Modified Ehlers' Index for Improved Detection of Heart Rate Asymmetry in Poincaré Plot

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Abstract

Heart rate asymmetry (HRA) is a quantifiable and visible phenomena in Poincaré plot which is defined with respect to line of identity (RR(i)=RR(i+1)). In general, third moment measure (skewness) is most appropriate for quantifying asymmetry of any time series signal. Existing Elhers' index (EI) is the third moment measure but it is defined based on the actual time series signal. The aim of this study is to redefine EI as EI_R in view of stated HRA definition. The new index calculated as a third moment along the minor axis of the plot from the derived signal along this axis. To show the benefit of EI_R over EI, we have calculated both index values of 54 Normal Sinus Rhythm (NSR) and 272 Arrhythmia subjects taken from Physionet NSR and Arrhythmia databases. The results showed that EI_R (ROC area =0.80) discriminates NSR from Arrhythmia subjects better than EI (ROC area=0.59). This study could be useful for quantifying HRA in Poincaré plot and classifying different pathology conditions.

1. Introduction

Intuitively, asymmetry refers to the lack of symmetry i.e, the distribution of the signal is imbalanced and/or disproportionate [1]. This imbalance or dissimilarity can easily observe with geometry or physics. Asymmetry is expected to be present in physiological systems [2] as it is a fundamental property of non-equilibrium system [3]. Moreover, asymmetry is linked with the time irreversibility of the system, which is reported as greatest in healthy physiologic system [1, 17]. Thus, asymmetry represents the presence of complex nonlinear dynamics in the physiological signal. Surprisingly, little work has been published in defining and measuring asymmetry in physiological signal [4].

Heart rate variability (HRV), the variation of the period between consecutive heart beats over the time, is thought to reflect the heart's adaptability to adapt to changing circumstances. HRV is predominantly dependent on the extrinsic regulation of the heart rate (HR) [5]. Poincaré plot analysis is one of the popular techniques largely used by the researchers for both qualitative and quantitative analysis of HRV signal. In various studies, it has been shown to reveal patterns of heart rate dynamics resulting from nonlinear processes [6, 7]. In general, Poincaré plot of HRV signal is constructed as a two dimensional plot by plotting consecutive points of RR interval time series (i.e, *lag-1* plot). It is a representation of HRV signal on phase space or cartesian plane [8], which is commonly used to asses the dynamics of HRV [6, 9–11]. Tulppo *et. al.* [6] fitted an ellipse to the shape of the Poincaré plot and defined two standard descriptors of the plot $SD1$ and $SD2$ for quantification of the Poincaré plot geometry. These standard descriptor represent the minor axis and the major axis of the ellipse respectively as shown in figure 1. The description of $SD1$ and $SD2$ in terms of linear statistics, given by Brennan *et. al.* [7], shows that the standard descriptors guide the visual inspection of the distribution. In case of HRV, it reveals a useful visual pattern of the RR interval data by representing both short and long term variations of the signal [6, 7].

One of the visible phenomena present in typical Poincaré plot of HRV signal of healthy subject is asymmetry (as shown in figure 2), termed as heart rate asymmetry (HRA), with respect to line of identity (line with slope 45^0 and passes through the origin). Hence the asymmetry means imbalance between two parts of Poincaré plot, points above the line of identity (RR(i)$>$RR(i+τ), deceleration of heart rate) and points below the line of identity (RR(i)$<$RR(i+τ), acceleration of heart rate). From figure 2, it is obvious that the number of points above line of identity is higher than the number of points bellow line of identity. As a result the line through centroid shifts above the line of identity, which represents the apparent asymmetricity in the plot. In one study, authors have examined the asymmetry of Poincaré plot and showed the relationship between time reversibility, pattern asymmetry and nonlinear dynamics [12]. For doing so, the authors have used three different indexes namely Porta's index (PI), Guzik's index (GI) and Ehlers' index (EI) [13–15]. In general, third moment measure (skewness) is most appropriate for quantifying asymmetry of any time series signal. Among the previously used asymmetry indices [13], PI

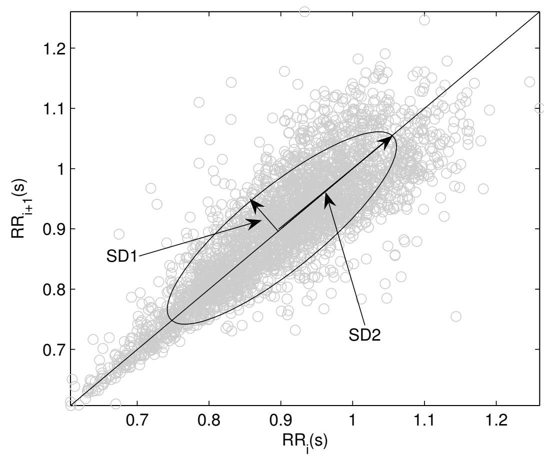

Figure 1. A standard Poincaré plot of RR intervals of a healthy person (N=2000). $SD1$ and $SD2$ are the standard descriptors of Poincaré plot, which measures short and long term variability of the plot respectively.

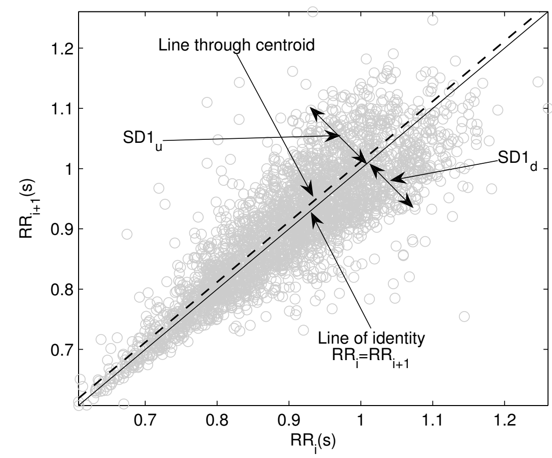

Figure 2. A *lag-1* Poincaré plot with line of identity and line through centroid. $SD1_u$ and $SD1_d$ represents the portion of $SD1$ above and below the line of identity respectively. The line through centroid indicates that $SD1_u > SD1_d$, which represents the visible asymmetricity in the plot.

and GI represents first and second moment of Poincaré plot respectively and are based on the HRA definition using Poincaré plot as previously discussed. In contrast, EI represents the third moment measure which was defined based on the original time series and measures the skewness of the RR interval time series rather than visible HRA phenomena present in Poincaré plot.

The aim of this study is to redefine EI with respect to stated HRA definition; redefined EI index is termed as EI_R. To prove the importance of redefining the EI index, we have calculated asymmetry of 54 Normal Sinus Rhythm (NSR) and 272 Arrhythmia subjects taken from Physionet NSR and Arrhythmia databases.

2. Methods

2.1. Ehlers' index EI

Ehlers' et. al. [15] have used slope asymmetry as a nonlinear feature to measure the brain activity using electroencephalograph (EEG) signal. The slope asymmetry was calculated as the asymmetry of the distribution of the first time derivative of each EEG signal, which was estimated by the skewness of differences between successive samples. Hence, for RR interval time series it can be defined as:

$$EI = \frac{\sum_{i=1}^{N-1}(RR_i - RR_{i+1})^3}{(\sum_{i=1}^{N-1}(RR_i - RR_{i+1})^2)^{\frac{3}{2}}} \quad (1)$$

For any time series signal, skewness is a measure of symmetry, or more precisely, the lack of symmetry. Distribution of any signal, or data set, is symmetric if it looks the same to the left and right of the center point. Hence, Ehlers' index was appropriate for asymmetry measure of RR interval time series without considering the Poincaré plot.

2.2. Modified Ehlers' index EI_R

As mentioned in the definition of HRA, it is measured with respect to line of identity i.e, the distribution of points above line of identity does not look same as distribution bellow line of identity. This indicates that the asymmetry of the plot should be measured perpendicular to the line of identity. Let, i^th point of *lag-1* Poincaré plot is represented as $P_i(x, y) = \{RR_i, RR_{i+1}\}$. To calculate the skewness perpendicular to the line of identity we need to project all points of Poincaré plot along the minor axis of the fitted ellipse (figure 1). The general equation for projecting any point (x_i, y_i) on some line with slope θ can be written as

$$\begin{pmatrix} x_i' \\ y_i' \end{pmatrix} = \begin{pmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{pmatrix} \begin{pmatrix} x_i - \overline{x} \\ y_i - \overline{y} \end{pmatrix} \quad (2)$$

where, $\overline{x}$ and $\overline{y}$ is the centroid of all points $P_i(x_i, y_i)$ of the Poincaré plot. Now value for θ is chosen as 45^0 or 135^0 for projecting points over major or minor axis respectively as shown in figure 3.

However, in this study to measure HRA the univariate signal was generated by projecting all points perpendicular to line of identity which passes through the origin. Hence, projection of all points on the line perpendicular to the line of identity can be derived using equation 2 as follows:

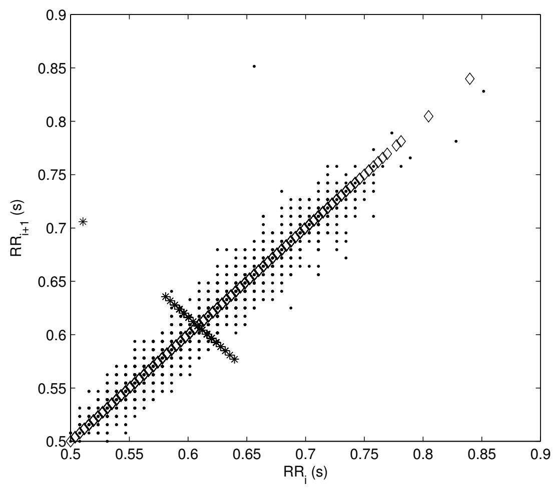

Figure 3. Projection of points of Poincaré plot on line of identity and line perpendicular to line of identity which passes through centroid of the plotted points.

$$\begin{aligned} P_{i(u)}(x) &= \frac{(RR_i - RR_{i+1})}{2} \\ P_{i(u)}(y) &= \frac{(RR_i - RR_{i+1})}{2} \end{aligned} \tag{3}$$

where $P_{i(u)}$ represents the corresponding univariate point or projected point of P_i. This shift of points from centroid of the plot to the origin does not have any impact on the skewness value as it is independent of origin and scale of measurement. Moreover, skewness is a measure to describe the shape of the function rather than the amplitude of it. Now EI_R is calculated from the projected points as follows:

$$EI_R = \frac{\sum_{i=1}^{N-1} (P_{i(u)}(x) - \overline{P_{(u)}(x)})^3}{(\sum_{i=1}^{N-1} (P_{i(u)}(x) - \overline{P_{(u)}(x)}))^{\frac{3}{2}}} \tag{4}$$

where $\overline{P_{(u)}(x)}$ is the mean of all $P_{i(u)}(x)$ values.

2.3. ROC area analysis

In order to provide the discriminative performance of all measures, receiver-operating characteristic (ROC) analysis was used [16], with the areas under the curves for each feature represented by the ROC area. A ROC area value of 0.5 means that, the distributions of the features are similar in two groups with no discriminatory power. Conversely, a ROC area value of 1.0 would mean that the distributions of the features of the two groups do not overlap at all. ROC plots are used to gauge the predictive ability of a classifier over a wide range of threshold values. A threshold value was applied such that a value below the threshold was assigned into one category whereas a value equal to or above the threshold was assigned into another category. ROC curves were plotted using results to examine qualitatively the effect of threshold variation on the classification performance. The area under ROC curve was approximated numerically using the trapezoidal rules [16] where the larger the ROC area the better the discriminatory performance.

3. Results and discussion

Table 1 summarized the mean and standard deviation (STD) of EI and EI_R of three two of subjects. From the mean value of both EI and EI_R, it was obvious that the arrhythmia subjects are highly positively skewed than the healthy subjects. The highest ROC area (0.80) between NSR and Arrhythmia group was found for asymmetry index EI_R as shown in table 1. However, using EI the ROC area found between two groups was 0.59. The ROC curve for EI and EI_R are shown in figure 4.

Table 1. *Mean* $\pm$ *Standard deviation* of EI and EI_R for normal and arrhythmia subjects. ROC area is given for both EI and EI_R between two subject groups.

	NSR	Arrhythmia	ROC area
EI	0.24 ± 0.61	1.03 ± 2.39	0.59
EI_R	0.54 ± 0.76	1.99 ± 1.65	0.80

Asymmetry is related with nonlinear dynamics and time irreversibility, which exhibit the most complex interrelationships [1, 17]. Guzik et. al. [14] have reported that the asymmetry in heart rate variability might be related to the response of the baroreflex to increase or decrease the blood pressure [18]. However, exact reason for such asymmetry is largely unknown. From the result it was obvious that redefining Elhers' index improved the detection of asymmetry and as a result the discriminatory capability, measured by the ROC area, of the index increased from 0.59 to 0.80. Moreover, asymmetry was found to be a promising marker that can be used for differentiating pathology from healthy condition.

4. Conclusions

A modified Elhers' index to measure asymmetry in Poincaré plot is proposed. The proposed modification provides an improvement in analyzing asymmetricity of HRV signal. The index EI_R has been shown to perform better in discriminating arrhythmia from normal sinus rhythm subjects using heart rate series. In future, it would be interesting to look at use of redefined index in other pathological condition.

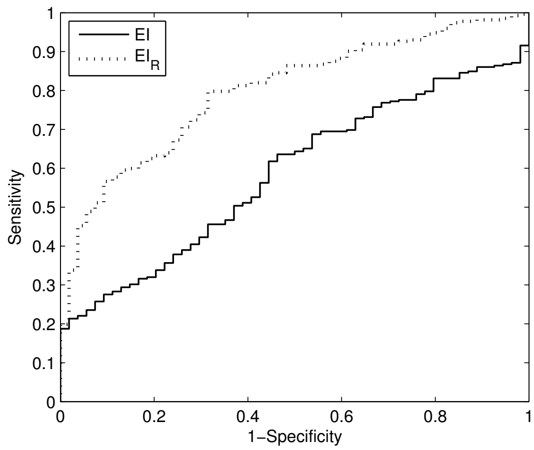

Figure 4. ROC curve of EI and EI_R. The area under the curve for EI_R (0.80) is significantly higher than $EI(0.59)$.

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