Time Reversibility in Short-Term Heart Period Variability

A Porta[1], S Guzzetti[2], N Montano[2], T Gnecchi-Ruscone[3], R Furlan[2], A Malliani[2]

[1]DiSP LITA di Vialba, Universita' degli Studi di Milano, Milan, Italy
[2]DiSC "L. Sacco", Universita' degli Studi di Milano, Milan, Italy
[3]Cardiologia, Ospedale S.L. Mandic, Merate, Lecco, Italy

Abstract

We propose a simple normalized index (i.e. the percentage of positive variations between two successive samples, PV%) and a procedure based on surrogate data to detect irreversible time series. This index was applied to short term heart period variability series (~300 cardiac beats) derived from 10 young healthy humans at rest (R), during head-up tilt (T) and controlled respiration at 10, 15 and 20 breaths/minute (R10, R15 and R20).

We found that heart period variability is time irreversible in 30%, 60%, 60%, 60% and 40% of the subjects at R, T, R10, R15 and R20 respectively. Mostly during T, R10, R15 and R20 the values of PV% indicate the presence of bradycardic runs (i.e. sequences characterized by heart period lengthening) lasting less than tachycardic ones, thus indicating a specific asymmetry of the temporal features present in the heart period variability series.

1. Introduction

A time series x={x(i), i=1,…,N} is said to be reversible if its statistical properties are invariant with respect to time reversal. This definition implies that the joint probability of (x(i),x(i+1)) equals that of (x(i+1),x(i)). Therefore, if the first return map of x in the plane (x(i),x(i+1)) is not symmetric with respect to the line x(i)=x(i+1), the series is irreversible. As points with Δx=x(i+1)-x(i)>0 stay above the line x(i)=x(i+1) and those with Δx<0 below and the distance of points from the line x(i)=x(i+1) is k·|Δx| (with $k=2^{1/2}$), the asymmetry of the first return map with respect to x(i)=x(i+1) can be evaluated by assessing the asymmetry of the distribution of Δx with respect to 0. Figure 1a shows a time series generated according to a nonlinear map (i.e. the tent map, described by x(i+1)=2·k·x(i) for 0<x(i)<0.5 and x(i+1)=2·k·(1-x(i)) for 0.5<x(i)<1 with k=0.9). This series is irreversible because the first return map is not symmetric with respect to x(i)=x(i+1) (Fig.1b) and, accordingly, the distribution of Δx is not symmetric with respect to 0 (Fig.1c).

Previous observations support the utilization of the skewness of the distribution of Δx to detect irreversible series [1]. Unfortunately, the skewness of the distribution of Δx strictly depends on the magnitude of the variations, thus being very sensible to outliers.

The aim of this study is to propose a new simple normalized index and a procedure based on surrogate data to detect irreversible time series. This index, based on the evaluation of the asymmetry of the temporal features present in the series, will be applied to short beat-to-beat variability series of heart period obtained in experimental conditions characterized by a sympathetic activation (head-up tilt) and by the periodical perturbation of the

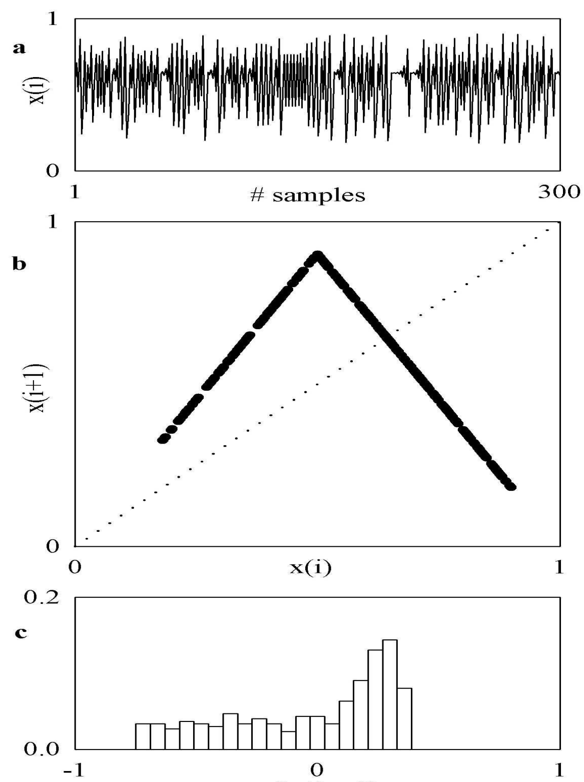

Figure 1. Realization of chaotic dynamics derived from a tent map (a), first return map in the plane (x(i),x(i+1)) (b, the dotted line is the line x(i)=x(i+1)) and probability distribution of Δx (c).

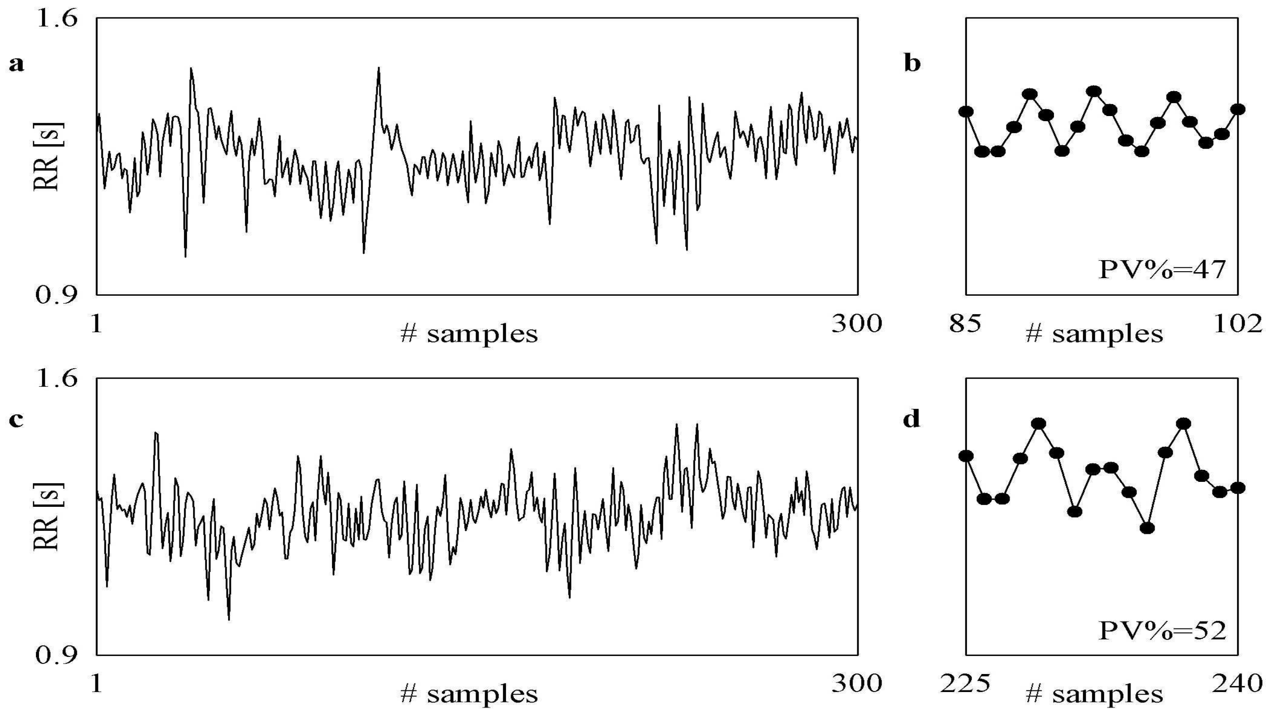

Figure 2. Original heart period variability series at R (a) and an example of FT surrogate (c) derived from it. Panels (b) and (d) show representative examples of the fastest features derived from (a) and (c) respectively.

cardiovascular control system (controlled respiration at different breathing rates).

2. Detecting irreversible series

Instead of considering the magnitude of Δx, we suggest to evaluate the percentage of positive variations (PV%) as the number of Δx>0 divided by N-1 (multiplied by 100). If the series is stationary and samples are equally spaced in time (heart period variability series are equally spaced in the beat-to-beat domain), values of PV% larger (or smaller) than 50 indicate an asymmetry of the features of the series. Indeed, PV%<50 reveals that the magnitude of |Δx| with Δx>0 is larger than that of |Δx| with Δx<0 and the distribution of Δx is skewed towards positive values. The reverse situation is observed with PV%>50. At difference of the skewness of the distribution of Δx, this index is normalized and does not depend on the magnitude of the variations. In case of the non linear dynamics shown in Fig.1a PV%=59 indicates that the series is irreversible as expected.

3. Surrogate data and statistical test

To detect if PV% is significantly different from 50 we utilized a surrogate data approach. We generated Fourier transform based (FT) surrogates [2] by, firstly, taking the FT of the original series, then, by substituting the Fourier phases with uniformly distributed random numbers ranging from 0 to 2π, and, finally, by performing the inverse FT. Since FT surrogates maintain the power spectrum of the original series and their distributions are symmetric (even though different from that of the original series), they cannot, by construction, be labeled as irreversible and have the same linear dynamical properties of the original series. We utilized a non parametric test over a set of 100 surrogates. The test parameter PV% was calculated over the surrogate data ($PV\%_s$) and over the original series ($PV\%_o$). The critical values $PV\%_{s,0.025}$ and $PV\%_{s,0.975}$ indicating the most extreme 2.5 and 97.5 percent of $PV\%_s$'s identify the range of values indistinguishable from 50. If $PV\%_o$ was smaller than $PV\%_{s,0.025}$ or larger than $PV\%_{s,0.975}$, PV% was significantly smaller or larger than 50 respectively and the original series was said to be irreversible.

4. Experimental protocol

Ten healthy young subjects (age from 24 to 32, median=28) underwent recordings of ECG (lead II) at rest (R) in supine position. Next, three sessions of paced respiration (according to a metronome) at 10, 15 and 20 breaths/minute were performed (R10, R15 and R20). The last recording was made during 80° head-up tilt (T). ECG was sampled at 300 Hz. Heart period was extracted on a beat-to-beat basis as RR interval. We analyzed RR sequences of ~300 samples.

5. Results

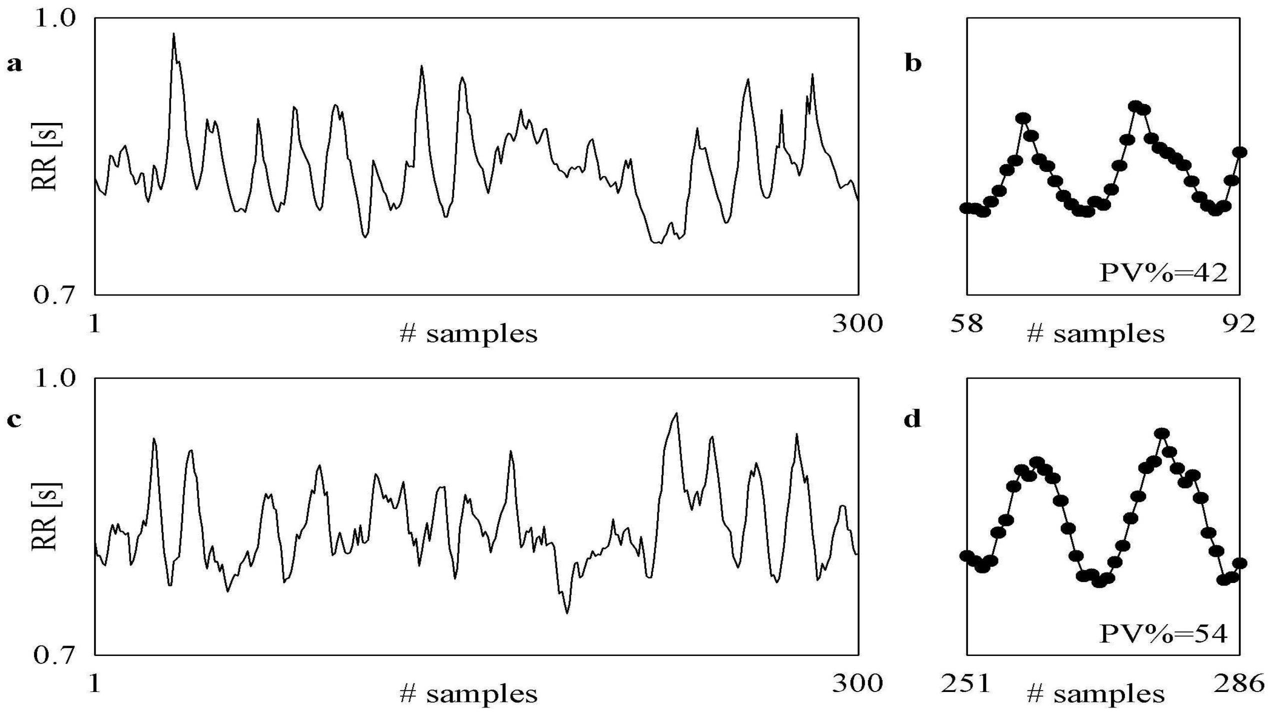

Figure 3. Original heart period variability series at T (a) and an example of FT surrogate (c) derived from it. Panels (b) and (d) show representative examples of the fastest features derived from (a) and (c) respectively.

Examples of heart period variability series at R, T and R10 are shown in Figs.2a, 3a and 4a. The smaller panels (Figs.2b, 3b and 4b) permit a better assessment of the shape of the fastest features present in the series depicted in Figs.2a, 3a and 4a (the samples are represented by solid circles). The index PV% calculated over the series of Figs.2a, 3a and 4a is 47, 42 and 37 respectively (reported in Figs.2b, 3b and 4b). Thus, positive variations are less numerous than the negative ones (see Figs.2b, 3b and 4b) and this finding is less evident at R (Fig.2b). Figs.2c, 3c and 4c shows an example of FT surrogate derived from the original series depicted in Figs.2a, 3a and 4a. The index PV% calculated over these surrogates is 52, 54 and 52 respectively (reported in Figs.2d, 3d and 4d). Accordingly, a more balanced presence of negative and positive variations can be observed in Figs.3d and 4d. Surrogate data approach detected as irreversible the series of Figs.3a and 4a.

We found that PV% is significantly different from 50 in 30%, 60%, 60%, 60% and 40% of the subjects at R, T, R10, R15 and R20 respectively. The index PV% was significantly smaller than 50 in 33%, 100%, 83%, 67% and 75% of the subjects characterized by irreversible heart period series.

6. Discussion

We suggest a simple index, i.e. percentage of the positive variations between two successive samples, to check if a series is time irreversible. If this index is larger (or smaller) than 50, the series is said irreversible. The significance of the departure from 50 is checked according to a surrogate data approach that utilizes artificial series derived from the original one by maintaining linear dynamical properties (i.e. power spectral density) but rendering symmetric the distributions. Our approach cannot prove that short-term heart period variability (~300 cardiac beats) in healthy humans is time irreversible. Indeed, at R the heart period variability series is time irreversible in a few cases (30%). However, this percentage increases during the sympathetic activation produced by T and during the periodical forcing action produced by controlled respiration at 10 and 15 breaths/minute. Mostly during T, R10, R15 and R20 PV% is significantly smaller than 50%, thus indicating the presence of bradycardic runs (i.e. sequences characterized by heart period lengthening) lasting less than tachycardic ones and evidencing an asymmetry of the patterns present in heart period variability series.

Other groups reported this asymmetry [3,4]. Barbi et al [3] found that the distribution of Δx is skewed towards negative values, thus leading them to model the respiratory sinus arrhythmia with an ascending part lasting more than the descending one. In our data during T, R10, R15 and R20 we observe mostly the opposite situation (see e.g. Figs.3 and 4). Only at R the number of subjects with PV%>50 (i.e. negative skewness) is larger than that with PV%<0 (positive skewness). More recently

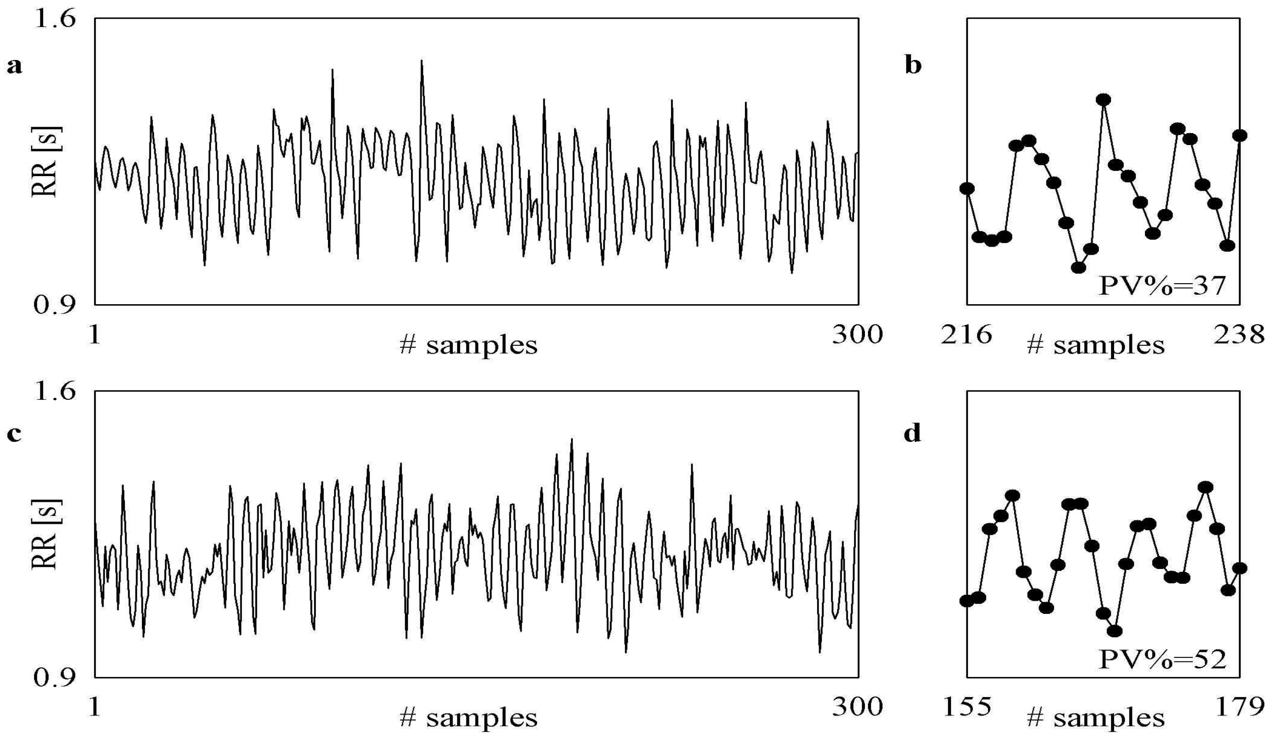

Figure 4. Original heart period variability series at R10 (a) and an example of FT surrogate (c) derived from it. Panels (b) and (d) show representative examples of the fastest features derived from (a) and (c) respectively.

Guzik et al [4] have proposed a different index quantifying the asymmetry of the distribution of Δx (i.e. the sum of the squared positive variations normalized by the sum of the squared positive and negative variations). According with our findings they found that the distribution of Δx is skewed towards positive values and, thus, that the ascending part of the heart period features lasts less than the descending part. However, with respect to our data they found at R a larger percentage of irreversible series.

The physiological reasons underlying the asymmetry of the temporal features of short heart period variability series and its more important presence during T, R10 and R15 are still unknown. Guzik et al [4] speculated that it is related to the asymmetric response of the baroreflex to increases or decreases of blood pressure [5]. However, this observation does not explain the differences between experimental conditions (e.g. between R and R10) and the presence of subjects characterized by PV%<50 and of subjects characterized by PV%>50 (even though subjects with PV%>0 are much more infrequent) in all the experimental conditions except during T.

7. Conclusions

The study of time reversibility of the heart rate variability series might provide insightful physio-pathological indexes. Specific experiments are needed to elucidate physiology underlying the asymmetry of the observed temporal features.

References

[1] Ehlers CL, Havstad J, Prichard D, Theiler J. Low doses of ethanol reduce evidence for nonlinear structure in brain activity. J Neurosci 1998, 18:7474-7486.

[2] Theiler J, Eubank S, Longtin A, Galdrikian J. Testing for nonlinearity in time series: the method of surrogate data. Physica D 1992, 58:77-94.

[3] Barbi M, Chillemi S, Di Garbo A, Balocchi R, Menicucci D. A minimal model for the respiratory sinus arrhythmia. Biol Cybern, 2006, 94:225-232.

[4] Guzik P, Piskorski J, Krauze T, Wykretowicz A, Wysocki H. Heart rate asymmetry by Poincaré plots of RR intervals. Proceedings of the IV ESGCO Congress, May 15-17, 2006, Jena, Germany, 248-251.

[5] Eckberg DL, Nonlinearities of the human carotid baroreceptor-cardiac reflex, Circ Res, 1980,47:208-216.

Address for correspondence.

Alberto Porta, PhD
Universita' degli Studi di Milano
Dipartimento di Scienze Precliniche (DiSP)
LITA di Vialba
Laboratorio di Modellistica di Sistemi Complessi
Via G.B. Grassi 74
20157, Milan, Italy

E-mail: alberto.porta@unimi.it