Sudden Cardiac Death Prediction Using

Poincaré Plot of RR Interval Differences (PORRID)

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Abstract

Installation of an implantable cardioverter defibrillator (ICD) in patients at risk of sudden cardiac death (SCD) requires the accurate identification of patients condition. This study uses RR interval data obtained from ECG recordings of non-SCD and SCD prospective subjects. The successive RR interval data was used as input for Poincaré plot of RR Interval Differences (PORRID). The points in the PORRID were colored base on position of current and previous points as green, red, and yellow color. The identified characteristics of subject who will experience SCD was used as the basis for prediction of SCD events. The experimental result show that sudden cardiac death can be predicted using PORRID by the accuracy of 85%, in up to 20 hours before the onset of SCD.

Keywords: heart rate variability, Poincaré Plot of RR Interval Differences, PORRID, sudden cardiac death, SCD

1 Introduction

Sudden cardiac death (SCD) is an unexpected death due to heart problems in someone with known or unknown heart disease, within 1 hour of onset of change in clinical status [1]. In the United States, the incidences of SCDs are about 400,000 deaths per year [2]. Mortality rate of SCD can be reduced by preventive therapy through installing an implantable cardioverter defibrillator (ICD) in patients who are at risk for SCD [3]. The ICD implantation decreased the mortality of about 30% [4], however, the ICD implantation cost is still expensive [5]. Due to the high cost of ICD implantation, the ICD should be installed on patients who will actually experience SCD [6]. For this reason, we need an early and accurate method for detection of patients who will actually experience SCD.

The mechanism of death in the majority of patients dying of SCD is ventricular fibrillation; as a consequence, there may be no prodromal symptoms associated with the death [7]. Before occurring of SCD, there is no significant difference between the ECG signal for a person who is susceptible to cardiac death and the ECG signals of normal persons. Cardiology Experts cannot distinguish between normal ECG and patients which prone to SCD [8].

Heart rate variability (HRV) is a clinical variable that has an important prognostic value. HRV has become an independent predictor of all-cause cardiac death [9]. One of HRV analysis methods is Poincaré plot of successive RR interval, with SD1 and SD2 as standard descriptors. The primary limitation of the standard descriptors is the lack of embedding temporal information [10]. Two Poincaré plots with the same SD1 and SD2 may give different temporal information.

Another HRV analysis method is Poincaré Plot of RR Interval Differences (PORRID) [11]. Each point in a PORRID is derived from RR interval triplets and still has the temporal information. This study used the PORRID features for characterizing the HRV of subjects who will actually experience SCD (further they are called as SCD subjects), and then applied it in SCD prediction.

2. Materials and Methods

RR Interval Data
This study used various ECG recordings of SCD, normal sinus rhythm (NSR), arrhythmia, and congestive heart failure (CHF) databases, and obtained the RR interval data from the ECG recordings by using a soft ware called WAVE [12].

Poincaré Plot of RR Interval Differences (PORRID)
We made PORRID of N RR Interval data in the following steps [11].
- Made a data vector of RR interval differences.

$$\overline{\Delta RRI} = \overline{RRI}_{n+1} - \overline{RRI}_n = (\Delta RRI_1, \ \Delta RRI_2, \dots, \Delta RRI_M) \qquad (1)$$
where M = N-1

- Made $\overline{\Delta RRI}_1$ and $\overline{\Delta RRI}_{n+1}$:

$$\overline{\Delta RRI}_n = (\Delta RRI_1, \Delta RRI_2, \dots, \Delta RRI_{M-1})$$

$$\overline{\Delta RRI}_{n+1} = (\Delta RRI_2, \Delta RRI_3, \dots, \Delta RRI_M)$$

(2)

- Made PORRID for each record of the databases by plotting every pair of ΔRRI_n and ΔRRI_{n+1} as follow:

$$P_n = (\Delta RRI_n, \Delta RRI_{n+1})$$

(3)

Colored PORRID

In order to get more temporal information the points in the PORRID were colored base on the position of current and previous points as shown in Table 1.

Table 1. Colors of the points that depend on position of current and previous points. The quadrant numbers are as defined in Eq. 4.

No	Position of the Point		Color of the Current Point
	Current Point	**Previous Point**	
1	Quadrant 1	Quadrant 4	Green
2		Quadrant 1	Yellow
3	Quadrant 2	Quadrant 4	Red
4		Quadrant 1	Green
5	Quadrant 3	Quadrant 2	Green
6		Quadrant 3	Yellow
7	Quadrant 4	Quadrant 2	Red
8		Quadrant 3	Green

The Average of Total Absolute Variability, R_{ac}

The resulted colored PORRIDs then were observed to obtain the HRV characteristic of SCD subjects through qualitative and quantitative analysis. We analyzed qualitatively through observation on the shape and size of pattern formed by points in each color. Based on the qualitative analysis result, we analyzed the colored PORRID quantitatively through calculating the absolute variability of points in each color. The absolute variability of a point for certain color c in quadrant q, R_{cq}, were calculated by using Eq. 4 below:

$$R_{cq} = \sqrt{(\Delta RRI_n)^2 + (\Delta RRI_{n+1})^2}$$

(4)

where: q = quadrant number
 c = color of the point.
c = G for green points (in quadrant 1: $q=1$, $\Delta RRI_n>0$, $\Delta RRI_{n+1}>0$, and $\Delta RRI_{n-1}<0$; in quadrant 2: $q=2$, $\Delta RRI_n>0$, $\Delta RRI_{n+1}<0$ and $\Delta RRI_{n-1}>0$; in quadrant 3: $q=3$, $\Delta RRI_n<0$,

$\Delta RRI_{n+1} < 0$, and $\Delta RRI_{n-1} > 0$; in quadrant 4: $q=4$, $\Delta RRI_n < 0$, $\Delta RRI_{n+1} > 0$, and $\Delta RRI_{n-1} < 0$).

c = R for red points (in quadrant 2: $q=2$, $\Delta RRI_n > 0$, $\Delta RRI_{n+1} < 0$, and $\Delta RRI_{n-1} < 0$; in quadrant 4: $q=4$, $\Delta RRI_n < 0$, $\Delta RRI_{n+1} > 0$, and $\Delta RRI_{n-1} > 0$).

c = Y for yellow points (in quadrant 1: $q=1$, $\Delta RRI_n > 0$, $\Delta RRI_{n+1} > 0$, and $\Delta RRI_{n-1} > 0$; in quadrant 3: $q=3$, $\Delta RRI_n < 0$, $\Delta RRI_{n+1} < 0$, and $\Delta RRI_{n-1} < 0$).

For N points in c color in quadrant q the total absolute variability R_{tcq} was calculated by using Eq. 5 below:

$$R_{tcq} = \sqrt{\left(\sum_{n=1}^{N} \Delta RRI_n\right)^2 + \left(\sum_{n=1}^{N} \Delta RRI_{n+1}\right)^2} \tag{5}$$

where ΔRRI_n and ΔRRI_{n+1} as defined in Eq. 4.

The average of total absolute variability for C colored points, R_{ac}, was calculated with Eq. 6:

$$R_{ac} = \frac{\sum_{q=1}^{4} R_{tcq}}{k} \tag{6}$$

where $k = 4$ for the green, or $k = 2$ for the red and the yellow PORRIDs.

Implementation of Colored PORRID in SCD Prediction

The RR interval data from subjects with NSR, arrhythmia, CHF, and SCD categories were used as many as 10 subjects for each category. As many as 1850 of RR interval data samples (about 30 minutes of ECG recording) were taken from each subject as input of colored PORRID. Each colored PORRID was analyzed to find the SCD subject characteristics. Based on the characteristics the SCD evens were predicted from 20 SCD subjects and 20 non-SCD subjects. The non-SCD subjects consist of three categories i.e. NSR, arrhythmias, and CHF.

Evaluation

The ability of PORRID in prediction of SCD was evaluated using accuracy, sensitivity, specificity, precision, and false positive rate as follows [8].

$$Accuracy = \frac{TP+TN}{TP+TN+FP+FN} \tag{7}$$

$$Sensitivity = \frac{TP}{TP+FN} \tag{8}$$

$$Specificity = \frac{TN}{TN+FP} \tag{9}$$

$$Precision = \frac{TP}{FP+TP} \tag{10}$$

$$False\ Positive\ Rate = \frac{FP}{FP+TN} \tag{11}$$

where TP refers to true positives, TN refers to true negatives, FN refers to false negatives and FP refers to false positives.

3. Result

The resulted PORRIDs are shown in Fig.1. PORRID of normal subject

produces small circular pattern as shown in Fig. 1(a) and PORRID of SCD subject produces relatively large elliptical pattern as shown in Fig. 1(b).

(a)   (b)
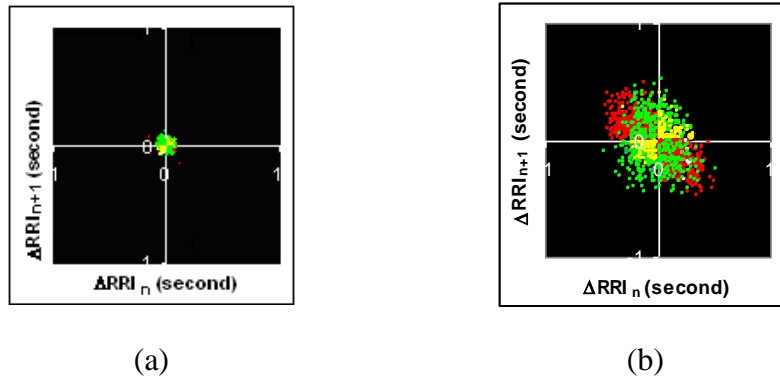
Fig1. Colored PORRID of (a) a normal subject, and (b) an SCD subject

In order to observe colored PORRID more accurately each color is presented separately in Fig. 2. Fig. 2(a) shows PORRID of normal subjects just in a green (left), red (middle) and yellow (right) colors. It can be seen that the green PORRID has a circular shape with a small radius. Both the red and the yellow PORRIDs produce two patterns of a quarter-circle shape. Points of the red PORRID are located in quadrant 2 and quadrant 4, and points of the yellow PORRID are located in quadrant 1 and quadrant 3. The pattern of the red and the yellow PORRIDs have almost the same radius as the green PORRID. Fig. 2(b) shows PORRIDs of SCD subjects. It is evident that the PORRIDs of SCD subjects have similar shape with PORRIDs from normal subjects, but they have a larger size.
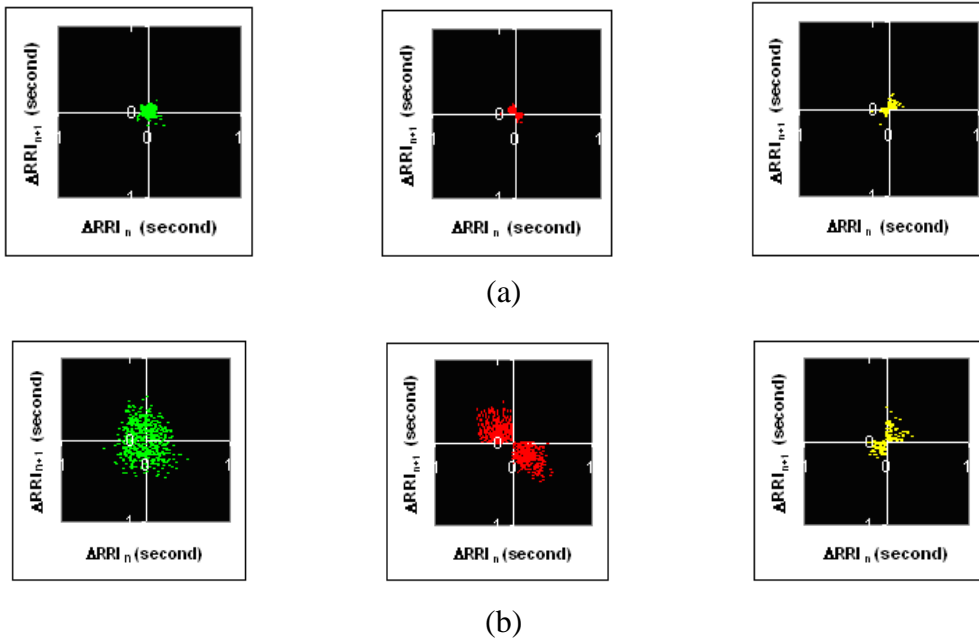

(a)

(b)

Figure 2. PORRIDs with separated colors for (a) normal, and (b) SCD subjects

The average of the total absolute variability of each color, R_{ac}, was estimated by using Eq. 4 to Eq. 6, and the values then was compared between SCD and non-SCD subjects. The result shows that the red PORRID has the best ability to distinguish SCD from non-SCD subject. The maximum value of total absolute variability of the red PORRID R_{aR} for non-SCD subjects is 27.3s while the minimum R_{aR} value for SCD subjects is 26.2s. This result shows that the SCD subjects are characterized by $R_{aR} > 26$s. By using this value as threshold for R_{aR} value of SCD subject, some tests were conducted. The test results are shown in Table 2 as contingency table, and give the prediction performance: *Accuracy* = 0.85, *Sensitivity* = 0.85, *Specificity* = 0.85, *Precision* = 0.85, and *False Positive Rate* = 0.15.

Table 2. The SCD contingency table

		Actual Condition	
		SCD	Non-SCD
Detection Result	SCD	TP = 17	FP = 3
	Non-SCD	FN = 3	TN = 17

4. Discussion

PORRID is a portrait of the heart rate regulation dynamics. Locations of points in the PORRID describe how and how large the RR intervals (heart rates) vary. Fig.3 shows the relationship between locations of these points and variation of the RR intervals.
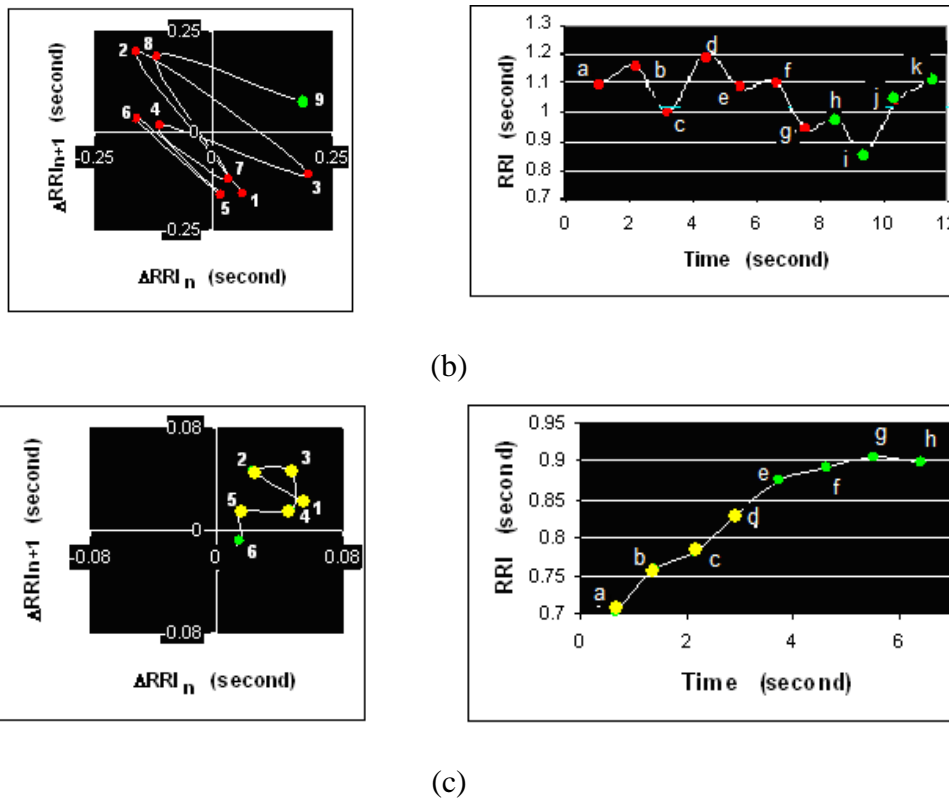

(a)

(b)

(c)
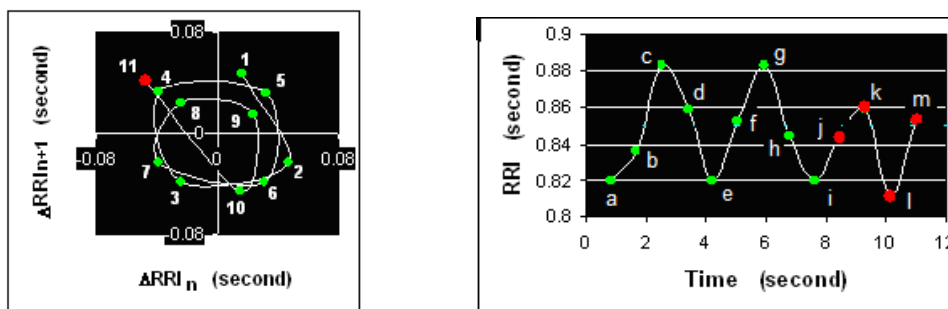
Fig. 3. RR interval variations (right) that result variations of trajectories in PORRID (left),(a) the spiral trajectories of green points, (b) the elliptical trajectories of red points, and (c) the trajectories in the same quadrant of yellow points

Fig. 3(a) (left) shows some (i.e. 11) points in a PORRID. In order to show the trajectory of these points, every two successive points are connected with a curve tracer. Each point in Fig. 3(a) (left) summarizes the variation of three successive RR intervals (triplets) in Fig. 3(a) (right). Fig. 3(a) (right) shows the variation of the RR intervals. Point 1 in Fig. 3(a)(left) are obtained from points a, b, and c of Fig. 3(a)(right), point 2 in Fig. 3(a)(left) are obtained from points b, c, and d of Fig. 3(a)(right), and so on.

It can be seen in Fig. 3(a) (right) that RR intervals vary regularly, i.e. alternate between twice up and twice down (except for point k, l, and m). These variations result the spiral trajectory shown in Fig. 3(a)(left).The trajectories rotate clockwise at a speed of one quadrant per point (from quadrant 1 to quadrant 2, to quadrant 3, to quadrant 4, to quadrant 1 and so on). We call such trajectory as a normal or regular trajectory. The points that have such trajectory are colored in green.

By coloring the points, one point in PORRID now summarize not only three, but four of RR interval variations. The green PORRID depicts that one period of autonomic nervous system activity produces four heart beats.

Sometimes the RR intervals vary abnormally as illustrated by points j, k, l, and m in Fig. 3(a) (right) which results point 11 in Fig. 3(a) (left). The trajectory of point

10 to point 11 is a leap from quadrant 2 to quadrant 4directly without going through quadrant 3. Point 11 is not colored in green but in red since it does not follow the normal trajectory. The abnormal trajectory (the red point) indicates an irregularity in heart rhythm (arrhythmia) at that time interval. Such arrhythmic can occur even in normal subject, but with smaller value and incidence than in abnormal subject.

A larger arrhythmic occur in SCD subject, as shown in Fig. 3(b). Fig. 3(b)(left) shows some red points with the trajectories are from quadrant 2 to quadrant 4 and vice versa. Such trajectory is call as fast trajectory, since one period of autonomic nervous system activity produces only two heartbeats. The red points are generated by successive RR intervals which vary up and down alternately as shown in Fig. 3(b)(right).

The other rhythm abnormalities produce trajectories in the same quadrant twice or more successively. Such trajectory is call as slow trajectory since one period of autonomic nervous system activity produces more than four heartbeats. These rhythms are shown by the yellow points in Fig. 3(c)(left) and are resulted from the increase or decrease in RR intervals three times or more successively as shown in Fig. 3(c)(right).

Table 2 shows that from 20 of SCD subjects, there are 3 subjects detected as non-SCD. These subjects were failed to be detected as SCD since they have PORRID with the same characteristics as CHF or NSR categories. It is suspected that for better result of prediction other PORRID characteristics are needed, i.e. relative variability, absolute variability in the axes, or the number of points with zero value of absolute variability.

Table 2 shows that there are 3 CHF subjects detected as SCD. This detection may be wrong but it may also be true, since patients with CHF are including in people who are at risk for SCD [13]. They are suspected will experience SCD in the future.

The experimental result show that the implementation of PORRID can predict SCD by the accuracy of 85%, and it can predict up to 20 hours before the SCD occurrence. This much earlier than another experiment which combine Time-Frequency and Nonlinear features that can predict SCD by the accuracy of 99.73%, 96.52%, 90.37% and 83.96% for the first, second, third and forth one-minute intervals, respectively, before SCD occurrence [8].

It is convinced in the future, that an early warning system that warns physicians at least in 24 hours before the onset of SCD may be created based on our novel method. Through this early warning, the physicians can do something to prevent the onset of SCD and to save the lives of their patients.

This study still has limitations that produce three false negative and three false positive. In the next study other features of PORRID will be involved to improve the accuracy.

5. Conclusion

Subjects who will experience SCD are characterized by the red PORRID, and expressed by the mean value of the total absolute variability, R_{aR}. For 30 minutes of ECG samples, the candidates for SCD are characterized by $R_{aR} > 26$s. The experi-

mental result shows that the PORRID can be used to predict SCD by the accuracy of 85%, in up to 20 hours before the onset of SCD.

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