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Linear and nonlinear analysis of normal and CAD-affected heart rate signals

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ABSTRACT

Coronary artery disease (CAD) is one of the dangerous cardiac disease, often may lead to sudden cardiac death. It is difficult to diagnose CAD by manual inspection of electrocardiogram (ECG) signals. To automate this detection task, in this study, we extracted the heart rate (HR) from the ECG signals and used them as base signal for further analysis. We then analyzed the HR signals of both normal and CAD subjects using (i) time domain, (ii) frequency domain and (iii) nonlinear techniques. The following are the nonlinear methods that were used in this work: Poincare plots, Recurrence Quantification Analysis (RQA) parameters, Shannon entropy, Approximate Entropy (ApEn), Sample Entropy (SampEn), Higher Order Spectra (HOS) methods, Detrended Fluctuation Analysis (DFA), Empirical Mode Decomposition (EMD), Cumulants, and Correlation Dimension. As a result of the analysis, we present unique recurrence, Poincare and HOS plots for normal and CAD subjects. We have also observed significant variations in the range of these features with respect to normal and CAD classes, and have presented the same in this paper. We found that the RQA parameters were higher for CAD subjects indicating more rhythm. Since the activity of CAD subjects is less, similar signal patterns repeat more frequently compared to the normal subjects. The entropy based parameters, ApEn and SampEn, are lower for CAD subjects indicating lower entropy (less activity due to impairment) for CAD. Almost all HOS parameters showed higher values for the CAD group, indicating the presence of higher frequency content in the CAD signals. Thus, our study provides a deep insight into how such nonlinear features could be exploited to effectively and reliably detect the presence of CAD.

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1. Introduction

Coronary arteries supply nutrients and oxygen to heart muscles. Coronary Artery Disease (CAD) is a pathological condition where the diameter of the arteries decreases either due to the formation of cholesterol plaque on its inner wall [1] or due to the contraction of the whole wall for other reasons, such as tobacco smoking [75] and environmental pollution [2]. The condition is often ominously silent, but progressive in nature. If it is not treated appropriately, it will eventually lead to ischemia (i.e., interruptions of blood supply) and then infarctions (i.e., the complete loss of blood supply). Usually one of the reasons for Sudden Cardiac Death (SCD) is CAD [3]. Hence, early detection of CAD is essential to prevent SCD.

One of the most commonly used techniques for CAD detection is the Exercise Stress Test (EST). EST increases the workload of the heart and records exaggerated electrophysiological information. For this test to be accurate, a target Heart Rate (HR) has to be attained. Not all CAD patients can reach this rate. Furthermore there is considerable risk for the patient, because such a stress test can trigger Ventricular Tachycardia (VT) or cardiac arrest [4].

Electrocardiogram (ECG) could be a useful physiological measurement tool to detect the presence of CAD. However, visual interpretation of the ECG signals is not so effective as 50–70% of CAD patients do not show any notable difference in their ECGs [5]. However, the minute variations in the ECG signals have to be identified in order to diagnose specific type of heart disease. Due to the presence of noise and baseline wander, it is tedious to detect the minute variations by evaluating the morphological features of ECG signals. Hence, in this study, we extracted the HR from the ECG signals and used them for analysis. The study of heart rate variability (HRV) is a better technique to diagnose CAD risk levels. HR is a nonlinear, non-stationary signal which indicates the subtle variations of the underlying ECG signal [6]. The HRV evaluates the changes in the consecutive heart rates and it assesses the health of the autonomic nervous system (ANS) non-invasively. The HRV analysis conveys information about homeostasis of the body [7]. Standard methods to analyze the HRV were proposed in various domains [8].

Various cardiac and non-cardiac diseases have been diagnosed using HR signals [6,9–12]. They have analyzed the HR signals using various linear and non-linear techniques [6]. Huikuri et al. (1994) have analyzed the CAD subjects using HRV signals and showed that, the circadian rhythm decreases in CAD subjects. Hayano et al. [13] have shown a correlation between CAD severity and a reduction low-frequency power reduction decrease in high frequency power were shown in CAD subjects Lavoie et al. [14], Nikolopoulos et al. [15] and features of time and frequency domain were found to be lower for CAD subjects Bigger et al. [16]. The statistical measures changes with time and hence time domain analysis is not effective and effectiveness of frequency domain analysis decreases with reduction in the signal to noise ratio [17].

Nonlinear techniques are more in tune with the nature of physiological signals and systems, therefore, they outperform time and frequency domain methods. Hence, they are widely used in many biological and medical applications [18,19]. Owis et al. [20] performed ECG-based arrhythmia detection and classification based on nonlinear modeling. Sun et al. [21], Acharya et al. [22] and Chua et al. [23] used nonlinear techniques to analyze cardiac signals for the development of cardiac arrhythmia detection algorithms. Schumacher [24] elaborated the effectiveness of linear and nonlinear techniques in analyzing HR signals. The onset of various cardiovascular diseases like, Ventricular Tachycardia (VT) and Congestive Cardiac Failure (CCF) can be predicted using non-linear analysis of HR signals [25]. Chua et al. [26] introduced a method to extract features like bispectral entropy from HR signals by employing Higher Order Spectra (HOS) techniques. In their study, HOS features from HR signals were used to differentiate between a normal heart beat and seven arrhythmia classes. CAD results in reduced Baroreflex Sensitivity (BRS) and reduced vagal activity which can be understood by HRV analysis. BRS is an indicator of increased risk of SCD in myocardial infarction patients. Arica et al. [27] used HR and systolic pressure signals to assess BRS.

The main aim of this paper is to present time, frequency and non-linear features for normal and CAD-affected HR signals. For this analysis, we extracted and analyzed features in the time domain, frequency domain, and also studied features derived using nonlinear methods. Furthermore, we have proposed various ranges for these features and presented unique nonlinear plots for the normal and CAD classes. Our results show that CAD subjects have less variability in their heart rate signal when compared to normal subjects. This reduced variability can be used as a single measure to diagnose CAD from ECG signals which were obtained under normal conditions. We predict that the consequent use of HRV measures will reduce the need to conduct stress ECG measurements, and therefore, expose patients to less risk.

2. Data used

ECG signals from 10 CAD patients and an equal number of healthy volunteers were recorded using the BIOPAC^{TM} equipment http://www.biopac.com/ [74]. The sampling frequency of ECG signal was 500 Hz. The average age of both normal and CAD subjects was 55 years (age varied from 40 to 70 years). The CAD patients used for this study, were taken from Iqraa Hospital, Calicut, Kerala, India. Subjects having normal blood pressure, glucose level and ECG were considered in the *normal* category. For the *CAD* patients, coronary angiography (CAG) was performed. Patients with more than 50% narrowing in the left main artery were considered for this study. Patients suffering from bundle branch block (left or right bundle branch block), hypertrophy, atrial fibrillation, congestive heart failure, myopathy, and taking any cardiac medication are excluded in this study. The patients were selected by a cardiologist based on the similarity of their medications. It was assumed that the drug effects on the HR signal were similar. The data comprised a total of 61 normal and 82 ECG CAD datasets; each set had 1000 samples from 10 subjects. The variations of ECG signals in CAD and normal subjects are shown in Fig. 1.

The ECG beats were sent via a band pass filter with a lower cut off frequency of 0.3 Hz to eliminate baseline wander and higher cut off frequency of 50 Hz to eliminate the noise. A