Recurrence Quantification Analysis to Characterise the Heart Rate Variability Before the Onset of Ventricular Tachycardia

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Abstract. Ventricular tachycardia or fibrillation (VT) as fatal cardiac arrhythmias are the main factors triggering sudden cardiac death. The objective of this recurrence quantification analysis approach is to find early signs of sustained VT in patients with an implanted cardioverter-defibrillator (ICD). These devices are able to safeguard patients by returning their hearts to a normal rhythm via strong defibrillatory shocks; additionally, they are able to store at least 1000 beat-to-beat intervals immediately before the onset of a life-threatening arrhythmia. We study these 1000 beat-to-beat intervals of 63 chronic heart failure ICD patients before the onset of a life-threatening arrhythmia and at a control time, i.e. without VT event. We find that no linear parameter shows significant differences in heart rate variability between the VT and the control time series. However, the results of the recurrence quantification analysis are promising for this classification task.

1 Introduction

Implantable cardioverter defibrillators (ICD) are a safe and effective treatment for ventricular tachycardia or fibrillation (VT) [1-3]. These fatal cardiac arrhythmias are the main factors triggering sudden cardiac death. Therefore, an accurate identification of patients who are at high risk of sudden cardiac death is an important and challenging problem. Nowadays, third generation ICD offer not only important advances in arrhythmia treatment, but also permit the correct characterisation of the rhythm leading to intervention [4,5]. Additionally, they are able to store at least 1000 beat-to-beat intervals immediately before the onset of a life-threatening arrhythmia.

In this contribution we study the heart rate variability (HRV) of chronic heart failure ICD patients before the onset of a life-threatening arrhythmia and at a control time, i.e. without VT event. HRV parameters have been used to predict the mortality risk in patients with structural heart diseases [6,7]. Linear parameters only provide

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limited information about the underlying complex system, whereas nonlinear descriptions often suffer from the curse of dimensionality. This means that there are not enough points in the time series to reliably estimate these nonlinear measures. Therefore, we favour measures of complexity which are able to characterise quantitatively the dynamics even in rather short time series [8-10]. For ICD stored HRV data sets we found some evidence for predictability of VT in patients with a low number of ectopic beats [10]. In this investigation, we apply the concept of recurrence quantification analysis to find some precursors independently from the ectopy.

2 Methods

2.1 Patients

We studied the ICD stored 1000 beat-to-beat intervals before the onset of 131 VT episodes and at 74 control intervals without VT in 63 ICD patients of the Franz-Volhard-Hospital with severe congestive heart failure. No patient had received a class I or class III antiarrhythmic drug for 18±9 months prior to the study. Time series including more than one episode nonsustained VT, episode of induced VT, or ventricular pacing are excluded from the analysis. To estimate the amount of ventricular premature beats we use an adaptive filtering algorithm for preprocessing, which tends to be superior to standard algorithms [11]. The beat-to-beat intervals of the VT at the end of the time series were removed from the tachograms so that we analysed only the dynamics occurring immediately prior to VT.

2.2 Standard heart rate variability analysis

To detect early signs of life-threatening VT, we applied a multiparametric analysis. Before starting the analysis, ventricular premature beats and artifacts usually should be removed from the time series to construct the so-called "normal-to-normal" beat time series (NN). We used the adaptive filtering algorithm [11] for preprocessing of the data. As a basically analysis a certain number of standard HRV parameters from time and frequency domain were calculated (e.g. *sdNN, pNN50, LF/HF*) [12]. These standard parameters of HRV analysis are based on linear techniques. To classify dynamic changes in the time series, we present the following nonlinear concepts of recurrence quantification analysis outlined below.

2.3 Recurrence quantification analysis

Recurrence plots (RP) were firstly introduced to visualise time dependent behaviour of orbits in the phase space [13]. They represent the recurrence of the phase space trajectory to a state. The recurrence of states is a fundamental property of deterministic dynamical systems [14,15] - to quantify this effects Zbilut and Webber have introduced the *recurrence quantification analysis* (RQA) [16]. They define

measures using recurrence point density, diagonal segments and paling in the recurrence plot, *recurrence rate*, *determinism*, *averaged length of diagonal structures*, *entropy* and *trend*. Two of these parameters turned out to be of interest in this paper: the *determinism* and *entropy*. *Determinism* is defined as the ratio of recurrence points forming diagonal structures to all recurrence points. The *entropy* denotes the Shannon entropy of the histogram of diagonal line segment lengths and reflects the complexity of the deterministic structure in the system. First promising applications of the RQA method to heart rate variability data are described in [17-19].

2.4 The intermittency approach

The described measures are using only diagonal structures in the RP. However, a RP contains more geometrical structures which may contain important information. Therefore, we introduce measures quantifying also horizontal and vertical structures, which give qualitative information about laminar behaviour and intermittency.

Analogous to the definition of averaged length of diagonal structures, we define the averaged length of vertical structures

$$TT := \sum_{v=v_{\min}}^{N} v \cdot P(v) \Big/ \sum_{v=v_{\min}}^{N} P(v) \tag{1}$$

what we call *trapping time TT*. $P(v)$ is the probability distribution of vertical line of length v; the computation of TT is realised for values of v which exceed a minimal length v_{min}. This was done to avoid the major influence of sojourn points, as described in [20]. TT emphasises parts of the RP with vertical lines represent laminar states in the system: A system consisting mainly of laminar (or trapped) states has a high TT, a system without laminar states has a very low TT.

Similar the definition of the *determinism* [16], we can compute the ratio of the recurrence points forming the vertical structures, the so called *laminarity L*:

$$L := \sum_{v=v_{\min}}^{N} v \cdot P(v) \Big/ \sum_{v=1}^{N} v \cdot P(v) \tag{2}$$

The *laminarity* decreases if the RP consists of more single recurrence points than vertical structures. Finally, the Shannon-entropy of the distribution of the vertical line lengths $P(v)$ is calculated which is a measure for the variability of the vertical structures. If there are vertical structures with varying lengths, the entropy will be high; a lot of vertical structures with the same (or similar) lengths will cause a small entropy.

3 Results

3.1 Standard heart rate variability

We observed 131 VT episodes in 63 patients. Sixty-four episodes were not included because of atrial fibrillation, permanent pacing, incessant VT, incomplete storage of episodes, or storage artifacts. The remaining 67 VT episodes and 47 control series from 46 patients comprise the report. The mean VT cycle length was 310±53 ms. Comparing the HRV parameters of all 67 VT and 47 control time series, only the mean sinus rhythm cycle length showed differences, the time series leading to VT had a significantly shorter cycle length (meanNN 694.4±138.1 ms), than the control time series (meanNN 760.8±140.2 ms). The ectopy time, calculated as the sum of the coupling interval and the following pause of all premature beats, did not differ between the VT and control time series. The ectopy time of the VT group was 96.0±129.9 sec according to 14% of all 1024 beat-to-beat intervals and 68.2±98.1 sec, according to 9% of the control time series ($p>0.05$).

3.2 Recurrence quantification analysis

All parameters described in section 2.3. were calculated for the heart rate data before VT and at a control time. Embedding dimensions were chosen from 3 to 15, the delay equal to 1, radii from 5 to 50 % for a relative scaling approach and radii ranging from 10 to 100 ms for absolute scaling. This investigation was a totally exploratory data analysis, we had to be aware of multiple testing problems in the statistical analysis. Nevertheless, we found some significant differences between both groups of time series (see table 1).

Table 1. Significant parameters in the RQA approach. The statistical analysis was based on the two-sided t-test as well the non-parametric Mann-Whitney-U-test.

Parameter	Embedding dimension	Radius	P
Absolute scaling			
Entropy	4	10	<0.05
Determinism	12	20	<0.01
Determinism	13	30	<0.05
Entropy	14	40	<0.05
Determinism	15	70	<0.05
Relative scaling			
Determinism	15	5	<0.01
Determinism	15	10	<0.01
Determinism	5;6	15	<0.05
Entropy	10	20	<0.05

As one can see, significant results were obtained only for small radii and for high embedding dimensions. Figure 1 shows a typical example for the distribution of the

RQA parameter. Significant differences were found because of zero recurrences in the control group 0. These results are in agreement with our findings in [10], intermittently decreased epochs of short HRV before VT lead to higher number of recurrences.

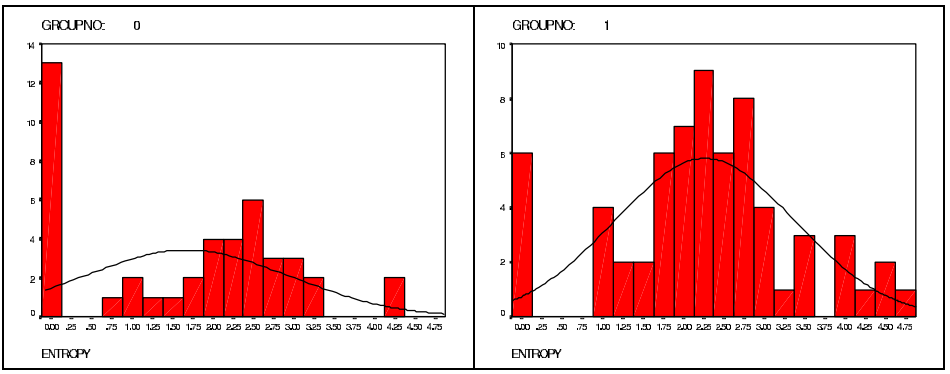

Fig. 1. The distributions of the *entropy* parameter for control group 0 as well as for VT group 1 calculated with an embedding dimension of 4 and a radius of 10 (absolute scaling).

Using the intermittency approach we could detect 8 VT time series out of all series which show extremely laminar behaviour. Non of the remaining data sets, neither control nor VT series, showed such short epochs with intermittently decreased HRV.

In a next step we tested the hypothesis if there is a correlation between the VT cycle length and some recurrence parameters before the onset of this VT. For small embedding dimensions and a fixed radius we found a increasing *laminarity* with increasing VT cycle length (see fig. 2). This means that serious VT with slow cycle length are characterised by a lower *laminarity*.

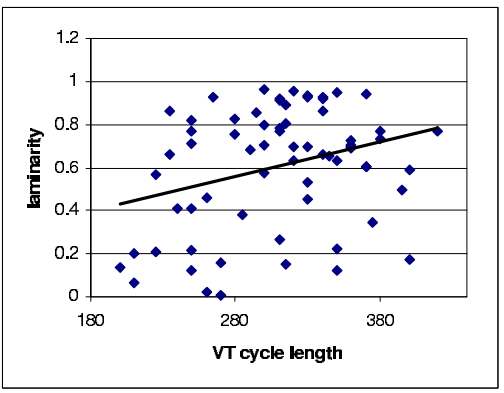

Fig. 2. The relation between the *laminarity* and the VT cycle length for an embedding dimension of 1 and a radius of 10 (absolute scaling).

4 Discussion

We identified significant differences in the dynamic behaviour of beat-to-beat intervals between the VT and control time series by means of RQA parameters. They reflect increased short laminar phases with low variability in patients with congestive heart failure preceding the onset of VT.

Another important findings in this study were the significant RR interval differences before the onset of slow and fast VT. The onset of slow VT was characterised by a significant increase in heart rate and an increase in *laminarity*. We assume that these differences illustrate a different role of autonomic regulation prior to the start of VT in both groups. Whereas slow VT began during sympathetic activation the fast arrhythmias were preceded by decreased heart rates and a low degree of *laminarity*.

Limitations of our study were the relatively small number of time series and the subsequently limited statistical analysis in terms of subdivisions concerning age, sex, and heart disease. Thus, these results must be validated with a larger data base. Our data offer the possibility of developing automatic ICD algorithms based on nonlinear dynamic HRV parameters.

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