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Chaos based nonlinear analysis to study cardiovascular responses to changes in posture

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HIGHLIGHTS

- Study of ECG and BP in different posture using MFDXA.
- Different degree of auto and cross-correlation for both ECG and BP signals observed.
- Degree of multifractality (W) and degree of correlation (γ) are studied.

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ABSTRACT

Cardiovascular responses to changes in posture have been the focus of numerous investigations in the past. Analysis of ECG and arterial blood pressure (ABP) data for different postures, obtained from ‘Physionet’ was done from a new perspective of analyzing nonlinear time series having multifractal features. Multifractal detrended fluctuation analysis (MFDFA) and also the cross-correlation between ECG and BP with another technique Multifractal detrended cross-correlation analysis (MFDXA) reveals ECG and ABP time series of different subjects to be multifractal in nature with different degree of complexity. Different degree of auto and cross-correlation for both ECG and ABP signals is also observed for all subjects.

Further significant information obtained from the cross-correlation parameters obtained from MFDXA analysis is very important and relevant particularly for understanding the dynamics of orthostatic stress.

1. Introduction

Physiological systems are generally complex involving several nonlinearities. A characterization of interactions between dynamical systems from the analysis of signals recorded from them is the key to understanding many phenomena studied in natural and social sciences [1]. The analysis of variability of various physiological signals has undergone considerable growth in the recent years. Analysis of linear statistics (e.g., mean values, variability measures and spectra analysis) of physiological signals does not directly characterize their complexity, irregularity or predictability. Methods based on non-linear dynamics

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and "chaos" theories reveal subtle abnormalities in the cardiovascular regulation mechanisms that may not be uncovered by traditional (i.e., "linear") measures of variability, and thus, they provide a useful tool for in depth evaluation of the properties of complex physiological systems [2].

Cardiovascular research in the field of non-linear dynamics has mainly focused on heart rate and less importance has been given to blood pressure (BP) variability, though continuous BP fluctuations are intrinsic characteristics of cardiovascular system [2].

Blood pressure (BP) is one such physiological signal which is of great concern to experts in the field of health as there is no alternative method of measuring other than the sphygmomanometer. The Electrocardiogram (ECG) signal represents the electrical activity of heart cells. This impulse causes the rhythmic contraction of the heart, where the electrical performance of the heart is represented by beats [3]. Several authors have advocated the fact that conventional time and frequency domain analysis techniques based on the linear fluctuation of heart rate is insufficient to outline the changes in heart rate dynamics [4–15] thus, new methods based on nonlinear dynamics have been introduced to quantify complex heart rate dynamics and complement conventional measures of its variability [16].

1.1. Review of existing work

Pioneer work of Glass et al. introduced nonlinear approaches into heart rhythm analysis [17]. Ritzenberg et al. were the first to provide evidence of nonlinear behavior in ECG and arterial blood pressure traces of a dog that had been injected with noradrenaline [18]. In 1987 Goldberger and West were the first to study HR variability using nonlinear fractal dynamics [19].

Evidence [20] of a close nonlinear coupling between the respiratory and cardiovascular system was provided in 1993 by Novak et al. [21]. Peng et al. [22] applied detrended fluctuation analysis (DFA) to quantify the fractal structure of the HR, which was later validated in 1999 [23]. The discovery of the multifractal nature of HR dynamics by Ivanov et al. [24] showed that the heartbeat modulation is even more complex than previously suspected, requiring multiple scaling exponents for its characterization. A very promising way to quantify complexity over multiple scales was introduced by Costa et al. [25,26].

Papaioannou et al. [2] investigated the effect of caffeine on indices expressing the complex and "chaotic" nonlinear characteristics of BP variability. Pachauri et al. [27] investigated the phase synchronization between ECG and arterial BP in order to find the interactions between the two signals. Estrada et al. [3] with the use of neural networks demonstrated the existence of a relationship between ECG signals and BP.

Špulák et al. in a study found the correlation coefficients between systolic BP and parameters computed from ECG and photoplethysmography (PPG) to vary strongly subject to subject [28]. Gesche et al. [29] in a work showed that the created pulse wave velocity (PWV)-BP function, including a one-point calibration, produced significant correlation between BP derived from the PWV and the systolic BP measured by sphygmomanometer Ahmad et al. [30] presented a method whereby ECG-assisted oscillometric and pulse transit time (PTT) analyses were seamlessly integrated into the oscillometric BP measurement paradigm. The method bolstered oscillometric analysis (amplitude modulation) with more reliable ECG peaks provided a complementary measure with PTT analysis (temporal modulation) and fused this information for robust BP estimation.

The autonomic nervous system (ANS) which is a part of the central and peripheral nervous system can be divided into sympathetic and parasympathetic nervous system. Their activities affect heart rate (HR), respiration rate, blood pressure etc. The activation of the sympathetic nervous system can raise BP and accelerate the HR and the parasympathetic nervous system can slow down the HR [31]. Heart rate variability (HRV) is used to estimate the ANS activities of human traditionally [32–34].

Various physiological maneuvers have been used to gain a deeper insight into the functioning of the autonomic nervous system. Investigators often use a change in posture by either passive head-up tilt or active standing to impose perturbation on the steady state functioning of the ANS [35]. Cacioppo et al. [36] have suggested that vagal activity is highest and sympathetic activity is lowest in the supine posture. The reverse occurs in the standing posture and combination is characteristic for sitting posture [36]. Thus body position and postural changes determine a gravitational gradient acting upon the cardiovascular and pulmonary systems [37]. The maintenance of upright posture not only requires coordinated neuromuscular control of postural muscles [38], but also cardiovascular reflexes to maintain BP. Several researchers have investigated the relationship between postural changes and cardiovascular response via the HR and BP [39–43].

Bishop et al. [44] employed the wavelet modulus maxima technique to characterize the multifractal properties of HR and mean arterial BP physiology retrospectively for four patients during open abdominal aortic aneurysm repair. Several other authors using a variety [20] of nonlinear techniques investigated the interactions and couplings between HR and respiration and HR and BP, respectively [45–49]. Some studies investigated spectral analysis of HRV in response to the posture changes maneuver and dynamic exercise [50–60]. Tulppo et al. [61] reported the behavior of the alpha-1 during the passive tilt test. The knowledge of physiological responses induced by autonomic tests is relevant to provide further information regarding autonomic cardiac regulation and autonomic dysfunction diagnosis [62]. Though the responses caused by the passive orthostatic test are elaborated in [50,51] but it was not clear how long the autonomic nervous system spends to induce sympathetic and parasympathetic changes immediately after the change of position. So in order to provide methodological information regarding this autonomic test, Souza et al. [63] aimed to investigate the effects of the posture changes maneuver on fractal exponents through DFA in young women, as well as the time and frequency domains indexes of HR.