Analysis of Heart Rate Variability Linked with Autonomic Nervous System

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ABSTRACT
The electrocardiogram (ECG) is a time-varying signal reflecting the ionic current flow which causes the cardiac fibres to contract and subsequently relax. The mammalian brain guides the body by regulating heart and other organs through autonomic nervous system. This physiological variation of heart rate, supervised by autonomic nervous system, is called Heart Rate Variability (also commonly known as HRV). The heart rate can be estimated from ECG and it has the greater significance in risk stratification in cardiovascular system. HRV can be analyzed by time domain, frequency domain and nonlinear methods. HRV can be used as a template to investigate the sympathetic and parasympathetic function of the ANS. The modulation of LF/HF ratio in frequency domain, short term and long term variability in nonlinear method constitute a novel technique to determine the status of human body.

Keywords— Heart rate variability (HRV), Autonomic nervous system (ANS), SDRR, RR tachogram, RMSSD, LF/HF

I. INTRODUCTION
The electrocardiogram (ECG) signal [1, 2] is one of the most important effects of the human heart operation. The oscillation between systole and diastole states of the heart is reflected in the heart rate (HR). The surface ECG is obtained by recording the potential difference between two electrodes placed on the surface of the skin. A single normal cycle of the ECG represents the successive atrial depolarization/repolarisation and ventricular depolarization/repolarisation which occurs with every heartbeat. These can be approximately associated with the peaks of P, Q, R, S, and T. Extraction of useful clinical information from the real (noisy) ECG requires reliable signal processing techniques. These include R-peak detection QT-interval detection, and the derivation of heart rate and respiration rate from the ECG [3, 4, 5]. The time between successive R-peaks is referred to as an RR-interval, and an RR-tachogram[6] is then a series of RR-intervals. Variability in this time series has been widely used as a measure of heart function, and this helps to identify patients at risk for a cardiovascular disease and death. Analysis of variations in this time series is known as heart rate variability (HRV) analysis. At present, new biomedical signal processing algorithms are usually evaluated by applying them to ECGs in a large database such as the Physio net database. While this always gives the user an indication of accuracy of a given algorithm when applied to real data, it is difficult to conclude how the performance would vary in different clinical settings with a range of noise levels and sampling frequencies. Having access to realistic artificial ECG signals may facilitate this evaluation. HRV refers to the variations in the beat intervals or correspondingly in the instantaneous HR. The normal variability in HR is due to autonomic neural regulation of the heart and the circulatory system. Heart rate variability (HRV) is a non-invasive indicator of cardiac autonomic function with important prognostic value. Measurement involves collection of consecutive R-R intervals (RRI) from an electrocardiogram (ECG) or HR monitor. Commonly, either long-term recordings of 24 hours or short-term recordings of five minutes duration are analyzed. Since overall variability is dependent upon the length of the recording, HRV should only be compared within or between individuals if the same length of data was analyzed. It is necessary to remove non-sinus rhythm beats, such as premature ventricular contractions, before analysis. A number of different mathematical analyses may be carried out to calculate HRV. The balancing action of the sympathetic nervous system (SNS) and parasympathetic nervous system (PNS) branches of the ANS controls the HR. Increased SNS or diminished PNS activity results in cardio-acceleration. Conversely, a low
SNS activity or a high PNS activity causes cardio-deceleration. The degree of variability in the HR provides information about the functioning of the nervous control on the HR and the heart’s ability to respond. As heart attack is a major problem in today’s society, this result was received with much enthusiasm, as HRV is a cheap, non-invasive technique that could lead to significantly better health care and recovery management. HRV is becoming a valuable tool for the clinician. Many studies have been done on the use of HRV as an indicator of disease, and an index of risk for sudden death.

Therefore, Heart rate variability, i.e., the amount of HR fluctuations around the mean HR, can be used as a mirror of the cardio respiratory control system. It is a valuable tool to investigate the sympathetic and parasympathetic function of the ANS. The most important application of HRV analysis is the surveillance of post infarction and diabetic patients. HRV gives information about the sympathetic-parasympathetic autonomic balance and thus the risk for sudden cardiac death (SCD) in these patients. HRV measurements are easy to perform, noninvasive, and have good reproducibility, if used under standardized conditions.

II. THE AUTONOMIC NERVOUS SYSTEM

The ANS have sympathetic and parasympathetic components. Sympathetic stimulation, occurring in response to stress, exercise and heart disease, causes an increase in HR by increasing the firing rate of pacemaker cells in the heart’s sino-atrial node. Parasympathetic activity, primarily resulting from the function of internal organs, trauma, allergic reactions and the inhalation of irritants, decreases the firing rate of pacemaker cells and the HR, providing a regulatory balance in physiological autonomic function. The separate rhythmic contributions from sympathetic and parasympathetic autonomic activity modulate the heart rate (RR) intervals of the QRS complex in the electrocardiogram (ECG), at distinct frequencies. Sympathetic activity is associated with the low frequency range (0.04–0.15 Hz) while parasympathetic activity is associated with the higher frequency range (0.15–0.4 Hz) of modulation frequencies of the HR. This difference in frequency ranges allows HRV analysis to separate sympathetic and parasympathetic contributions evident. This should enable preventive intervention at an early stage when it is most beneficial.

III. PHYSIOLOGICAL BASIS OF HRV ANALYSIS

Several physiological rhythms modulate heart rate via the autonomic nervous system. Instantaneous heart rate represents the total summation of all the effects on the autonomic nervous system. In the normal healthy subject there are several reflexes that operate in a simultaneous manner. These reflexes contain rhythms that are transmitted to the cardio-regulatory systems in the brain and are affected in heart rate. The correspondence between these rhythms and branches of autonomic nervous system allows HRV analysis to provide information on the function of the different sections of the autonomic nervous system.

a) Respiration

Respiratory sinus arrhythmia (RSA) [6] refers to the clinical variation in heart rate associated with breathing. Breathing causes disturbances in blood pressure, which are sensed by the baroreceptors. The baroreflex arc processes the changes in blood pressure and causes a corresponding fluctuation in heart rate. Because respiration is roughly periodic with a relatively short period (about 3 s), the fluctuations are mediated solely by the parasympathetic nervous system [7, 8]. As a result, parasympathetic control is able to operate on a rapid time scale, whereas the sympathetic systems cannot. RSA also relies on the baroreceptor reflex to operate and therefore assess the functioning of the baroreceptor reflexes. RSA indicates the entire level of parasympathetic activity.

b) Vasomotor oscillations

Vasomotor oscillations are a low-frequency spontaneous oscillation in blood pressure with a period of roughly 10 s. Constricting of the cross-sectional area of the arteries via smooth muscle activation regulates blood flow to different regions of the body. This process is controlled in a nonlinear manner by the brain stem and the baroreceptors. Due to delays in the processing system and the properties of smooth muscle activation, a spontaneous oscillation of roughly 0.1 Hz appears in blood pressure. This oscillation is detected by the baroreceptors and is superimposed onto the heart rate by the baroreceptor reflex arc. Vasomotor oscillations are mediated by the sympathetic nervous system.

c) Sympathetic-Vagal Interactions

There is usually a balance between both divisions of the autonomic nervous system with heart rate reflecting the net effect of the two opposing arms of the system. At rest the vagal system is dominant; however with increasing levels of activity the vagus decreases and the sympathetic increases. However, although heart rate reflects the combined activity of both arms of the autonomic nervous system, it cannot be used to gauge the individual effect of the vagal or sympathetic system. It has been shown that the activity of the vagus nerve is accentuated when heart rate has been accelerated by sympathetic stimulation.

d) Heart rate control

Short-term heart rate control can be considered as a control system where the physiological system is broken down into the following components:

- Cardiovascular system: the plant
- Cardio-regulatory system: the controller
• Autonomic nervous system: control inputs/outputs
• Vasomotor and respiration: disturbances

Fig. 1 shows these components as a feedback control system [9]. The disturbances in blood pressure are transmitted via the autonomic nervous system to the controller, which causes sympathetic and parasympathetic activity to fluctuate in rhythm. The fluctuations in blood pressure are therefore seen in heart rate also.

IV. ANALYSIS METHODS

The HRV indices can be divided into three major categories: time domain, frequency domain and nonlinear. The time-domain indices were developed quite early in the field and are still very popular. The frequency-domain indices were developed later and allow the variability to be divided into separate rhythms based on frequency. The nonlinear methods are based on the premise that HRV is a chaotic time series. To emphasize that edited RR intervals are being analyzed, often the RR intervals are quoted as NN intervals. The NN intervals are the normal-to-normal intervals that result from editing ectopic beats and noise from the RR intervals. Either short-term or long-term recordings are analyzed. Data may be taken from Physionet database [10].

a) Time domain

a.1) Statistical Techniques

The statistical techniques are based on various moments of the RR intervals and the delta RR intervals [11]:

a.1.1) SDRR

SDRR is the standard deviation of the RR intervals. This is a measure of total variability of the RR intervals. Low values indicate practically no HRV and this property alone have made it possibly the most used index. SDRR increases as the length of time the measurement is taken over increases. It is able to be used for long-term recordings. Normal subjects have a value of 141 +/- 39 ms.

a.1.2) SDSD

The standard deviation of the successive differences of the RR intervals, denoted by SDSD, is an important measure of short-term HRV. It is defined as the square root of the variance of the sequence of successive difference of RR interval. Normal subjects have a value of 127 +/- 35 ms.

a.1.3) RMSSD

RMSSD denotes root mean square of the successive differences of the RR intervals. This is a measure of short-term HRV. It is also given the name SDSSD, which stands for standard deviation of successive differences. The measure is best used on long-term recordings, but is often employed for short-term recordings. It is the most common time-domain measure of short-term HRV. Normal subjects have an RMSSD value of 27 +/- 12 ms. As short-term variability is mediated purely by the parasympathetic system, RMSSD measures parasympathetic modulation of heart rate. RMSSD has better immunity to ectopic beats and has nicer statistical properties, so it is the preferred measure of short-term HRV.

a.1.4) NN50

The number of interval differences of successive NN intervals that are greater than 50 ms. This is a measure of short-term HRV. This measure correlates highly with RMSSD. NN50 measures parasympathetic modulation of heart rate.

a.1.4) pNN50

The mean number of times an hour in which the change in successive normal sinus (NN) intervals exceeds 50 ms. This is another measure of short-term HRV. This measure correlates very highly with RMSSD. For the same reasons as NN50 are RMSSD are the preferred methods of measuring short-term HRV.

If the time-course of the RR intervals is denoted by RRn, with n = 1…N. It is assumed that only a finite number of intervals are available. Poincaré plots are most often taken of 5–10-min intervals, or of a 24-h segment. For 5–10-min segments, wide-sense stationarity may be assumed, and the following basic properties are, for practical purposes, true: E[RRn] = E[RRn+1] and E[(RRn)2] = E[(RRn+1)2]. Then

SDRR = \sqrt{E[RR_n^2] - \bar{RR}^2} (1)

where the mean RR interval is denoted by \bar{RR} = E[RR_n]

SDSD = \sqrt{E[\Delta RR_n^2] - \Delta RR^2} (2)

where \Delta RR_n = RR_n - RR_{n+1} (the delta-RR intervals)

\Delta RR_n = E[RR_n] - E[RR_{n+1}] = 0, for stationary intervals. This means that the root-mean square (rms) of the successive differences is statistically equivalent to the standard deviation of the successive differences

SDSD = rmsSD = \sqrt{E[(RR_n - RR_{n+1})^2]} (3)

a.2) Geometric Techniques

The geometric techniques convert the RR interval data into a geometric pattern. Various qualities of the
shape or pattern are measured and form the HRV indices. The geometric techniques generally have better performance on poorly edited data. The most popular techniques are:

**a.2.1) HRV Triangular Index**

First the sample density histogram is constructed. The most frequent RR interval length is established and denoted by is the most frequent RR interval length. The triangular index is given by dividing the total number of RR intervals by the most frequent RR interval length. The HRV triangular index has a value of 37+/−15 in normal subjects. It is a measure of total HRV, but it takes into account long-term fluctuations more than the short-term.

**a.2.2) Poincaré Plot**

The Poincaré plot is a scatter plot of the RR intervals against the next RR interval. The plot resembles a cloud oriented along the line of identity. The shape of the cloud provides a very useful description of HRV. The length of the plot corresponds to the level of long-term variability and width of the plot measures short-term variability. Poincaré width is considered a pure measure of parasympathetic activity. Fig. 2 displays a typical Poincaré plot. The main problem with Poincaré plot analysis is the lack of clear quantitative descriptions of the plot.

![HRV Poincaré plot showing the length and width.](image)

Fig. 2HRV Poincaré plot showing the length and width. Figure adapted from Brennan et al. (2002).

**b) Frequency Domain**

**b.1) Short-Term Recordings**

There are three main spectral components in a short-term recording of which only two are of physiological importance, which has been shown in Fig. 3. They are [12]:

**b.1.1) HF power**

It ranges from 0.15–0.4 Hz. HF power is a measure of parasympathetic activity. The band is roughly centered on the average respiration frequency for a normal subject. For a normal subject, a peak in the PSD curve exists in this band at roughly 0.3 Hz caused by respiration.

**b.1.2) LF power**

It ranges from 0.04–0.15 Hz. LF power is the subject of some controversy. Some consider it to be a measure of both sympathetic and parasympathetic activities, while others consider it a pure measure of sympathetic activity. For a normal subject, a peak exists in the LF band caused by vasomotor oscillations. The band is roughly centered on the frequency of the vasomotor oscillations, at roughly 0.1 Hz.

**b.1.3) VLF power**

It ranges from 0–0.04 Hz. VLF does not correlate with any known physiological rhythms. The VLF band is basically treated as noise and effects due to non-stationarity. No peaks are present in this band.

The total power is given by VLF + HF + LF. The HF and LF components are often used to quantify the autonomic activity of the sympathetic and parasympathetic branches. The balance between the two systems is often quantified by BAL= LF/ HF. However, this quantity is interpreted differently by those who consider LF power to reflect sympathetic and parasympathetic activity. In this case LF/ HF represents the sympathetic activity. The indices may be normalized by dividing LF and HF by total power. This gives more consistent results, especially when comparing subjects under different autonomic stresses.

**b.2) Long-Term Recordings**

Long-term recordings used for spectral analysis are usually 24 h recordings. An extra band is included for long-term recordings:

**b.2.1) HF**

It is same as for short-term recordings.

**b.2.2) LF**

It is same as for short-term recordings.

**b.2.3) VLF**

It is very-low-frequency band (0.003–0.04Hz). The VLF band only extends down to 0.003 Hz.

**b.2.4) ULF**

It is ultra-low-frequency band (0–0.003 Hz). The ULF band is included for long-term recordings.

The physiological mechanisms that generate the peaks in the HF and LF bands still produce peaks in long-term recordings. However, as the oscillations of these systems are not stationary over long periods of time, the modulations are averaged over the 24 h and detail is lost.
Therefore, the use of LF and HF is not recommended for 24 h records. The LF and HF bands normally account for 5% of the variability over 24h.

c) Nonlinear dynamics

Considering the variety of factors influencing heart rate, e.g. respiration or mental load, it becomes apparent that heart rate regulation is one of the most complex systems in humans. Many techniques suggested by nonlinear dynamics have been applied to the classification of HRV. The application of these techniques is motivated by the fact that the control systems for HRV have been shown to be nonlinear because of its high complexity and the nonlinear interactions between the physiological subsystems. Several of those indices have been proven to be of diagnostic relevance or have contributed to risk stratification. The following nonlinear methods/indices have been employed [13].

- Fractal measures (e.g. power-law correlation, detrended fluctuation analysis, multifractal analysis).
- Entropy measures (e.g. approximate entropy, sample entropy, compression entropy).
- Symbolic dynamics measures.
- Poincaré plot.

The methods from nonlinear dynamics provide additional prognostic information and complement traditional time and frequency-domain analyses of HRV. Poincaré plot analyses play a more and more important role, are easier to understand and interpret and are already widespread in holter ECG analysis.

V. QUANTATIVE ANALYSIS OF POINCARÉ PLOT

Ellipse fitting technique

To characterize the shape of the plot mathematically, most researchers have adopted the technique of fitting an ellipse to the plot, as Fig. 4 details. A set of axis oriented with the line-of-identity is defined. The axis of the Poincaré plot are related to the new set of axis by a rotation of \( \theta = \pi/4 \) rad.

\[
\begin{bmatrix}
  x_1 \\
  x_2
\end{bmatrix} =
\begin{bmatrix}
  \cos \theta & -\sin \theta \\
  \sin \theta & \cos \theta
\end{bmatrix}
\begin{bmatrix}
  R_{n} \\
  R_{n+1}
\end{bmatrix}
\]

(4)

In the reference system of the new axis, the dispersion of the points around the \( x_1 \) axis is measured by the standard deviation denoted by SD1. This quantity measures the width of the Poincaré cloud and, therefore, indicates the level of short-term HRV [14]. The length of the cloud along the line-of-identity measures the long-term HRV and is measured by SD2 which is the standard deviation around the \( x_2 \) axis. These measures are related to the standard HRV measures in the following manner:

\[
SD_1^2 = \text{Var}(x_1) = \text{Var}\left(\frac{1}{\sqrt{2}}R_{n} - \frac{1}{\sqrt{2}}R_{n+1}\right) = \frac{1}{2} \text{Var}(R_{n} - R_{n+1}) = \frac{1}{2}S_{SD}^2
\]

(5)

Thus, the SD1 measure of Poincaré width [15, 16] is equivalent to the standard deviation of the successive intervals, except that it is scaled by \( 1/\sqrt{2} \). This means that we can relate SD1 to the auto covariance function

\[
SD_1^2 = \varrho_{RR}(0) - \varrho_{RR}(1)
\]

(6)

With a similar argument, it may be shown that the length of the Poincaré cloud is related to the auto covariance function

\[
SD_2^2 = \varrho_{RR}(0) + \varrho_{RR}(1)
\]

(7)

By adding (6) and (7) together, we obtain the result

\[
SD_1^2 + SD_2^2 = 2SD_{RR}^2
\]

(8)

Finally

\[
SD_2^2 = 2SD_{RR}^2 - \frac{1}{2}SD_{SD}^2
\]

(9)

Equation (9) allows us to interpret SD2 in terms of existing indexes of HRV. It can be argued that SD2 reflects the long-term HRV.

VI. RESULTS AND OBSERVATIONS

Here we have tried to get some analysis based on data taken from Physionet database. Here we have chosen the data from PTB diagnostic ECG database of myocardial infarction patients. We have done some comparative studies based on time domain and frequency domain parameters. Those patients belong to the age group between 62-81 year and both male and female. We have also chosen one healthy individual also for comparison.
Fig. 5 ECG signal of a myocardial infarction subject of age 81, F with sampling frequency of 1000 Hz.

Fig. 6 RR interval series of an ECG signal of myocardial infarction subject of age 81, F.

Fig. 7 Poincare plot of RR interval series of an ECG signal of myocardial infarction subject of age 81, F.

Fig. 8 Power spectral density of RR interval series of an ECG signal of myocardial infarction subject of age 81, F.

Fig. 9 ECG signal of a myocardial infarction subject of age 63, M with sampling frequency of 1000 Hz.

Fig. 10 RR interval series of an ECG signal of myocardial infarction subject of age 63, M.

Fig. 11 Poincare plot of RR interval series of an ECG signal of myocardial infarction subject of age 63, M.

Fig. 12 Power spectral density of RR interval series of an ECG signal of myocardial infarction subject of age 63, M.
Here in Fig. 5 to Fig. 20 we have plotted the ECG signal, RR tachogram, Poincare plot and PSD of the signals of four subjects whose data are taken from Physionet. By using the time domain, frequency domain and nonlinear analysis we got the following results.
indicate no variability and it is possibly the most used and they have less variability but we can see for the SDNN, as they all were affected by myocardial infarction variability (HRV) time series. Low values of SDNN in frequency domain and nonlinear analysis of heart rate measure reflects both sympathetic and para-sympathetic of power spectrum range between 0.04 and 0.15 Hz. This is represented by LF when respiration rate is lower than 7 breaths per minute or during taking a deep breath. Thus, when subject is in the state of relaxation with a slow and even breathing, the LF values can be very high indicating increased parasympathetic activity rather than increase of sympathetic regulation. Low Frequency band is calculated in milliseconds squared (ms²). So in TABLE 2 if we observe for subject 1, 2 and 3 the ratio of LF/HF is much higher i.e., when the ratio increases the sympathetic activity increases and as well as the parasympathetic activity reduces but for healthy subject we can see that the ratio becomes 0.45. In a wide spectrum of cardiac patients, long-term values of LF/HF ratio higher than 4.8 were considered to reflect predominant sympathetic and those lower than 1.3 predominant vagal modulation activity. Therefore in this present study subject 2 has predominant sympathetic activity, healthy individual has predominant parasympathetic activity and subject 1 and subject 3 have balanced relationship. In nonlinear analysis given in TABLE 3 shows the short term variability and long term variability of all the subjects and healthy individual.

VII. CONCLUSION

Heart rate variability analysis has become an important tool in cardiology, because its measurements are noninvasive and easy to perform, have relatively good reproducibility and provide prognostic information on patients with heart disease. HRV has proved to be a valuable tool to investigate the sympathetic and parasympathetic function of the ANS. Spectral analysis of HR has clarified the nature of modulation in frequency domain in term of four subjects (data taken from Physionet) that encounter the ANS. Nonlinear parameters can be used to analyze the health of the subjects. In the future, individual therapy adjustments to aim at the most favorable sympathetic-parasympathetic balance in post infarction patients might be possible with the help of HRV analysis. From frequency domain analysis one can visualize how the LF/HF ratio is related to estimate the status of the health. In nonlinear analysis the modulation of sympathetic and parasympathetic activities are to determine the status of the human body.

REFERENCES


