Chaos and Real World: Nonlinear analysis of cardiovascular variability series

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Experimental findings support the hypothesis that the behavior of many biological systems could be generated by a low-dimensional nonlinear system.

Among these, the cardiovascular system shows the fractal structure of the electrical conduction system, the quasi-periodic but also erratic behavior of electrocardiographic, blood pressure and respiration signals.

Moreover the variability is one of the main properties of the healthy heart.
Cardiovascular Signals

Variability signals
Pathology of organs vs. Pathology of controlling systems

Dynamical Diseases
HRV in MI studies

Parameters of interest

**VARIANCE**


**POWER SPECTRAL PARAMETERS**


**1/f $\alpha$ POWER LAW**


Experimental Protocol

- 24-hour Heart Rate Variability signals (HRV) from Holter recordings (80,000-120,000 R-R values):
  - 10 Normal subjects
  - 10 Heart Failure (HF) patients
  - 7 Transplanted subjects
  - 8 survived + 9 dead in ICU

For simulation purpose:
- Fractional Brownian motions (Mandelbrot-Van Ness algorithm).
  - Hurst exponent values: $H=0.1-0.9$
Recent results show the heart rate variability signal (HRV) does not only contain linear harmonic contributions (traditionally identified through spectral analysis techniques) but it possesses a fractal like geometry.

HRV is characterized by many rhythmic components interacting over different scales.

HRV time series can show fractal characteristics in their patterns, as well as in the temporal scales.

HRV with different degrees of magnification of time step, shows patterns possessing self-similar characteristics (at a more or less extent).

This observed pattern can be modified if pathological heart conditions take place.
**HRV** (short and long period analysis)


**Heart Rate Variability, standard of measurement, physiological interpretation and clinical use,**

Cardiovascular control systems

**Short time**

- 300 beats ~ 5 min
- Sympathetic and Parasympathetic control (sympatho-vagal balance)
- **Analysis by LINEAR approaches**
- (PSD estimation by AR modelling)

**Long time**

- 20,000-100,000 beats ~ 6-24 hours
- Long period “global” control
- **Analysis by NONLINEAR methods**
HRV of Normal (A) and Transplanted (B)

Delay Maps of Heart failure subjects
Methods: an overview

Systems with Deterministic-Chaotic dynamics

- Time series analysis

  Choice of \( \tau \) interval for reconstruction

Criteria for the \( \tau \) choice:
1. First zero of the AutoCorrelation function (AC).
2. First minimum of the Mutual Information criterion (MIC).

Attractor reconstruction from data

  Criteria for the \( m \) choice:
1. False Nearest Neighbors
2. Singular Value Decomposition

  Nonlinear noise filtering in the space state

Methods for the estimation of geometric and dynamic attractor parameters

- Correlation Dimension \( D_2 \)
- Correlation Entropy \( K_2 \)
- Self-Similarity Parameter \( H \)
- Lyapunov Exponents \( \lambda_1, \lambda_2, \ldots, \lambda_m \)

  Entropy \( K = \lambda_i^+ \)

  Kaplan-Yorke: \( \text{Dim } D_{KY} \)

Determinism tests on surrogate data

Parameter and algorithms evaluation on:
- Simulated data from known systems (Lorenz, Rossler, Henon...)
- Heart Rate Variability series in normal and pathological subjects
**the Lorenz system example**

**A** - Sampled time series

**B** - Reconstructed Lorenz attractor (it looks similar to the original). \( \tau \) is the time delay.

**C** - Evaluation of state space dimension (FNN)

**D** - Correlation Dimension. Flat region provide \( D_2 \) near 2

**E** - Lyapunov Exponent (LE) spectrum

**F** - LE values for growing \( m \)
Nonlinear noise filtering - algorithm

- **d**: dimension for the attractor reconstruction;
- **τ**: delay time of reconstruction;
- **k**: dimension of local subspaces;
- **ν**: number of points of each neighborhood.
Reconstructed Lorenz attractor and relevant time series:

- a) Original without noise
- b) 10% white noise added
- c) After nonlinear noise reduction (GAIN=13.5 dB after 26 iterations;

Algorithm parameters d=20, \( \tau = 1 \), k=2, \( \nu = 40 \).
Nonlinear noise filtering - results on HRV signal of a Normal subject during Night

Nonlinear noise filtering - results on HRV signal of a Heart Transplanted subject during Night

a) reconstructed attractor before and after noise reduction

b) Tachogram (2000 points) before and after de-noise procedure.
Results in AMI subjects

- **D2** and \( \alpha \) perform a **significant classification** \((p<0.05)\) of AMI subjects.
- They **separate** the **group** of subjects who after MI keep a **good performance of the cardiac pump** (NEF) **vs.** the group which after MI shows an **alteration of this function** (REF).
- \( \alpha \) values: \(1.19 \pm 0.25\) (LEF) vs. \(0.98 \pm 0.16\) (NEF) over 100,000 R-R values (24 hours)
- **D2** values: in day epoch are \(5.2 \pm 1.0\) (LEF) vs. \(6.2 \pm 0.7\) (NEF). R-R values \(=30,000\) (6-7 hours)
- Variance of HRV series was not able to significantly separate NEF and LEF group.
α slope of 1/f spectrum of HRV signal

- 9 normal, 6 hypertensive, 11 heart failure, 7 heart transplant
- HRV signals collected in the 24 hours

Increase of α slope with pathology
Conclusion

- Nonlinear parameters are able to **significantly separate** patients with different pathological conditions.

- These parameters **coupled together with others more classical indicators** of the cardiac neural control function, **could improve understanding of heart dynamics**.

- **Nonlinear characteristics** of the HRV control can assume a **clinical and predictive relevance**.

- As some authors hypothesized, healthy systems have good lines of communication. On the opposite, **systems in diseased state** can show reduced speed in crucial biological messages transfer and reception, until they become **unable to connect with other system components**.

- **Complexity in biological control system** seems related to a **nonlinear model driving the system dynamics**. The knowledge of these system properties introduces a **new insight into the heart pathophysiology** study together with **more sensitive predictive parameters**.
Anaxagoras, fragment no. 12 (500 B.C.)

νους δὲ πας ομοιός εστὶ καὶ ο μείζων καὶ ο ελαττωσ.

The Mind is self-similar, no matter whether it refers to the large or to the small