INTERMITTENCY IN HUMAN HEART RATE VARIABILITY*

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Intermittency in time series of the time intervals between heart beats (RR intervals) extracted from 24 hour (portable) ECG is found for some cases of humans with arrhythmia. Laminar phases are found by sweeping a short (5 intervals) time window through the time series and calculating the standard deviation of the series in each window. 8 of the 18 arrhythmia cases studied had a bimodal distribution of the standard deviation values indicating some kind of intermittency. The distribution of lengths of the laminar phases identifies the intermittency obtained in human heart rate variability as Type I in the Pomeau and Manneville classification. Although the arrhythmia cases studied were medically very different — in those instances that intermittency did occur the probability distributions of laminar phase lengths were strikingly similar.

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1. Introduction

Intermittency is a phenomenon characteristic of many nonlinear dynamical systems [1]. Its primary feature is that the behavior of the system may be divided into phases which occur irregularly but whose lengths obey certain scaling rules. Several types of intermittency in dynamical systems have been identified [1]. The type of intermittency depends on the kind of bifurcation that occurs in the system. If intermittency comprises phases of regular behavior separated by chaotic bursts then intermittency of type I, II and III of Pomeau-Manneville occurs depending on whether the system is close to a tangent, a Hopf or a period doubling bifurcation, respectively.

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Chaos–chaos intermittency is due to crisis phenomena in the system [2]. On–off intermittency is related to a symmetry breaking bifurcation [3].

Theoretical analysis [1,4,5] has explained the intermittency observed in numerical experiments (see *e.g.* [6]). However, care must be taken when comparisons of the simplified models of specific intermittency types are made with both numerical calculations and with experimental data. For example, for type I intermittency it is usually accepted that the probability of obtaining a given laminar phase length l scales as l^{-2} [1]. However, this is true only in the simplified model which assumes a symmetric probability of reinjection of the trajectory into the intermittency channel. For the full logistic equation (which may be considered generic) this certainly does not occur. Hence an asymmetric laminar length distribution is obtained for the full logistic map (compare Fig. 7 with Fig. 15 and related text in [4]).

Experimental observations of intermittency have been conducted [1,6]. It has been shown that several kinds of intermittency may occur in a single system depending on the type of measurement or on the choice of parameter range [1,6]. The specific type of intermittency is identified usually by the measurement of the scaling properties of the laminar phase lengths. A very important factor in the experimental identification of intermittency is the existence of noise in the time series analyzed [4,6].

Many phenomena in biology and medicine are known to occur in an intermittent way. However, intermittency is mostly considered in the descriptive, and loosely intuitive sense only and formal intermittency analysis is still relatively rare. Since systems in biology are still most often treated as stochastic, intermittency effects are analyzed in terms of stochastic processes [7]. Although such an approach necessarily will not yield details of the intermittency process itself, the fact that intermittency quantified by means of the Hurst exponent promises to allow the assessment of the risk of heart failure [7] is interesting in itself. Type III has been identified in EEG time series measured in comatose patients [8] and during epileptic seizures [10]. Intermittency has been also found for arterial vasomotion [9] and in periodically driven pacemaker neurons [11]. Note also that, recently, new indications of the deterministic nonlinear nature of heart rate variability have been published, notably the study by Chi-Sang Poon *et al.* [12] and the control of fibrillation in humans [13].

The purpose of this paper is to analyze human heart rate data in order to assess whether intermittency occurs in the heart rate control process. It is shown that, in some cases, when some other than the normal sinus heart rhythm occurs, strong indications of intermittency are obtained. The type of intermittency is identified and features characteristic of the Pomeau-Manneville type I are found.

2. The data

Holter recordings of analog ECG were digitized at 256 Hz and the RR intervals extracted by means of the Del Mar 563 Strata Scan software. Each recording was checked for artifacts by a qualified cardiologist. 24-hour long time series were used (80000 to 120000 RR intervals).

18 patients with different types of arrhythmia were studied. For comparison 3 recordings of healthy individuals were analyzed.

3. Methods

In experimental observations of intermittency, the critical issue is the definition and identification of the phases of intermittency. A computer program for this purpose was developed.

The program allows to use two criteria by which the laminar phase is identified:

(a) as the range of the time series elements in which their standard deviation calculated in a sweeping time window falls below a certain critical value (or, alternately, exceeds that value),

(b) as the range of the time series in which its elements remain close to a certain given value (or values). This option of the program was useful for the verification of the other option on a time series generated from the logistic map for which the position of the fixed points is known.

In criterion (a) the important factor is the length of the sweeping time window. It was found that the best results were obtained for a time window of 3–10 time series elements. The results below are given for a 5 element long time window.

The program was tested on the intermittency which occurs before the period-3 window in the logistic map. 10000 laminar phases were used for the statistics. It was found that both methods yielded results which were very similar to each other.

4. Results

Fig. 1 depicts a 24 hour time series of RR intervals as measured in a 25 year old healthy male. It can be seen in Fig. 2 that the distribution of standard deviation of RR intervals, calculated as in the rest of this paper in a 5 RR interval long sliding window, decreases exponentially. For a healthy individual no intermittency can be found. Similar results were found for the other two time series recorded for healthy individuals.

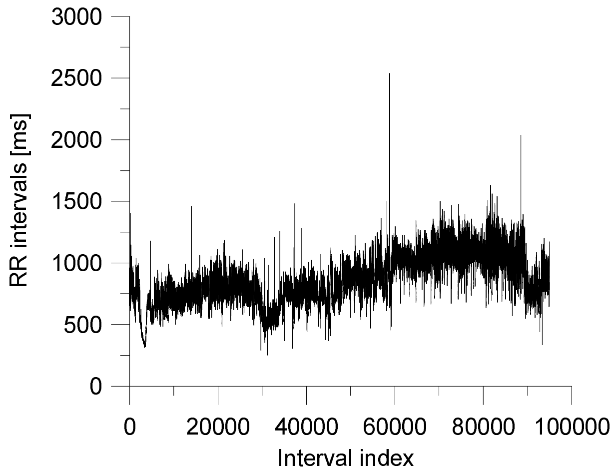

Fig. 1. A 24 hour long time series of RR intervals for a healthy, young male as a function of the interval index.

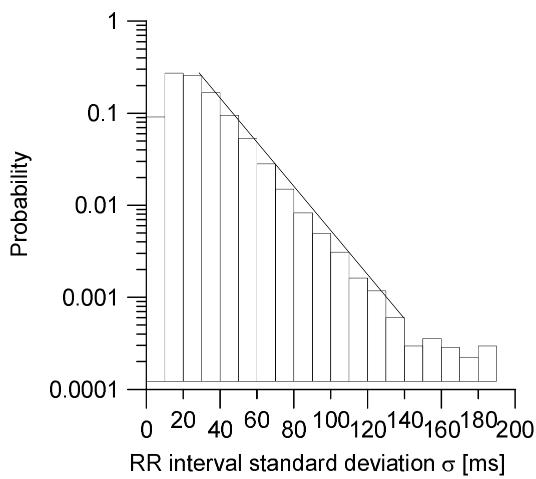

Fig. 2. Distribution of the standard deviation calculated in a 5 interval sweeping window for the data in Fig. 1.

In the case of heart rate variability, the choice of criterion for the definition of the laminar and chaotic phases is by no means obvious. Judging by typical illustrations of the type I intermittency for the logistic map [1,2,4], it would seem that the laminar phase should be defined as such a fragment of the time series in which the standard deviation of the signal analyzed is small. Consecutive iterations inside the channel are very close to each other. One should remember that, in parameter space, intermittency precedes a periodic window. The bifurcation creating such a period-n window is well visible when the n-th iterate of the map is depicted which is the case in textbooks. In the time series generated by the first iterate of the map in intermittency the consecutive iterations lie close to the period-3 orbit and their differences are not small. Consequently, the proper way to find the laminar phases of type I intermittency is to define them as those parts of time series in which the standard deviation is large.

If arrhythmia is to have anything to do with some kind of intermittency, the large standard deviation criterion is the proper discriminator of laminar phases. This may be inferred from the tachograms themselves. Fig. 3(a) depicts a case in which about 80% of the RR intervals were due to arrhythmia. It may be seen that arrhythmia is characterized by periods of large standard deviation. Moreover, in this case, the arrhythmia was of an extremely regular and for very long stretches of the time even simply periodic (Fig. 3(b)). It can be seen that the periods of arrhythmia correspond to large standard deviation values.

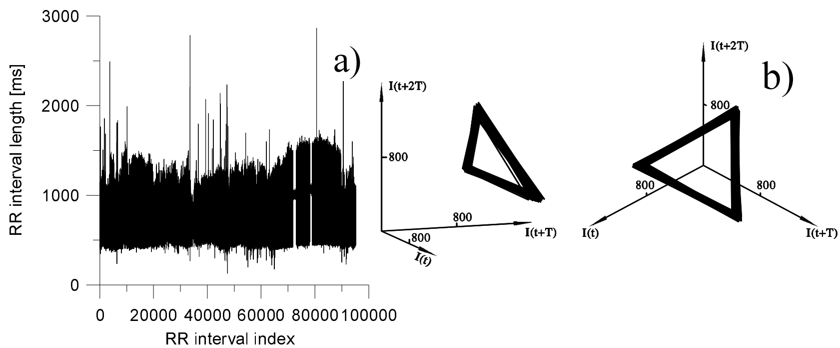

Fig. 3. Part (a) depicts the 24 hour time long series of RR intervals for an extreme case of highly ordered arrhythmia. Part (b) presents an example of 400 consecutive RR intervals in Takens delay coordinates (delay equal to 2 intervals) during one of the laminar phases in part (a) showing an almost exactly periodic behavior.

Fig. 4 depicts the time series of RR intervals of a 67 year old male who suffered a cardiac arrest in the last hour of the recording (the period of the cardiac arrest itself is missing from the time series because the R peaks could not be identified during that period). This is an example of a RR interval time series with periods of high order (see axial view in Fig. 5). It can be seen that periods of large standard deviation alternate with periods of low standard deviation in this time series. Fig. 6 depicts the distribution of standard deviation calculated in a sweeping time window of 5 RR intervals. It can be seen that there are two ranges: 0–50 ms (which is dominant) and larger than 50 ms. If one defines the laminar phases as periods of large

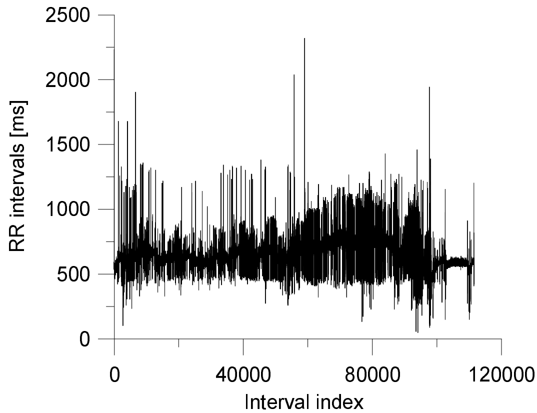

Fig. 4. The 24 hour long time series of RR intervals for the case of a 67 year old male with arrhythmia. A cardiac arrest occurred within the last hour of this recording. The event itself is missing from the time series as the R peaks were not recognizable at that period.

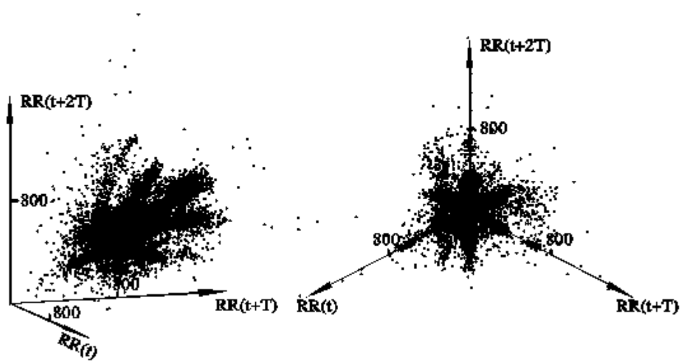

Fig. 5. The time series of Fig. 4 in the Takens delay coordinates with the delay equal to 2 intervals. Two projections are shown: a side projection and the axial projection. The outlying points seen in the latter are mostly due to arrhythmia.

standard deviation σ (*i.e.* $\sigma > 50$ ms) then the distribution of laminar phase lengths in Fig. 7 is obtained. The shape of this distribution strongly indicates that the intermittency seen in Fig. 4 and Fig. 6 is of type I in the presence of noise [4,6]. Note, that the shape of the distribution is not symmetric as would be expected from textbooks (*cf.* chapter 4 in [1]) and such asymmetry may be attributed to the asymmetry of the reinjection process [4]. The exponential tail at the large laminar phase lengths end of the distribution is due to noise [4,6]. The shape of the laminar lengths distribution obtained for the large σ criterion was very similar for all the arrhythmia cases for which the width of the distribution of the standard deviation was bimodal (almost 50% of the cases studied). A second, also typical example is shown in Fig. 8 (part (a) the distribution of 5 beat standard deviation values, part (b) — the laminar lengths distribution) for the case of a 50 year old woman with arrhythmia.

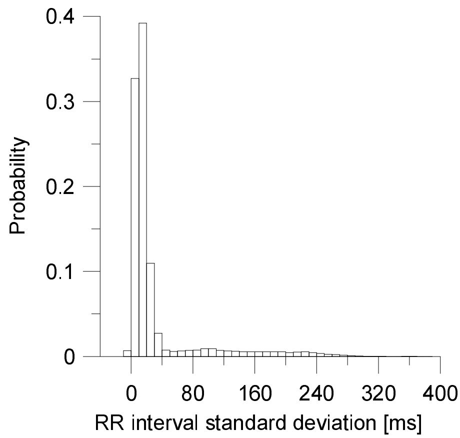

Fig. 6. Distribution of the standard deviation calculated in a 5 interval sweeping window for the data in Fig. 4 and Fig. 5.

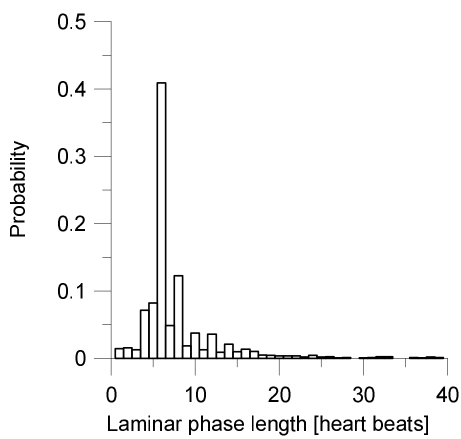

Fig. 7. Distribution of the lengths of the laminar phases for the times series in Fig. 4 (*i.e.* of all data with $\sigma > 50$ ms in Fig. 6).

An example of those cases which were medically classified as those of arrhythmia but which did not display any features of intermittency may be seen in Fig. 9. It can only be seen that the width of the distribution for such persons is much smaller than for the healthy persons (compare Fig. 2).

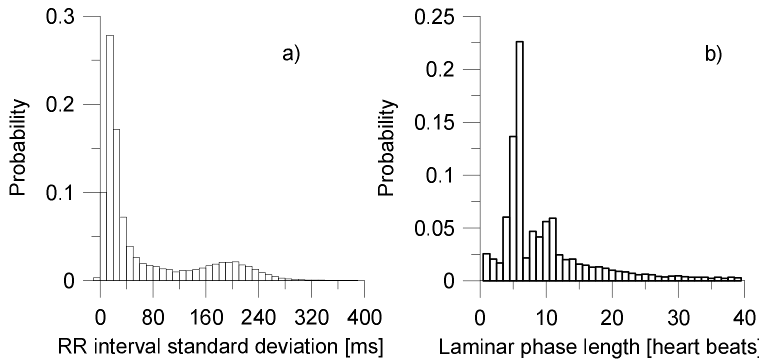

Fig. 8. Part (a): the distribution of the standard deviation calculated in a 5 interval sweeping window for the data for one of the arrhythmia cases studied. Part (b): the distribution of the lengths of the laminar phases for this times series (*i.e.* of all data with $\sigma > 100$ ms in part (a)).

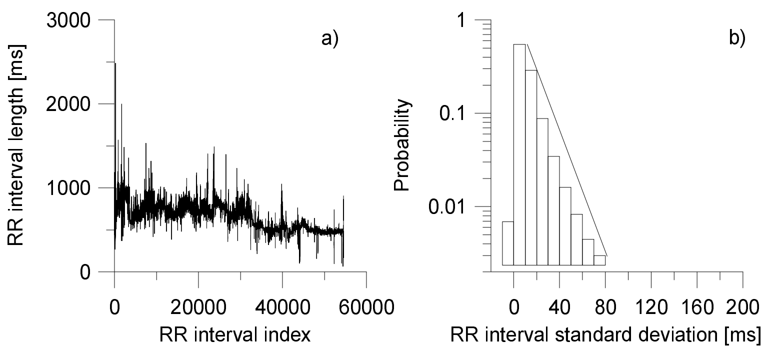

Fig. 9. Part (a): The 24 hour long time series of RR intervals for one of the arrhythmia cases studied which did not exhibit intermittency. Part (b): the distribution of the standard deviation calculated in a 5 interval sweeping window for the data in part (a).

Finally, it should be noted that very similar distributions of laminar lengths has been found when heart rate variability of certain patients with hypertrophic cardiomyopathy were examined. These patients had no arrhythmia so that only purely sinus rhythm was present. In spite of this, all results indicate that the intermittency obtained in these cases was of the same kind as in the data presented here. The group of patients with cardiomyopathy is currently being investigated and a fuller report will be published separately.

5. Conclusions

Statistical properties characteristic of type I intermittency in the presence of noise were identified in the heart rate variability of some of the patients with arrhythmia. Further research into this conclusion is needed however. In particular, laminar phases need to be examined one by one in order to analyze the return map structure.

Some indications that intermittency may be present in the heart rate variability of other groups of patients are currently being investigated. If the similarity obtained in the properties of intermittency in heart rate variability in very different groups of patients would be confirmed — especially in those with only sinus rhythm present — then the conclusion would be that the different kinds of disease create such a change of the control parameters of the heart rate variability regulation system that they drive it into intermittency. That would, however, mean that the system is predominantly deterministic and has the form of a iterated map.

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REFERENCES

[1] H.G. Schuster A, *Deterministic Chaos — An Introduction*, VCH Weinheim 1988.

[2] E. Ott, A, *Chaos in Dynamical Systems*, Cambridge University Press, N.Y. 1993.

[3] A.S. Pikovsky, *Z. Phys.* **B55**, 149 (1984); N. Platt, E.A. Spiegel, C. Tresser, *Phys. Rev. Lett.* **70**, 279 (1993); A. Krawiecki, A. Sukiennicki, *Acta Phys. Pol.* **A88**, 269 (1995).

[4] H. Hirsch, B.A. Huberman, D.J. Scalapino, *Phys. Rev.* **A25**, 519 (1982).

[5] K. Kacperski, J. Hołyst, *Phys. Rev.* **E60**, 403 (1999).

[6] J. Becker, F. Rodelsperger, Th. Weyrauch, H. Benner, W. Just, A. Cenyš, *Phys. Rev.* **E59**, 1622 (1999).

[7] D.R. Bickel, *Phys. Lett.* **A262**, 251 (1996).

[8] A.D. Rae-Grant, Y.W. Kim, *Electroencephalography & Clinical Neurophysiology* **90**, 17 (1994).

[9] J.L. Velazquez, H.K. Lozano, B.L. Bardakjian, P.L. Carlen, R. Wennberg, *Eur. J. Neuroscience* **11**, 2571 (1999).

[10] N. Stergiopulos, C.A. Porret , S. De Brouwer, J.J. Meister, *Am. J. Phys.* **274**, H1858 (1998).

[11] O. Diez Martinez, P. Perez, R. Budelli, J.P. Segundo, *Biol. Cyb.* **60**, 49 (1988).

[12] Chi-Sang Poon, C.H. Merill, *Nature* **389**, 492 (1997).

[13] F.X. Witkowski, K.M. Kavanagh, P.A. Penkoske, R. Plonsey, M.L. Spano, W.L. Ditto, D.T. Kaplan, *Phys. Rev. Lett.* **75**, 1230 (1995).