the use of standard peak detection algorithms. The aim of this paper is to describe the various QRS detection techniques to analyze HRV. In this paper reviews for various time and frequency domain HRV parameters are also included. The significance and meaning of these different measures of HRV are a potential area of research and clinical approaches toward pathological detection.

Keywords- *Heart rate, Heart Rate Variability - HRV, ECG, QRS complex, RR interval, IBI.*

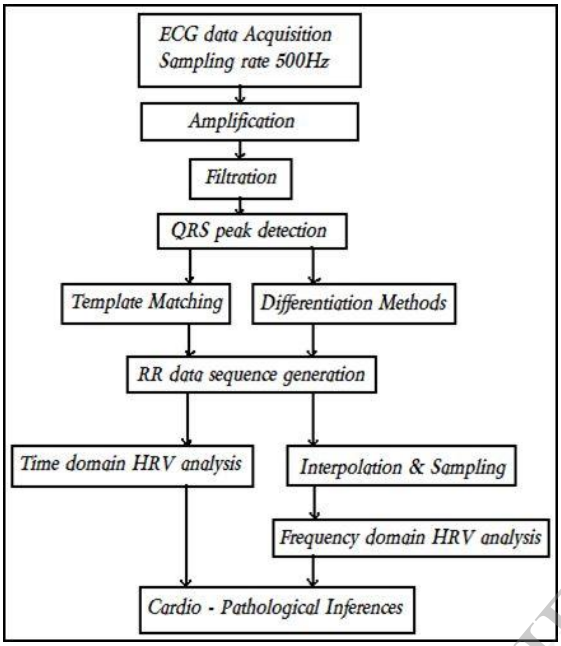
"1. Introduction"

ECG records are quantitative measures of the heart's electrical activity. ECG analysis has been widely and routinely used in safety assessment in drug development and medical diagnosis [1]. Corresponding to every heart beat in the ECG signal, the quasi-periodic sequence of P, QRS and T- wave can be observed. The QRS complex in this sequence is the most important parameter used for HRV analysis. As it has the highest amplitude and its peak detection helps in calculating the intervals between the two consecutive RR peaks. The variation in these RR intervals is referred to as the Heart Rate Variability (HRV). QRS detection therefore provides the fundamental for almost all automated ECG analysis algorithms as it is the measure parameter for analysis. Several algorithms for recognition of QRS complexes have been reported in literatures based on Pattern recognition [5], Hilbert transform[6], Wavelet transform [7], Neuro-fuzzy technique[8], Filtering method [9], Derivative based algorithms [10] etc. HRV is found to depend on various factors like gender, age, respiration and health status. Thus for a regular cardiac system, the heart rate may vary due to age, cardiac disease, neuropathy, respiration, maximum inhalation and cardiac load [11]. Heart Rate Variability has become the universally approved term to define variations of both instantaneous heart rate and RR intervals. Hence HRV may be used as a clinical and cost effective method to assess a patient's cardiac details. In this paper reviews of the basics of Heart Rate Variability and standard measurement techniques to detect QRS complexes from ECG waveforms are being included. Various time and frequency domain parameters used for analyzing HRV have also been discussed here.

"2. QRS Detection Methodology"

Various data acquisition systems are now available that accurately acquire and process physiological signals and capable of interface to a

computer [12]. Application software such as MATLAB and LabVIEW allow proficient realization of ECG processing algorithms. For acquisition of ECG signal, a three lead (RA, RL, LA- Lead I) arrangement is sufficient as it gives the maximum QRS complex. Once data is acquired, the detection of QRS complexes is achieved to evaluate the RR interval. A flow chart showing steps to be included for the acquisition and processing ECG signal for HRV analysis is shown in Fig.1.



"Figure 1. Flow chart for ECG acquisition, processing and HRV Analysis".

ECG signal is very much susceptible to artifacts caused due to power-line (AC) interference, electrode motion (em noise), baseline wander (BW), high frequency noise i.e. Electromyogram noises [1]. Most of the frequencies in the QRS complex are around 20 Hz. Thus a band pass filter in the 10 – 40 Hz range is used to remove low frequency noise such as baseline wandering and high frequency noises such as muscle artifacts. Mostly MIT/BIH arrhythmia database is used to evaluate the QRS detection algorithm. For testing this method MATLAB's Simulink can be used. For QRS detection commonly used algorithms are based on Template matching and Differentiation methods and are discussed here in subsequent sections.

2.1. Differentiation based Methods

2.1.1 Simple High Speed QRS Width Detection Algorithm. Differentiation is implemented in many QRS detection algorithms. The signal processing steps of differentiation based algorithm is shown in Fig 2. A derivative based algorithm developed by Hewlett-Packard Company for use in their computerized ECG system [2]. It is based on the empirical observation that the first and second derivative of the signal when rectified and added together, give a pulse for each QRS Complex. The width of the pulse is approximately equal to the QRS duration. Its realization is as follows [2].

1st derivative equation

$$y_0(nT) = x(nT) - x(nT - 2T) \quad \text{.....(i)}$$

2nd derivative equation

$$y_1(nT) = x(nT) - 2x(nT - 2T) + x(nT - 4T) \quad \text{.....(ii)}$$

Smoothing of 1st derivative after rectification

$$y_0^{sm}(nT) = \frac{1}{4}[\,|\,y_0(nT)\,|\,+2\,|\,y_0(nT - T)\,| + |\,y_0(nT - 2T)\,|] \quad \text{.....(iii)}$$

Smoothing of 2nd derivative after rectification

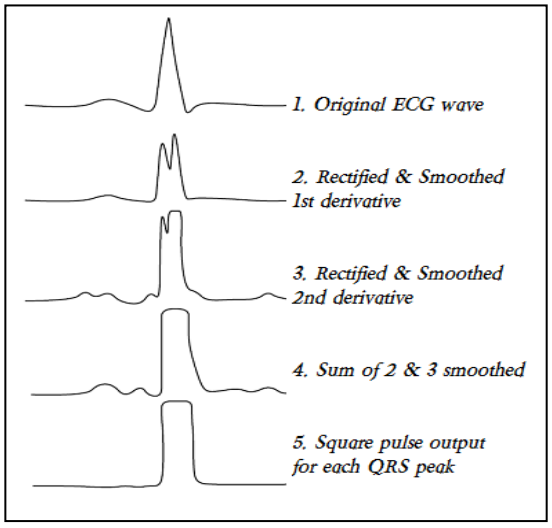
$$y_1^{sm}(nT) = \frac{1}{4}[\,|\,y_1(nT)\,|\,+2\,|\,y_1(nT - T)\,| + |\,y_1(nT - 2T)\,|] \quad \text{.....(iv)}$$

Scaling and summing of smoothed derivatives

$$y_2(nT) = 1.3y_0^{sm}(nT) + 1.1y_1^{sm}(nT) \quad \text{.....(v)}$$

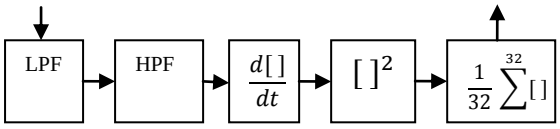
Thresholding to obtain rectangular pulse

$$y_2(iT) = V_{Th} \quad \text{.....(vi)}$$



"Figure 2. Steps for QRS detection based on Differentiation based method" [2].

2.1.2 High Speed QRS detection Algorithm. A real-time QRS detection algorithm was developed by Pan and Tompkins [18]. To attenuate noise in this method, the signal is passed through a band pass filter made of cascaded low-pass and high-pass filters. High slopes are found using differentiation, which distinguish the QRS complexes from other ECG waves. Then a nonlinear transformation that involves squaring of the signal samples is done to make the entire data positive before integration. It also highlights the higher frequencies in the signal obtained from the differentiation process. These higher frequencies denote the QRS complex. Then the squared waveform is passed through a moving window integrator and a decision is taken based on threshold detection.



"Figure 3. QRS detection using Pan and Tompkins method" [2].

LPF:

$$y(nT) = 2y(nT-T) - y(nT-2T) + x(nT) - 2x(nT-6T) + x(nT-12T) \quad \text{(vii)}$$

HPF:

$$y(nT) = y(nT-T) - x(nT)/32 + x(nT-16T) - x(nT-17T) + x(nT-32T)/32 \quad \text{(viii)}$$

Derivative:

$$y(nT) = (2x(nT) + x(nT-T) - x(nT-3T) + 2x(nT-4T))/8 \quad \text{(ix)}$$

2.2 Template Matching Methods

2.2.1 Template Cross-correlation. Cross correlation is defined as the degree of similarity or relation between two or more signal waveforms. A QRS detection technique based on template cross-correlation method is discussed by Dobbs et al [13]. This QRS detection technique, includes calculation of cross correlation (R_{xy}) between the incoming ECG data sequence and a template of QRS complex. Then the maximum value of R_{xy} is found to locate the QRS complex according to the property of the cross correlation. The incoming signal should be aligned with the template for correlation in two ways. The first way of aligning the template and the incoming signal is by using the fiducial points on each signal. These fiducial points have to be assigned to the signal by some external process. Another aligning process is done by continuous correlation between a segment of the incoming signal and the template. Whenever a new signal data point arrives, the oldest data point in time is discarded from the segment [2]. A correlation is performed between this signal segment and the template segment that has the same number of signal points. This technique does not require any processing time to assign fiducial points to the signal. The template is like a window that moves over the incoming signal one data point at a time [14]. Cross correlation is given by $r_{xy}(m)$ as

$$\begin{cases} \frac{1}{N}\sum_{n=0}^{N-m-1} x(n+n)y(n) : 0 \le m \le N-1 \\ \frac{1}{N}\sum_{n=0}^{N-|m|-1} x(n)y(n+m) : -(N-1) \le m \le 0 \end{cases}$$

2.2.2 Template Subtraction. This is a relatively simple QRS detection technique different from computing cross-correlation. A segment of the incoming ECG signal that corresponds to the QRS waveform is stored as the template. This template is then compared with the incoming ECG signal. Each point in the incoming signal is subtracted from the corresponding point in the template and results in a value close to zero. Small absolute values detected denote the location of QRS complex. The method is however prone to noise [14]. In this method we need extra pre-processing of the ECG signal to remove the noise [2].

"3.Heart Rate Variability"

3.1 Definition

The phenomenon that focuses on the oscillation in the interval between consecutive heartbeats as well as the oscillations between consecutive instantaneous heart rates is known as the Heart rate variability. Heart Rate Variability has become the conventionally accepted term to describe variations of both instantaneous heart rate and RR intervals. Hence, Heart rate variability (HRV) is the physiological phenomenon of variation in the time interval between heartbeats and it is measured by the variation in the beat-to-beat interval [1]. Heart rate variability (HRV) refers to the beat-to-beat alterations in heart rate. The interval between

adjacent QRS complexes is termed as the normal to normal (NN) or the R to R (RR) intervals. ECG of healthy individuals exhibits periodic variation in R-R intervals, under resting conditions. The HRV measurements are captured noninvasively from the ECG signal. The results obtained from HRV data are capable of portraying physiological condition of the patient moreover they are an important indicator of cardiac disease. Variability in heart rate is clinically linked to various lethal arrhythmias, hypertension, coronary artery disease, congestive heart failure, organ transplant, tachycardia, bradycardia, neuropathy, and diabetes etc. [11].

3.2 Analysis of HRV

3.2.1 Time Domain Analysis. The estimation of HRV can be done by the time domain measures. In real means the HRV was measured manually from the mean R-R interval in time domain and its standard deviation is measured on short-term 5 minute ECG segment. On the basis of these methods either the heart rate or each QRS complex or the RR intervals between successive normal complexes are determined and then analyzed. Simple time–domain variables include the mean RR interval, the mean heart rate etc., the difference between maximum and minimum heart rate. Table 1 shows detail of the various time domain parameters of HRV, their description & mathematical expressions [3] [4] [11].

"Table 1. Time domain parameters of HRV".

Parameter	Description & Mathematical Expression
NN 50 Count	No. Of adjacent RR intervals differing by more than 50 ms in entire ECG recording.
pNN 50	NN 50 count divided by total number of all RR Intervals. $pNN\ 50\% = [(\frac{NN\ 50}{N-1}) * 100]$
Max-Min	Difference between shortest and longest RR interval.
SDNN	Standard deviation of all RR intervals. $sdnn = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2$
SDNN Index	Mean of the standard deviations of all RR intervals for all 5 min segments in the entire recordings.
SDANN	Standard deviation of averages of RR intervals for all 5 min segments in the entire recordings.
RMSSD	Root mean square of the difference of successive RR intervals. $rmssd = \sqrt{[\frac{1}{N-1}\sum_{i=1}^{N-1}(x_{i+1} - x_i)^2]}$
SDSD	Standard deviation of differences between adjacent RR intervals. $sdsd = \sqrt{[\frac{1}{N}\sum_{i=1}^{N}(dx_i - \bar{dx})^2]}$
HRV Index	Total number of all RR intervals divided by amplitude of all RR intervals.

But the recordings for a longer period of 24 hours sometimes lead to complex statistical time-domain analysis. These statistical parameters may be derived from direct measurements of the RR intervals or from the differences between RR intervals. The simplest variable to calculate is square root of variance i.e. the standard deviation of the NN interval (SDNN).

3.2.2 Frequency Domain Analysis. Frequency Domain Analysis includes the frequency measures on the ECG data and frequency measures involve the spectral analysis of HRV. The RR interval time series are irregularly time-sampled signal and considered in the frequency domain but are not the issue for consideration in time domain. If the spectrum estimate is calculated from this irregularly time-sampled signal, additional harmonic components appear in the spectrum, and then interpolation is required. The RR interval signal is then interpolated before the spectral analysis so that they can recover an evenly sampled signal from the irregularly sampled event series. The HRV spectrum contains the high frequency (0.18 to 0.4 Hz) component, which is due to respiration and the low frequency (0.04 to 0.15 Hz) component that appears due to both the vagus and cardiac sympathetic nerves [11]. Ratio of the low-to-high frequency spectra is used as an index of parasympathetic sympathetic

balance. Frequency domain HRV variables are detailed in Table 2 [3] [4] [11].

"Table 2. Frequency domain parameters of HRV".

Parameter	Description	Frequency
	Absolute Measures	
Total Power	Variance of all RR intervals.	TP [ms^2] < = 0.4 Hz
ULF	Power in Ultra Low Frequency Range.	ULF [ms^2] < = 0.003 Hz.
VLF	Power in Very Low Frequency Range.	VLF [ms^2] = 0.003 Hz – 0.04 Hz.
LF	Power in Low Frequency Range.	LF [ms^2] = 0.04 Hz – 0.15 Hz.
HF	Power in High Frequency Range.	HF [ms^2] = 0.15 Hz – 0.4 Hz.
	Relative Measures	
VLF Normalized	Normalized Very Low Frequency Power.	VLF_n [%] = (VLF/TP)*100.
LF Normalized	Normalized Low Frequency Power.	LF_n [%] = (LF/TP)*100.
HF Normalized	Normalized High Frequency Power.	HF_n [%] = (HF/TP)*100.
Ratio of LF/HF	Ratio of Low and High Frequency.	.....

"4. Discussions"

QRS waves are the important parameter for HRV analysis. Hence precise RR interval calculations are mandatory to depict the physiological state accurately, and for smaller standard deviation of R-R intervals show the lower HRV. The accuracy of the R-wave occurrence time estimates is often required to be about 1 ms and thus, the sampling frequency of the ECG should be at least 500 Hz [11]. If the sampling frequency of the ECG is less than 500 Hz, the errors in R-wave occurrence times can cause critical distortion to HRV analysis results [22]. From several studies we came to know that there is a link between negative emotions (such as anxiety and hostility) and reduced HRV [21]. In normal subjects, both sympathetic and parasympathetic tone keeps on fluctuating throughout the day [23]. HRV is more at lower heart rates which shows that it is rate dependent [24]. HRV is sensitive and responsive to acute stress so mental load like making complex decisions lead to lower HRV. Resting heart rate does not change significantly with advancing age, but there is a decline in HRV. But we have seen that for an individual, the HRV is highest during sleep where as regular physical activity however lead to raise HRV. It has been seen that distinct spectral variations can be detected in human subjects according to varying postures or body angle. HRV studies of subjects on a tilt table can produce information about sympathetic and parasympathetic regulation of cardiac cycle and function. Power spectrum analysis of HRV may be used to describe the extent of sympathetic and vagal adaptation in patients. HRV data analysis provides additional insight into cardio-pathologies [11].

"Conclusion"

The analysis of HRV both by time-domain and spectral approaches offer a non-invasive method of evaluating cardiac functioning. The major reason for the interest in measuring HRV stems from its ability to predict survival after heart attack and hence the measurement of HRV is becoming increasingly standardized. Different studies in this field lead to different results and we came to know that reduced HRV predicts sudden death in patients. Although, the assessment of HRV requires expertise in this field a minor mistake may lead to different result which may totally different from the actual result. The requirement is only ECG equipment which is not so expensive, microprocessors, and relevant software for carrying out time and frequency domain analyses. Various experimental and simulation data appear to us indicates that the different methods of expressing HRV are largely equivalent to each other, and more over there is no evidence that any one method is superior to another, provided measurement windows are 5 minutes or longer so that the analyses for the HRV can be made with reliability and accuracy which can help us in pathological detection.

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