

Recurrence Quantification Analysis based on P-P Intervals Measurement in Postinfarction Patients with Frequent Ventricular Ectopy

N Balogh¹, S Khor², T Szuszai¹, I Kecskes¹,
K Fugedi², I Kovacs², I Simon¹, S Rubicsek¹

¹Medartintech Ltd, Budapest, Hungary
²Szent Istvan Hospital, Budapest, Hungary

Abstract

Frequent ventricular ectopy results a great problem of any heart rate variability analysis method, because the interpolation of the R-R intervals significantly disturbs the intrinsic rhythm's features. Recurrence quantification analysis (RQA) is a valuable tool for predicting serious cardiovascular events. Our ambulatory ECG (AECG) system (RhythmPattern, SzivLeso) processes the 1 kHz ECG recordings, calculates various non-linear heart rate parameters, and analyses the P- and R-waves

The study population (age 61.9 ± 8.6) consists of 89 postinfarction patients, where frequent ($> 6000/24$ hours) ventricular ectopic beats were found. The ambulatory ECG monitoring was repeated in every month; the mean follow-up was 38.8 months. The patients were divided into two groups: 72 pts were alive (Group_A), and 17 pts (Group_B) died at the end of the study. The P-P tachogram was determined instead of R-R intervals. The standard parameters of RQA were calculated. Significant ($p < 0.01$) differences were found of the majority of RQA parameters, when the P-to-P wave tachograms were used instead of R-to-R wave ones.

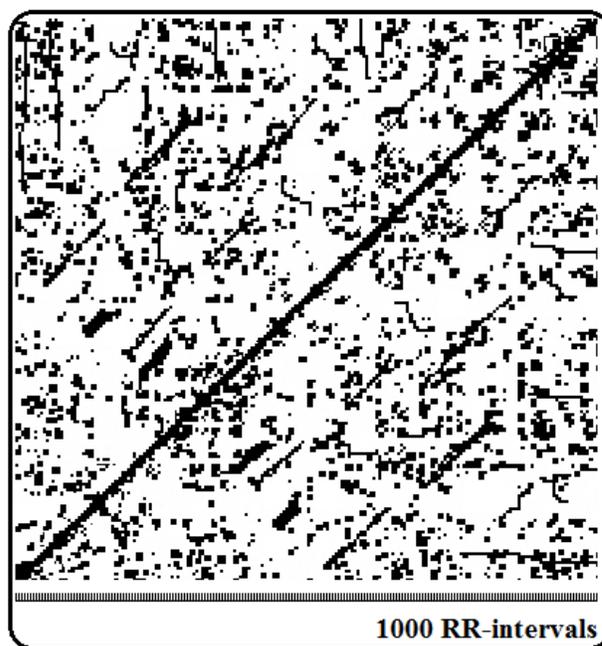


Figure 1. Recurrence plot of the heart rate representing 1000 R-R intervals.

1. Introduction

The method of recurrence plot was introduced to visualize the behavior of trajectories in the m-dimensional phase space. The recurrence of the phase space trajectory to a certain state is visualized by plotting black (or by changing the basic parameters: in color) dots in an $N \times N$ matrix. A recurrence plot is simply a graphical depiction of the recurrence matrix. The recurrence plot is an autocorrelation plot of $x(t)$ with $x(i)$ along the abscissa and $x(j)$ along the ordinate. Only those points that satisfy $x(i) = x(j)$, defined as values of i and j that fall within a specified radius or distance of one another, are plotted. The diagonal lines represent dynamic behavior; the horizontal and vertical lines show unchanged state (Figure 1).

The recurrence quantification analysis (RQA) provides measures based on the diagonal, horizontal and vertical structures [1-2]. Studies examined the usefulness of RQA based on heart rate variability (based on R-R tachograms) [3-4]. Frequent ventricular ectopy results a great problem of any heart rate variability analysis method, because the interpolation of the R-R intervals significantly disturbs the intrinsic rhythm's features. Recurrence quantification analysis (RQA) is a valuable tool for predicting serious cardiovascular events. Our ambulatory ECG (AECG) telemedicine system (RhythmPattern, SzivLeso) processes the 1 kHz ECG recordings, calculates various non-linear heart rate parameters, and analyses the P- and R-waves separately. The commercial ambulatory ECG (AECG) equipments (Holter) does not calculate the non-

linear heart rate variability (HRV) parameters, cannot determine the p-waves. Our self-developed equipment (HeartPattern, SzivOrzo) [4] registers and stores the full 24-hour ECG, the “full-disclosure” means really the retrieve of the full ECG with the p-waves. Beside the view function, the software calculates the following non-linear heart rate and arrhythmia parameters:

1. Instantaneous heart-rate variability: from Poincare plot the SD1, SD2 and SD1/SD2, the alpha-1 and alpha-2 from DFA, approximate entropy (ApEn), the sampling entropy/scale factor (from scale=3 to 12) based on multiscale entropy analysis, the RQA analysis (with the 10 parameters discussed later),
2. Ventricular arrhythmia pattern analysis: the ratio of ventricular premature beat (VPB) and the total number of QRS; the SD1, SD2, SD1/SD2, alpha-1 and alpha-2 of DFA, and ApEn of the separately calculated (independent of instantaneous sinus heart rate) VPB rhythm,
3. The synchronization between the instantaneous heart rate and VPB “rhythm”: the number and the duration of synchronization.

2. Methods

The study population (age 61.9 ± 8.6 years) consists of 89 postinfarction patients with normal ejection fraction, where frequent ($> 6000/24$ hours) ventricular ectopic beats were found.

The ambulatory ECG monitoring was repeated in every month; the mean follow-up was 38.8 months. The patients were divided into two groups: Group_A (72 pts) alive, and 17 pts (Group_B) died at the end of the study. The RQA was performed on the 4 hours daily registration of AECG in all patients; in Group_B before at least 4 weeks of death.

The signal analysis of the P-waves of the 24-hour AECGs was much more similar to the signal averaged ECG: p-wave detection in the ectopic QRS based on the matching of the ectopy-QRS waves, and the signal-averaging enhances the hidden P-waves.

The signal analysis program consists of the following parts:

1. Filtering,
2. R-wave detection,
3. Clusterization the QRS complexes into three categories: narrow (N), where QRS duration is less than 120 ms, wide (W): longer, than 120 ms, and undefined (X),
4. Searching for N-W-N' template (pattern), where $N-W < 0.2 * \text{mean R-R}$ AND $W-N' > 0.2 * \text{mean R-R}$
5. Finding the p-waves before N and N',
6. Determining the region of interest (ROI) at the middle between P-wave (N) and P-wave (N') $\pm 10\%$,

7. Signal averaging of premature ventricular complex with the use of N-W-N' template,
 8. Searching for the local minima of the smoothed first derivative of ECG in the ROI segment (virtual P-wave),
 9. Extracting the actual (virtual) P-wave max from the signal averaged ROI segment.
 10. Determining the P-P heart rate tachogram for RQA.
- The critical steps are illustrated in the next two figures (Figure 2. and 3.)

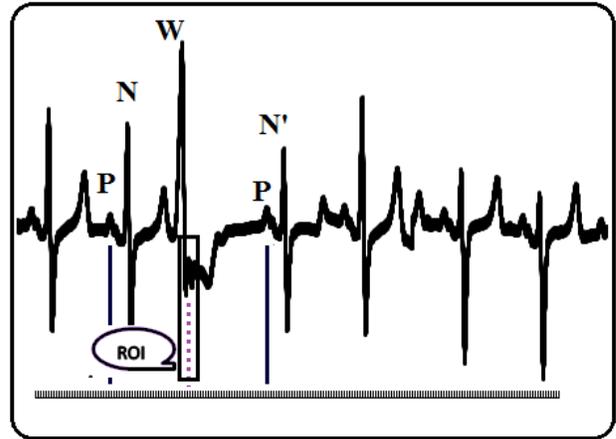


Figure 2. Signal processing: Step 5-6.

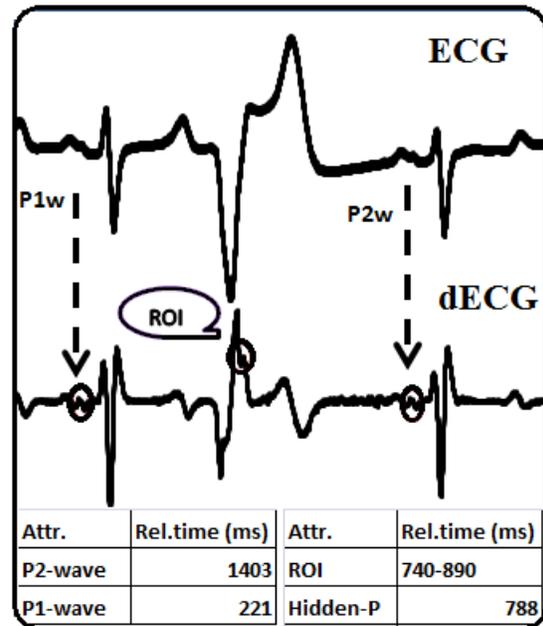


Figure 3. Signal processing: Step 7-9.

The standard parameters of RQA were calculated: recurrence rate (%RR), determinism (%DET), laminarity (LAM), the ratio between DET and RR (RATIO), averaged diagonal line length (L), trapping time (TT), the longest diagonal (Lmax) and vertical (Vmax), divergence (DIV), the entropy (ENTR), and the trend (TREND).

1. Recurrence Rate (RR), which is the density of recurrence points in a recurrence plot.
 2. Determinism (DET), which is the fraction of recurrence points forming diagonal lines. Diagonal lines represent epochs of similar time evolution of states of the system.
 3. Mean diagonal line length, corresponding to a mean prediction time or to the inverse of the divergence of the system (K 2 entropy).
 4. Entropy of the line distribution, measures the complexity of the recurrence structure.
 5. Laminarity (LAM), which is the fraction of recurrence points forming vertical lines. Vertical lines are typical for intermittency.
 6. Trapping time (TT), which is the mean length of vertical lines. TT measures the mean time that the system is trapped in one state or change only very slowly.
- Embedding dimension = 10, radius of 15%, time delay=4, window size=1024 were used.

The statistical calculation (Mann-Whitney (M-W) U test, multivariate discriminant analysis) was performed with SPSS V 15.0.

3. Results

At the first step, the above-mentioned standard RQA was performed in the two scenarios: “P-P” means that the heart rate tachogram was calculated by the P-wave-to-P-wave intervals, “R-R” means the R-wave-to-R-wave intervals. Table 1. and 2. show the statistics of Group_A and Group_B.

Table 1. Descriptive statistics of the two groups’ RQA values, when “P-P” heart rate tachogram was calculated.

“P-P”	Group_A	N=72	Group_B	N=17
	Mean	Std. Dev.	Mean	Std. Dev.
%REC	2.25	1.31	4.29	1.85
%DET	0.338	0.132	0.647	0.224
L	19.1	8.8	31.4	11.5
Lmax	299.4	117.2	425.5	84.9
Vmax	365.6	99.7	173.1	71.6
ENT	1.114	0.423	2.334	0.643
TT	29.99	7.42	20.37	6.19
RATIO	0.177	0.084	0.160	0.041
DIV	0.004	0.002	0.002	0.001
%LAM	0.087	0.021	0.060	0.018

Table 2. Descriptive statistics of the two groups’ RQA values, when “R-R” heart rate tachogram was calculated.

“R-R”	Group_A:	N=72	Group_B:	N=17
Parameter	Mean	Std. Dev.	Mean	Std. Dev.
%REC	3.292	1.329	3.595	1.965
%DET	0.884	0.348	1.071	0.406
L	23.77	8.69	26.57	11.88
Lmax	326.9	119.5	316.9	95.91
Vmax	429.8	96.79	389.2	91.2
ENT	1.392	0.505	1.770	0.776
TT	33.52	7.52	27.54	8.21
RATIO	0.289	0.123	0.347	0.184
DIV	0.004	0.002	0.004	0.001
%LAM	0.148	0.037	0.112	0.044

The two groups were compared with the M-W U test; Table 3. shows the results based on “P-to-P” wave tachogram, Table 4. based on “R-to-R” ones.

Table 3. Comparing the “P-P” RQA measurements, 1= Group_A, 2= Group_B (1 vs. 2).

1 vs. 2	M-W U	Sign.
%REC	178.5	6E-06
%DET	95	6.8E-08
L	237	9.1E-05
Lmax	233.5	7.8E-05
Vmax	72	1.7E-08
ENT	42	2.7E-09
TT	198	1.6E-05
RATIO	612	1
DIV	233.5	7.8E-05
%LAM	201	1.8E-05

Abbreviations: 1 vs. 2 means to compare the “P-P” RQA measurements; 1= Group_A, 2= Group_B.

Using the “P-to-P” analysis, only one parameter (RATIO) showed non-significant relation. Table 4. shows the high percentage of non significant changes of RQA parameters, when the R-to-R” wave solution was performed (exceptions were ENT, TT and %LAM parameters).

Table 4. Comparing the “R-R” RQA measurements; 3= Group_A, 4= Group_B (3 vs. 4).

3 vs. 4	M-W U	Sign.
%REC	606	0.9501
%DET	446	0.0832
L	553	0.5380
Lmax	605	0.9418
Vmax	470	0.1383
ENT	422	0.0474
TT	340	0.0045
RATIO	513	0.3015
DIV	608	0.9667
%LAM	335	0.0038

Figure 4 shows the statistical results of the combined analysis, where both methods (“P-P” and “R-R”) in the two groups (alive and died) were used.

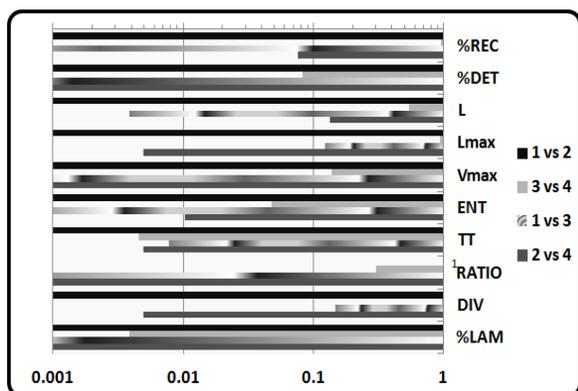


Figure 4. The combined MW U-test result of the various group: 1= Group_A (alive), 2= Group_B (died) based on “P-to-P-wave” RQA, 3= Group_A (alive), 4= Group_B (died) based on “R-to-R-wave” RQA. The x-axis represents the statistical significance in logarithmic scale.

4. Discussion and conclusions

The most important features in RQA is to select the Main. Firstly, we have to discuss the automatic measurement of our system (included the P-wave detection), and the traditional AE (without it). Figure 3. shows a patient recording, where the wide QRS does not represent ventricular ectopy: it is sinus rhythm with aberrant conduction (Figure 5.)

Secondly, the problem of measurement HRV in the case of frequent ectopy. The interpolated R-R interval does not represent the real R-R interval. The non-linear method just remembers one arbitrary value to the other.

The third important question is how to select the following nonlinear parameters: a.) the embedding dimension (suggested 8-10), b.) the radius (the three guidelines for selecting the proper radius: 1.) it must fall with the linear scaling region of the double logarithmic plot 2.) %REC must be kept low (e.g., 0.1 to 2.0%) and 3.) it may or may not coincide with the first minimum hitch in %DET. So the radius of 15% was selected), c.) the time delay, and d.) the window size.

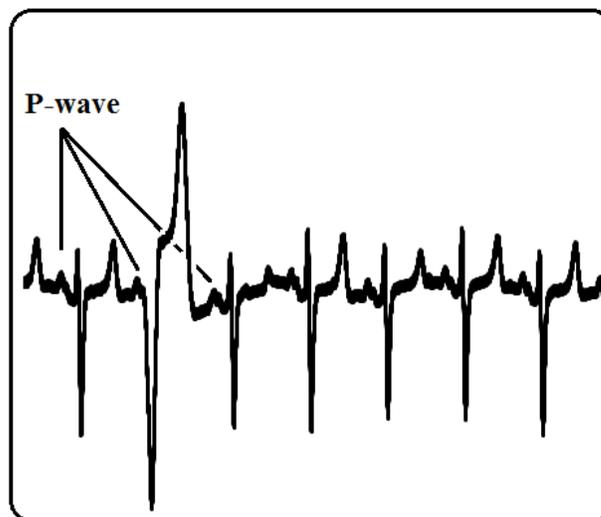


Figure 5. Misinterpretation of commercial AECG systems: the wide QRS is not a PVB, detection of p-wave (middle) shows the conduction aberrancy.

References

- [1] Marwan N, Wessel N, Meyerfeldt U, et al. Recurrence-plot based measures of complexity and their application to heart rate variability data. *Physical Review E* 2002;66:1-8.
- [2] Kurths J, Voss A, Witt A, et al. Quantitative analysis of heart rate variability. *Chaos* 1995;5:88-94.
- [3] Wessel N, Marwan N, Schirdewan A, Kurths J. Beat-to-beat complexity analysis before the onset of ventricular tachycardia. *Computers in Cardiology* 2003;30:477-480.
- [4] Balogh N, Khor S, Fugedi K, et al. Telemedicine assisted secondary prevention with individual forecasting based on ECG monitoring. *Computing in Cardiology* 2011;38:685-688

Address for correspondence

Nandor Balogh PhD
 Medartintech Ltd
 Attila u 30 IV.15.
 Budapest. Hungary. H-1201
 email: balnan2@gmail.com