A Literature Survey on Heart Rate Variability and its Various Processing and Analyzing Techniques

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Abstract – *Human heart being the electro-mechanical pump supplies blood via a cardiovascular network. Its rhythmic beating gives rise to a pattern which when recorded can be used to find out the functionality of a heart. The diagnostic tool is called as Electrocardiogram (ECG) and its tracing contains a lot of attributes whose proper analysis may detect any cardiac peculiarity. Among them, is an entity called as the beat-to-beat interval (R-R interval). The analysis of beat to beat fluctuations of heart rate is known as heart rate variability (HRV) which is a concise marker to study the health of the heart along with a lot of measures clinically. This paper talks about the importance of the HRV and the various processing yet analysis techniques used to calculate the HRV by researchers.*

Key Words: **ECG, Heart Rate, IBI, HRV, ANS**

1. INTRODUCTION

The human heart is a muscular organ that pumps blood through blood vessels via the network of cardiovascular system. The regular rhythmic beating is a result of the contraction and relaxation of the muscle tissue of the heart between 60 to 100 times per minute (BPM). The movement of ions constitutes the electrical signals which results in a combination of several consecutive cardiac cycles due to the depolarization and repolarization of the ions in the blood including a fairy period of waves, segments and intervals corresponding to the consecutive heart action phases. The representation of this electrical activity of the heart in exquisite detail is measured in terms of a diagnostic tool called as the Electrocardiogram (ECG) which was invented by Willem Einthoven in 1903 in Netherlands.

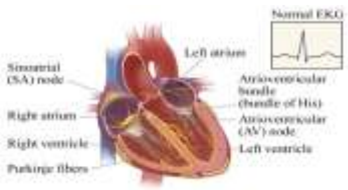

Fig -1: The Human Heart (Electrophysiological View)

Usually the ECG is recorded in an image consisting of all 12 channels or lead recordings interlaced by 3 second intervals from combinations of leads per row; (First row: I, AVR, V1, V4, Second row: II, AVL, V2, V5, Third row: III, AVF, V3, V6). The R-Peak is considered to be the most important fiducial point in the signal due to its larger amplitude and proper detection of the R-Peak is said to have a major contribution in determining a fundamental feature called as the RR interval or the inter-beat interval (IBI), which is one of the strongest driving factor in analyzing an ECG signal. Among all these attributes, the most important entity used to determine the heart rate variability (HRV) is the R-R interval which is obtained by finding out the distance between one R-peak and the next R-peak (successive R's).

The trace of an ECG consists of the following attributes as mentioned in the table:

Table -1: Features in an ECG Signal

Waves/Peaks	P, Q, R, S, T, U
Segments	PQ or PR, ST
Intervals	PQ or PR, R-R, P-P, QT, QU, TP, TQ
Complex & Points	J Point, QRS Complex

An efficient analysis of this parameter could help in accurate determination in the cardiovascular studies.

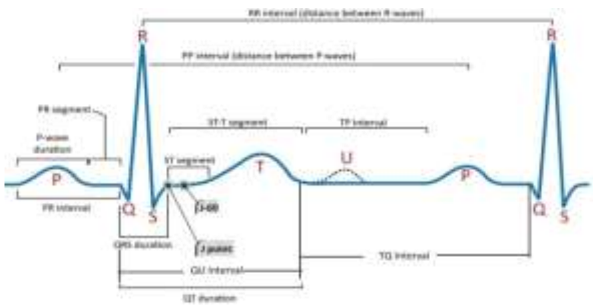

Fig -2: The ECG Waveform

2. THE CLINICAL IMPORTANCE OF THE HRV BACKGROUND

A nerve impulse stimulus to the heart generates an ECG which is a basic pattern of the electrical signal that varies as per the functioning of the heart [1, 2]. Earlier it was believed that the heart beats at a fixed rate until the discovery of the technology stated that there is some amount of variability present in the measurement of the heart rate. Heart rate is an indicator of how fast the person's heart could beat in a minute at regular rhythmic intervals. Within any given time period, the IBI is ever varying. HR is not constant, and presents variations as a means to adapt internal and external stress factors [24].

Autonomic regulation of heart results in Heart Rate Variability (HRV) [3]. HRV could be defined as a non-stationary signal that changes with time or varies between successive heart beats over time. Multiple biological rhythms overlay one another to produce the resultant pattern of variability. This variability in heart rate is an adaptive quality in a healthy body whose changes can be an indicative of the upcoming or the current peculiarity or disease [5].

HRV is a noninvasive marker relevant for physical, emotional, and mental function and is affected by its relevant experiences. Though the age, gender, lifestyle, sleep, nutrition, social situation, work situation, medications, environment, smoking status, the use of hormone therapy, body mass index (BMI), resting blood pressure, fasting concentrations of lipids and glucose can all play a role in HRV yet internal processes like circadian rhythm and hormonal fluctuations cause HRV to slowly rise and fall over the course of 24 hours [4, 7]. Although patterns of HRV hold considerable promise for clarifying issues in clinical applications, the inappropriate quantification and interpretation of these patterns may obscure critical issues or relationships and may impede rather than foster the development of clinical applications [24].

Current research suggests that each individual has a resonant frequency at which heart rate variability is the greatest, and this resonant frequency can be measured by biofeedback instruments. While there is no uniform ideal value for all persons, this resonant frequency is most frequently produced by persons in a relaxed mental state, with a positive emotional tone, breathing diaphragmatically at a rate of about 5-7 breaths per minute. Psychophysiological research suggests that these frequency ranges reflect different biological influences. The high frequency range is associated with parasympathetic pathways, the influences of respiration in normal frequencies on vagal tone. The low frequency range is associated with the influence of blood pressure (baroreceptors) on heart rhythms, and meditative/slow breathing augments this range. The very low frequency range is associated with sympathetic activation, or more probably the withdrawal of parasympathetic braking, and also the influences of visceral and thermal regulation. Studies have also shown that clinical depression lowers heart rate variability [5].

HRV can be helpful in analyzing a number of conditions, some of it to be mentioned would be:

- HRV analysis reflects the interplay of the sympathetic and vagal components of the autonomic nervous system (ANS) on the sinus node of the heart [24].
- Measurement of HRV helps in evaluating cardiac autonomic regulation and thus provides significant information regarding cardiac irregularities or injuries.
- It also provides quantitative information about the modulation of cardiac vagal and sympathetic nerve activities and information about the sympathetic parasympathetic autonomic balance.
- It is one of the most crucial markers proven to be beneficial in obtaining reliable stress diagnosis and its related disorders.
- Estimation of the anxiety or being extremely fatigue or drowsiness with respect to the autonomous nervous system activity can be detected using the HRV.
- Also, heart valvular defects can be figured out using the concept of HRV.
- Since HRV demands the heart rate to be increased with the increase in the physical activity, it can prove to be a good entity in determining the health and the flexibility of the human heart muscles along with the indication of proper blood flow through them.
- Reduced cardiac parasympathetic activity, indicated by a reduced level of high-frequency heart rate variability (HF-HRV), is associated with an increased risk for atherosclerosis and coronary artery disease along with calcification [7].
- Lower variability in heart rate predicts a greater risk for death after a heart attack.
- Changes in the rhythms of the heart occur before a fetus goes into distress may predict sudden infant death [5].
- Cardiac autonomic neuropathy, frequently detected as a reduced HRV, has been associated with increased mortality in diabetes and aging.
- It is also used to detect Arrhythmias. In clinical practice, low HRV suggests increased susceptibility to cardiac arrhythmias secondary to autonomic imbalance [9, 19].
- Recent research also states that cancer at early stages can be detected using HRV. Patients with rejection documented biopsy show acquisition significantly more variability [8, 21].
- The clinical use of HRV is also found to be predictive in case of Myocardial Infarction, Hypertension, Chronic Obstructive Pulmonary disease and Apnea [3].
- ANS is tied closely to processes in the body such as digestion and inflammation. This means that HRV can actually help a person detect when a diet is eliciting a negative physiological response prior to symptoms arising [20].

- HRV is also useful in determining blood pressure regulation, renal failure, humoral cardiac factors, and sinus node characteristics.

3. THE HRV DETECTION TECHNIQUES

One measure of heart rate variability is the difference between the highest heart rate and the lowest heart rate within each cardiac cycle, measured in beats per minute. This index is called HR Max – HR Min.

A second index of Heart Rate Variability, widely used in medical research is the Standard Deviation of the N-to-N interval. The N-to-N interval is the normalized beat-to-beat interval. The SDNN is the standard deviation of those intervals, a measure of their variability. A third index of variability is called pNN50. This index measures what percent of the Inter-beat Intervals differ from neighboring intervals by 50 milliseconds or more [5].

As the literature on heart rate variability (HRV) continues to burgeon, so does the detection and processing techniques, few of which are discussed below:

In a paper proposed by Klaudia PalaK et al, the influence of Deep Breathing on ANS activity in professional swimmers and non-trained persons was evaluated based upon the changes in Heart rate, or so to say the HRV. Since R-R interval is the main entity required to calculate the HRV, here the IBI interval was detected using certain HRV indices like the Mean — arithmetic mean, SD — standard deviation, mRR — average R-R interval of the sinus rhythm, SDNN — standard deviation of the average R-R intervals of the sinus rhythm, rMSSD — square root of the mean squared difference of successive R-R intervals, pNN50 — proportion of successive R-R intervals that differ by more than 50 ms, TP — total spectral power at the whole range of frequencies (0.0033–0.15 Hz), LF — low-frequency component (0.04–0.15 Hz), HF — high-frequency component (0.15–0.4 Hz), LF/HF — low-frequency to high-frequency component ratio. The differences between dependent variables were analyzed with the Wilcoxon test, while the differences between the experimental and the control group were tested with the non-parametric Mann-Whitney U test. The analysis was conducted with SPSS v.17 software.

The changes in heart rate variability were more pronounced during deep breathing test. Both their findings and literature data suggest that physical training is reflected by greater heart rhythm variability and trained individuals were characterized by greater variability of sinus rhythm than non-trained persons not only at rest but also in response to ANS stimulation [22].

In a paper proposed by Guger C et al, heart rate variability was shown to be used as a parameter that reflected the physiological state of the participant. And this physiological measure was used to describe the state of Presence in a virtual environment. In order to detect the HRV, the ECG was analyzed using the g.BSanalyze biosignal analysis software package. First detection of QRS Complex was done in order to find the IBI or the NN interval using the modified Pan Tompkins Algorithm. And then important features were calculated in time and frequency domains. The time domain measures were MeanRR - mean RR interval [ms], SDNN - standard deviation of NN intervals [ms], MaxRR - maximum RR interval [ms], MinRR - minimum RR interval [ms], MinMaxRR - difference between MaxRR and MinRR [ms], MeanHR - mean heart rate [bpm], SDHR - standard deviation of the heart-rate [bpm]. The segmented measures divided the recorded ECG signal into equally long segments to calculate SDANN - standard deviation of the average NN interval calculated over short periods, SDNNindex - mean of e.g. 1 min standard deviation of NN intervals calculated over total recording length which yielded differences between adjacent intervals determining the SDSD - standard deviation of successive NN differences [ms], RMSSD - square root of the mean squared difference of successive NN intervals [ms], NN50 - number of intervals of successive NN intervals greater than 50 ms, PNN50 - NN50 divided by the total number of NN intervals. Frequency domain measures provided information on how power was distributed as a function of frequency. RR time series were resampled with a frequency of 2 Hz. Then the power spectrum of the resampled time series was estimated with the Burg method of order 15. The RR sequence was detrended and a Hanning window was applied prior to the spectrum estimation which was followed by FFT. Therefore it was argued that the change was not initiated by dynamic exercise. Furthermore, an increased LF component and a decreased HF component normally indicated mental stress. A standard Einthoven I ECG derivation was used to calculate the HRV and event-related ECG to describe the physiological state of participants in VR environments [23].

Butta Singh et al proposed a paper where in commercial, online, portable software tool was used in HRV analysis and cardiovascular research. HRV parameters were categorized in time domain, frequency domain, time-frequency and non-linear methods. Time domain methods included estimation of variables such as the standard deviation of the normal-to-normal (NN) intervals (SDNN), square root of the mean of the sum of the squares of differences between adjacent NN intervals (rMSSD), percent of the number of pairs of adjacent NN intervals differing by more than 50 ms (pNN50). Another time-domain measure of HRV was the triangular index; a geometric measure obtained by dividing the total number of all NN intervals by the height of histogram of all NN intervals on a discrete scale with bins of 7.8125 ms. Frequency domain methods included spectral analysis. Both the methods were highly nonlinear, random and complex. Due to which time and frequency measures of HRV were not able to detect subtle, but important changes in the HRV. Therefore, nonlinear methods were developed to quantify the dynamics of HR fluctuations. As mentioned about few included a non-linear complexity index developed by Pincus called approximate entropy (ApEn), to quantify the randomness of physiological time-series. Richman and Moorman developed and characterized sample entropy (SampEn), a new family of statistics, measuring complexity and regularity of clinical and experimental time-series data and compared it with ApEn. The long-term variability of HRV (SD1) was also derived from Poincaré plots. Software tools like Kubios, GHRV, KARDIA, VARVI, RHRV, ARTiiFACT, Lab View, POLYAN, aHRV were used to analyze the HRV [24].

In a paper proposed by George E. Billman et al similar methodological considerations like time domain, frequency domain, and non-linear dynamic analysis techniques were used to analyze HRV as in [24] paper [25].

In a paper proposed by Mohamed Faisal Lutfi, results confirmed that degree of asthma control influenced pattern of autonomic modulations/HRV among AS. Frequency domain analysis and statistical methods were used to determine HRV [26].

Similar approach was applied in a paper proposed by GD Jindal et al where they assessed the ANS with respect to HRV. And similar time, frequency domain methods and non-linear methods were used to detect HRV [27].

Payal Patial et al [28] and Elio Conte [29] proposed a paper to analyze HRV using similar methods as described in [27].

Ivana Gritti et al proposed a paper where comparison between heart rate variability (HVR) and its components during sleep at low altitude and after 30 - 41 hours of acclimatization at high altitude (3480 m) in five mountain marathon runners controlled for diet, drugs, light-dark cycle and jet lag were done. Automatic analysis of HRV values was performed using Somnological 3 software (Embla), autoregressive model, order 12, following the rules of the Task Force. Also frequency domain methods and statistical analysis were done in order to analyze the HRV [30].

Sylvain Laborde et al proposed a paper with an aim of providing the field of psychophysiology with practical recommendations concerning research conducted with HRV, specifically highlighting its ability to index cardiac vagal tone, which is relevant for many psychophysiological phenomena, such as self-regulation mechanisms linked to cognitive, affective, social, and health. They believed that non-linear analyses might be more adequate and precise for HRV analysis than the prevalent linear measures. One of those linear indices was the Poincaré plot. The plot itself displays the correlation of R–R intervals by assigning each following interval to the, respectively, former interval as a function value (autocorrelation). The result was a plot which illustrated quantitative and qualitative patterns of one's individual HRV in the shape of an ellipse [31].

U. Rajendra Acharya et al proposed a paper wherein they have discussed the various applications of HRV and different linear, frequency domain, wavelet domain, nonlinear techniques used for the analysis of the HRV. Time-dependent spectral analysis of HRV using the wavelet transform was found to be valuable for explaining the patterns of cardiac rate control during reperfusion [32].

In a paper proposed by Károly Hercegfi, HRV monitoring was done during the Human Computer Interaction. The paper presented new results of a short, basic series of experiments, attempting to explore the boundaries of the temporal resolution of the method. The applied INTERFACE methodology was based on the simultaneous assessment of HRV and other data. Here windowing function has been used in order to find out the R-R interval to calculate the HRV which was analyzed using the ISAX software [33].

In a paper by Marek Malik, measurement of HRV were done using time domain methods, statistical methods, geometrical methods, frequency domain methods using spectral components and non-linear methods. The parameters which were used to measure non-linear properties of HRV included 1/f scaling of Fourier spectra, H scaling exponent, and Coarse Graining Spectral Analysis (CGSA). For data representation, Poincarè sections, low-dimension attractor plots, singular value decomposition, and attractor trajectories were used. For other quantitative descriptions, the D2 correlation dimension, Lyapunov exponents, and Kolmogorov entropy were employed [34].

In a paper tackled by Sonia Rezk et al, the inter-beat intervals analysis was done using a new tool of estimation based on algebraic approach. Their idea focuses on the fact that the estimation of the R wave occurrence is considered as a Time Delay Estimation (TDE) problem. The technique detected the peaks by ignoring the peaks that preceded or followed larger peaks by less than a waiting time equal refractory period. The peaks higher than the detection threshold were termed as the R peak else noise. Also if there were no R peaks detected within 1.5 R-to-R intervals then back search was applied where if a peak higher than half the detection threshold followed the preceding detection by at least 360ms was termed as R peak. Then this IBI feature was used to calculate the heart rate and HRV [35 and 36].

E. A. Whitsel et al proposed a paper where in the QT interval index and the R-R interval variation were determined as the felt that it may improve characterization of sympathovagal control and could also estimate the risk of primary cardiac arrest. Here in, the R-R intervals were determined using calipers from ECG and QT interval were obtained using a large field anastigmatic lens with four fold magnification. The IBI interval was later used to calculate the RRV [39].

In a paper published by Mourot L, it was seen that non-linear HRV indices obtained from short RR intervals series (256 points) gave clinically valuable information in cardiac disease which highlighted the deficiency of the neurocardiac regulation. HRV analysis was conducted with the aid of Kubios HRV Analysis Software 2.0. For the time domain, the root mean square of successive RR interval differences (rMSSD) and the fraction of consecutive RR intervals that differ by more than 50 ms (pNN50) were reported. For the frequency domain, the normalized low frequency power, normalized high frequency power, and the LF/HF ratio were reported. For non-linear indices, approximate (ApEn) and sample (SampEn) entropy and the short-term fluctuations in the R-R interval data calculated by detrended fluctuation analysis (DFA) were reported. Statistical analyses were performed using SigmaStat software [40].

Vala Jeyhani et al proposed a paper wherein HRV parameters were compared which were derived from Photoplethysmography (PPG) and Electrocardiography Signals. Usually, IBI entity is basically used to derive the HRV. But recently it was also seen that PPG signal was proposed as an alternative for ECG in HRV analysis to overcome some difficulties in measurement of ECG. PPG signal is often recorded by using a pulse oximeter which emits light to skin and measures changes in light absorption. First, detection of R peaks was done using the Pan Tompkins algorithm and then IBI along with P-P interval were calculated followed by HRV and its parameters. Poincare plots were constructed by plotting the R-R interval signal as a function of itself with a delay of one sample [41].

Elio Conte et al proposed a paper wherein a new method for HRV analysis was described. Softwares of the Biopac System and the Nevrokard software were used for HRV analysis [42].

Kaufmann, T et al proposed a paper where software called as ARTiiFACT was used for heart rate artifact processing and heart rate variability analysis. ARTiiFACT included time- and frequency-based HRV analyses and descriptive statistics which offered the basic tools for HRV analysis. ARTiiFACT is designed to provide researchers with a software tool covering the complete range of data processing steps, from raw ECG data to deriving HRV parameters for statistical analysis. ARTiiFACT offered a convenient data interface to RSAtoolbox, a freely available implementation of peak-valley analysis of RSA. Detection of R peak was done using the same software. A window-based linear detrending method was implemented in order to purge data from long time drifts. HRV analyses were performed in both the time and frequency domains, which provided several highly correlated parameters indicating the extent of HRV [43].

In a paper proposed by Devy Widjaja et al, a study was presented where an advanced automated algorithm was used to preprocess RR intervals obtained from a normal ECG. The proposed technique attempted to recover correct RR intervals by summing consecutive small intervals and thus removing spurious R peaks. To check whether an interval is too small, a reference RR interval (RRref), which was empirically set as a weighted average of three previous RR intervals, was used for comparison which was used to analyze HRV [44].

Fluctuation in the time intervals between individual heart beats quantifies the variation in the heart rate (HRV). Though R-R is visually inspected, detection of proper R peaks is very significant. In a paper devised by Mirja A. Peltola, methods involved in editing or pre-processing R–R interval time series influences a change in HRV has been talked about with an addition of detecting R peaks using various algorithms. It is claimed that the true marker for HR is the P wave onset, since the P wave is a more accurate marker of onset of the atrial depolarization than the R peak. Due to the low amplitude and difficulty in detection of P wave, R peaks are considered as the most accurate markers for detection of HRV. Several algorithms like Hilbert Transform; Digital Filtering methods like Pan Tompkins and Hamilton and Tompkins; Pattern Recognition and Wavelet Transform have been found to be useful in detection of R peaks. No standardized procedures for detecting R peaks have been recommended but it was seen that high-quality R–R interval software helped in getting a visual view of the actual point positions in the ECG signal of the R peak detection process and the possibility to correct any false points was also stressed upon [45].

4. CONCLUSION

It was seen that a lot of methods were used to detect and analyze the HRV by researchers which included using many calculative methods. Various time domain, frequency domain and non-linear methods were used in this procedure. It was also seen that few softwares were used to analyze the HRV which also yielded accurate results along with the rest. HRV is an emergent marker used to detect a lot of cardiac factors and peculiarities. It is necessary to detect this feature appropriately and accurately. Future research heading in this direction is necessary with a larger sample size in order to accurately pinpoint the various heart defects individually.

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