

Assessment of Cardiovascular Autonomic Control by the Empirical Mode Decomposition

E. P. Souza Neto¹, M. A. Custaud¹, J. C. Cejka¹, P. Abry², J. Frutoso¹, C. Gharib¹, P. Flandrin²

¹Laboratoire de Physiologie de l'Environnement, Université Claude Bernard, Lyon, France

²Laboratoire de Physique, Ecole Normale Supérieure de Lyon, Lyon, France

Summary

Objectives: Heart-rate variability (HRV) is an interesting tool for assessing cardiac autonomic system control, but nonstationarities raise problematic issues. The objective of this paper is to show that adapted signal processing tools may cope with nonstationary situations and improve the analysis of HRV.

Methods: We propose to use the recent method of Empirical Mode Decomposition (EMD), so as to analyze the cardiac sympatho-vagal balance on automatically extracted modes. The method, which is fully data-adaptive, consists in an iterative decomposition based on the idea that any signal can be locally represented as an oscillation superimposed to a more regular trend. When a signal is composed of distinct *nonstationary* components, EMD therefore achieves a time-varying filtering which effectively separates them.

Results: The method has been applied to situations where postural changes occur, provoking instantaneous changes in heart rate as a result of autonomic modifications. In the considered application where the sympatho-vagal balance is quantified by comparing the low-frequency (LF) and high-frequency (HF) components of RR intervals, EMD automatically achieves a separation of these components upon which further processing can be carried. Visualizing the decomposition in the time-frequency plane, we can identify local events due to the postural changes, and we can assess a (time-varying) HF vs. LF discrimination without resorting to some fixed high-pass/low-pass filtering.

Conclusion: Assessing cardiovascular autonomic control by resorting to LF/HF measurements may prove difficult in nonstationary situations where the use of a priori fixed filters can be questioned. Because it is both local and fully data-adaptive, EMD appears as an appealing and versatile pre-processing technique for overcoming some of the limitations that conventional spectral methods are faced with in nonstationary situations.

Keywords

Empirical mode decomposition, heart rate variability, sympatho-vagal balance

Methods Inf Med 2004; 43: 60–5

1. Introduction

The analysis of fluctuations in heart rate or in the intervals between consecutive heart beats (RR intervals, RRI) has become increasingly important in physiological studies because it could provide information about cardiovascular neural regulation [1]. The support for using heart rate variability (HRV) as an index of autonomic cardiovascular control comes from data demonstrating that HRV is virtually abolished after parasympathetic and sympathetic blockades. Human and animal studies support the hypothesis that the low frequency (LF) component of RRI could be used as a

marker of sympathetic modulation to the heart, high frequency (HF) component of RRI as a marker of cardiac vagal modulation and the LF/HF ratio of RRI as a marker of cardiac sympatho-vagal balance [2, 3]. Dynamical states, like standing position, are accompanied by an increased sympathetic activity characterized by a shift of the LF/HF balance in favor of the LF component; the opposite occurs during presumed increases in vagal activity [2, 4]. Thus, spectral analysis of heart rate variability has been a widely used non-invasive tool to assess sympatho-vagal drive to the heart. The most commonly used methods of spectral analysis of HRV are the (fast) Fourier transform and autoregressive models.

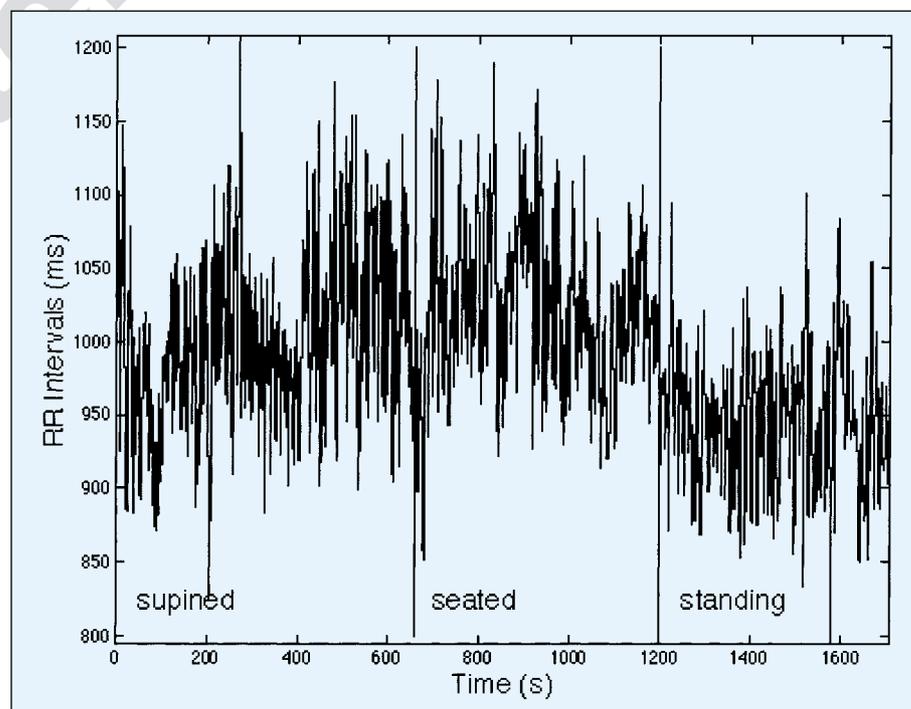


Fig. 1 RR intervals in time

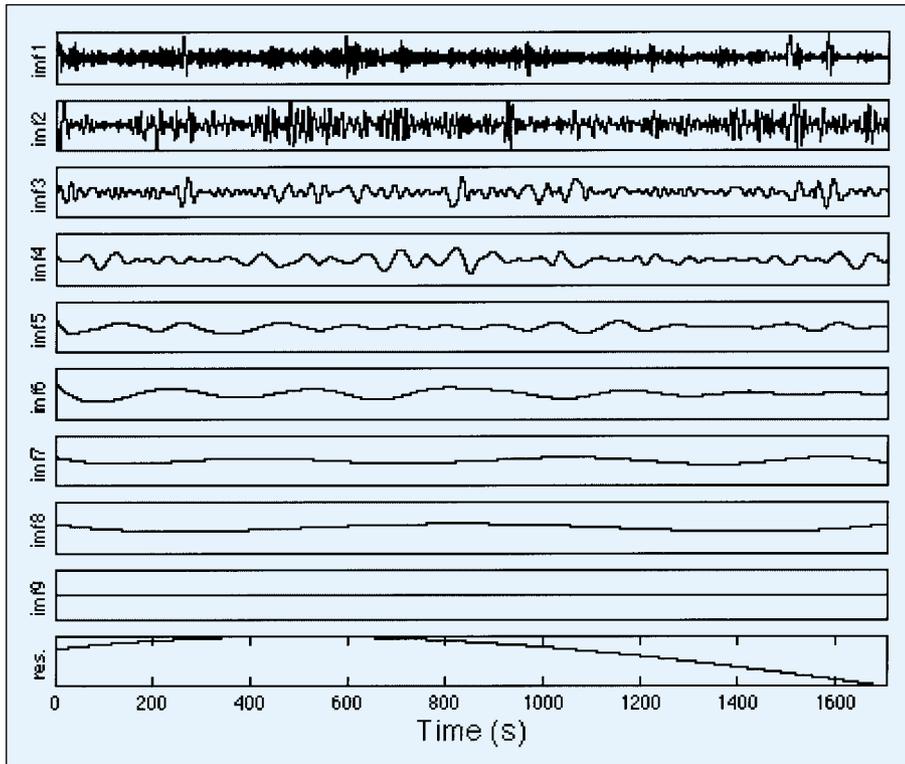


Fig. 4 Empirical Mode Decomposition of RR intervals

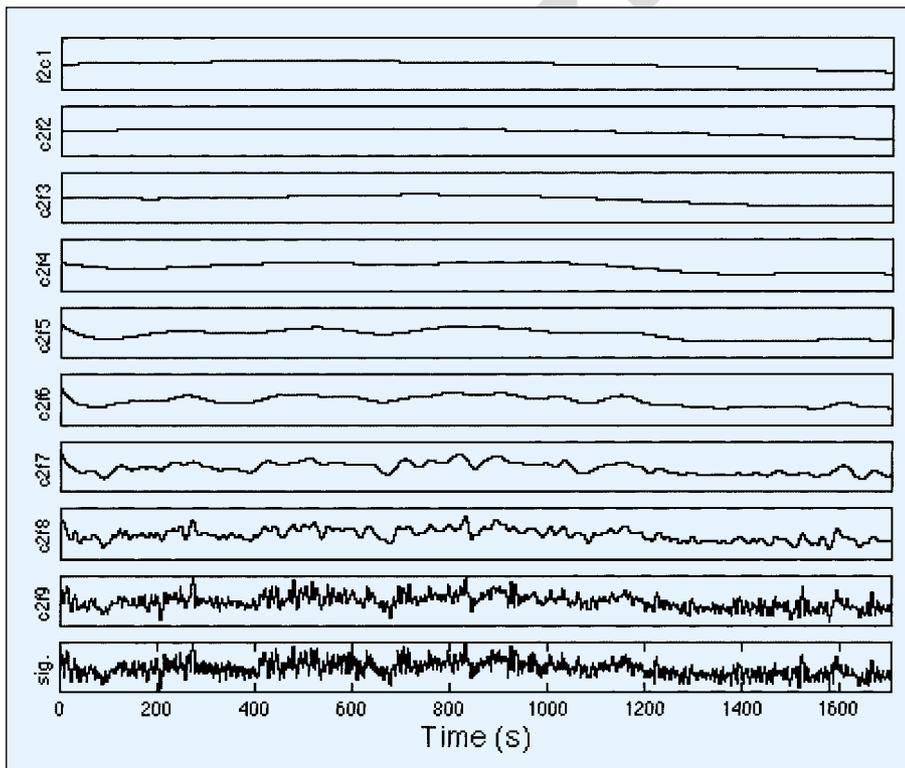


Fig. 5 Coarse to fine EMD reconstruction of RR intervals

as the one used in Figure 3 (although more elaborated methods could be used, the figure has been produced by computing a simple spectrogram for sake of simplicity [7]. It also has to be noted that, for improving readability of the diagram, the very low frequency contribution, associated in particular to “trends”, has been removed by rejecting all frequencies below 0.04 Hz). In this case, it becomes apparent that the two main frequency bands involved in Figure 2 are in fact related to the time evolution of two bandpass components. Determining the precise frequency support of these two bands (a pre-requisite for filtering them) is however difficult, and extracting corresponding AM-FM features also requires some extra post-processing (e.g., tracking of local maxima, or of local centroids).

Those difficulties suggest a different (*pre-processing*) approach which would first isolate in some way each of the two components, to which standard tools (such as instantaneous frequency estimation via the Hilbert transform) could be further applied. This point of view is the one put forward by Huang et al. [5], and referred to as “Empirical Mode Decomposition” (EMD).

2.1 Empirical Mode Decomposition

The starting point of EMD is to consider oscillations at a very local level. In fact, if we look at the evolution of a signal $x(t)$ between two consecutive extrema (say, two minima m_- and m_+ , occurring at times t_- and t_+ , respectively), we can heuristically define a (local) high-frequency part $d(t)$, or *local detail*, which corresponds to the oscillation which terminates at the two minima and which passes through the maximum M which necessarily exists inbetween m_- and m_+ . For the picture to be complete, one still has to identify the corresponding (local) low-frequency part $m(t)$, or *local trend*, so that we have $x(t) = m(t) + d(t)$ for $t_- < t < t_+$. Assuming this is done in some proper way for all the oscillations composing the entire signal, the procedure can then be applied on the residual consisting of all local trends. Constitutive components of a signal can therefore be iteratively extracted this way,

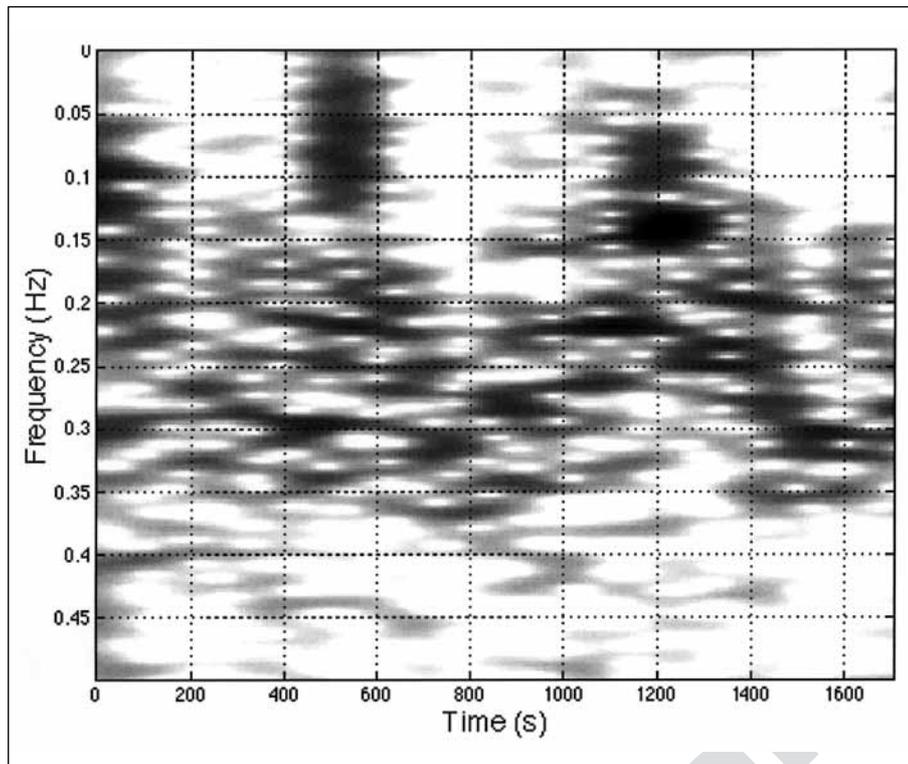


Fig. 8 HF component of RR intervals in time-frequency, identified as intrinsic mode 1 of the EMD

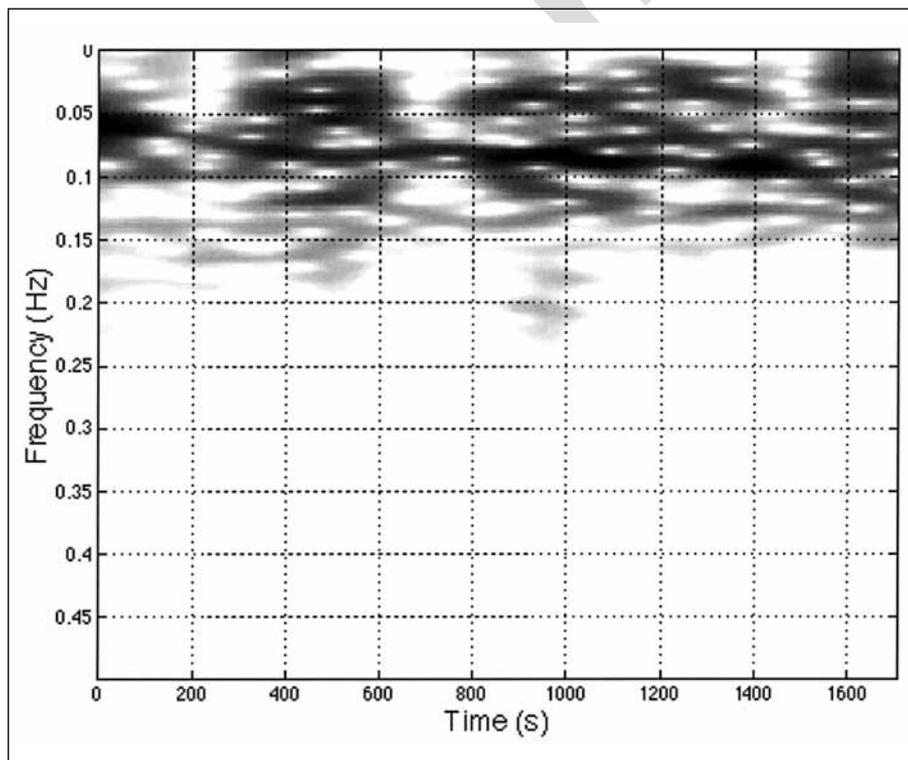


Fig. 9 LF component of RR intervals in time-frequency, identified as intrinsic modes 2+3 of the EMD

number of essential modes. In the considered case, comparing the time-frequency representation of the overall “detrended” signal (see Fig. 3) with that of the partial reconstruction built on the 3 first intrinsic modes (Fig. 7) reveals a striking agreement, thus justifying that most of the LF and HF structure of the signal has been captured. Moreover, it turns out that the obtained representation does not suffer from any arbitrary high-pass filtering aimed at removing the very low-frequency component attached to trends. This component is indeed adaptively removed (in a time-varying way) while not perturbing the adjacent LF component we are interested in. As a result, we can consider that the effective, time-varying, HF component can be identified by the first intrinsic mode of the decomposition, while the LF component is correctly described by the superposition of the second and third intrinsic modes.

This identification achieved, it becomes possible to process each of the two components independently, either by evaluating their AM-FM features, or by computing the LF/HF ratio of RRI as a marker of cardiac sympatho-vagal balance. The HF vs. LF separation is of particular importance if we consider in closer detail Figures 3 and 7, where it appears that, at the precise time instant (namely, $t = 1200$ s) where the position is changed from *seated* to *standing*, the most energetic contribution does not clearly belong to what is usually referred to the LF band (0.04-0.15 Hz) or the HF band (0.15-0.4 Hz), but rather sits on the borderline 0.15 Hz. Figures 8 and 9 display the time-frequency representations of both HF and LF components of RR intervals, evidencing the fact that this contribution is considered by the EMD as belonging to the HF part of RRI. The consequence of this identification is that the LF/HF ratio is likely to be diminished as compared to what would have been obtained with a crude filtering which would have attached part of the energy below 0.15 Hz to the LF component. The overall signal being nonstationary, and especially at changing points (with respect to position), this observation stresses the limitation of any conventional fixed filtering in a time-varying situation.

4. Conclusion

A link appears to exist between cardiac vagal or sympathetic activity and HF or LF oscillations of RRI. A number of approaches are currently available for analysing periodic components of RRI like the (fast) Fourier transform or autoregressive models. These methods can provide valid estimates of periodic components of HRV when the target rhythm is sinusoidal and the data is stationary. In recent years the study of data analysis has tended to focus far more on the methods that do not need linearity and periodicity of the signal. This comes from the fact that it has been quite difficult to satisfactorily handle the nonstationary mechanisms regulating the cardiovascular system using conceptualisations based on stationarity. In order to cope with nonstationarity issues and to adaptively separate the (time-varying) HF and LF components of RRI, we proposed here to make use of the recently introduced method of Empirical Mode Decomposition (EMD), so as to analyze the cardiac sympa-

tho-vagal balance on automatically extracted modes. Using this method and visualizing the result in the time-frequency plane, we can identify local events due to changing position, and we can assess a (time-varying) HF vs. LF discrimination without resorting to some fixed high-pass/low-pass filtering.

Acknowledgements

This work was supported by grants from CNES.

References

1. Parati G, Saul JP, Di Rienzo M, Mancia G. Spectral analysis of blood pressure and heart rate variability in evaluating cardiovascular regulation – A critical appraisal. *Hypertension* 1995; 25: 1276-86.
2. Pagani M, Lombardi F, Guzzetti S, Rimoldi O et al. Power spectral analysis of heart rate and arterial pressure variabilities as a marker of sympatho-vagal interaction in man and conscious dog. *Circulation Research* 1986; 59: 178-93.
3. Malliani A, Pagani M, Lombardi F, Cerutti S. Cardiovascular neural regulation explored in the frequency domain. *Circulation* 1991; 84: 482-92.
4. Wieling W, Borst C, Van Brederode JF, Van Dongen Torman MA et al. Testing for autonomic neuropathy: heart rate changes after orthostatic manoeuvres and static muscle contractions. *Clin Sci* 1983; 64: 581-6.
5. Huang NE, Shen Z, Long SR, Wu MC et al. The empirical mode decomposition and the Hilbert spectrum for nonlinear and non-stationary time series analysis. *Proc R Soc Lond A* 1998; 454: 903-95.
6. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Heart rate variability: Standards of measurement, physiological interpretation, and clinical use. *Circulation* 1996; 93: 1043-65.
7. Auger F, Flandrin P, Gonçalves P, Lemoine O. Time-Frequency Toolbox for Matlab. Freeware downloadable at URL <http://iut-saint-nazaire.univ-nantes.fr/~auger/tftb.html>

Correspondence to:

P. Flandrin
Laboratoire de Physique
Ecole Normale Supérieure de Lyon
■ Lyon
France
E-mail: flandrin@ens-lyon.fr