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An efficient automated technique for CAD diagnosis using flexible analytic wavelet transform and entropy features extracted from HRV signals

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ABSTRACT

Coronary Artery Disease (CAD) causes maximum death among all types of heart disorders. An early detection of CAD can save many human lives. Therefore, we have developed a new technique which is capable of detecting CAD using the Heart Rate Variability (HRV) signals. These HRV signals are decomposed to sub-band signals using Flexible Analytic Wavelet Transform (FAWT). Then, two nonlinear parameters namely; K-Nearest Neighbour (K-NN) entropy estimator and Fuzzy Entropy (FzEn) are extracted from the decomposed sub-band signals. Ranking methods namely Wilcoxon, entropy, Receiver Operating Characteristic (ROC) and Bhattacharya space algorithm are implemented to optimize the performance of the designed system. The proposed methodology has shown better performance using entropy ranking technique. The Least Squares-Support Vector Machine (LS-SVM) with Morlet wavelet and Radial Basis Function (RBF) kernels obtained the highest classification accuracy of 100% for the diagnosis of CAD. The developed novel algorithm can be used to design an expert system for the diagnosis of CAD automatically using Heart Rate (HR) signals. Our system can be used in hospitals, polyclinics and community screening to aid the cardiologists in their regular diagnosis.

1. Introduction

Nowadays, cardiovascular diseases are the major causes of death in the world. Every year almost 17 million people die due to cardiovascular diseases globally (Wong, 2014). Death due to Coronary Artery Disease (CAD) is higher than any other type of heart disease (Wong, 2014). In the case of CAD, plaque, a waxy substance, deposits inside the coronary arteries, which interrupts the blood flow into the heart muscles (National Heart, Lung & Blood Institute, 2015). The CAD affects the strength of heart muscles, which disturbs heart pumping and may ultimately lead to arrhythmias and heart failure (National Heart, Lung & Blood Institute, 2015). Therefore, early stage detection of CAD is of prime importance.

To detect the presence of CAD, physicians review the clinical history of the subject and perform diagnostic tests such as; stress test, Electrocardiogram (ECG), echocardiogram, chest X Ray, cardiac catheterization and coronary angiography (National Heart, Lung & Blood Institute, 2015). All these techniques have few limitations. In few cases, ECG recording may not show significant difference between CAD and normal patients (Giri et al., 2013). During stress test, for accurate analysis a target heart rate must be achieved. Few CAD patients can not attain this rate (Acharya et al., 2014). Cardiac catheterization and coronary angiography are invasive techniques and can be performed in the presence of expert clinicians (Giri et al., 2013; National Heart, Lung & Blood Institute, 2015). These difficulties can be overcome easily by using computer operated system for the diagnosis of heart diseases (Acharya, Bhat, Iyengar, Rao, & Dua, 2003; Giri et al., 2013).

Advanced digital signal processing techniques can be used to diagnose the CAD patients. These techniques may be helpful to extract the information provided by the Heart Rate (HR) signals. These signals show nonlinear and non-stationary nature, and may have valuable information about the nature of heart disease (Acharya, Kannathal, & Krishnan, 2004). The variations of heart rate signals are also termed as Heart Rate Variability (HRV). These signals have wide applications in biomedical for detecting diseases related to heart. In (Chua, Chandran, Acharya, & Lim, 2008), HRV signals of normal and arrhythmia subjects are investigated using

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higher order spectral analysis. Moreover, HRV signals are used to predict the risk of cardiovascular diseases (Acharya, Sankaranarayanan, Nayak, Xiang, & Tamura, 2008) and sudden cardiac death (Fujita et al., 2016). Other than heart diseases, these signals are also used to detect diabetes (Acharya et al., 2015; Pachori, Avinash, Shashank, Sharma, & Acharya, 2015; Pachori, Kumar, Avinash, Shashank, & Acharya, 2016).

Significant variations are noticed in the range of nonlinear features for normal and CAD HR signals (Acharya et al., 2014). Power spectral analysis and time-domain based features are obtained from HR signals (Bigger et al., 1995). All these parameters are found to be significantly lower for CAD patients. In Hayano et al. (1990), it is shown that spectral components of HR signals have relationship with the angiographic features of CAD. In Acharya, Bhat, Kannathal, Rao, and Lim (2005), wavelet transform and fractal dimensions are used to analyse the HR signals. Fractal dimension showed decreased for diseased heart. Nonlinear features such as, mutual information, embedding dimension error, fractal dimension, and recurrence percentage are found significantly different for ECG signals of CAD and non-CAD subjects (Antanavičius et al., 2008). Block entropies are estimated from healthy and CAD HR time series, which have higher values for healthy subjects as compared to CAD subjects (Karamanos et al., 2006). HRV signals of normal and CAD subjects are studied for different sample lengths (Sood, Kumar, Pachori, & Acharya, 2016). Five features namely, Amplitude Modulation (AM) bandwidth, Frequency Modulation (FM) bandwidth, Second-Order Difference Plot (SODP), Analytic Signal Representation (ASR) area and *mean* frequency of Fourier-Bessel expansion (FBE) are extracted from intrinsic mode functions. FM-bandwidth, AM-bandwidth and *mean* frequency of FBE showed more discriminating ability among five features. In (Ji et al., 2016), ECG signals and photoplethysmography of CAD and normal subjects are studied. Further, heartbeat interval series, diastolic time interval series, and systolic time interval series are constructed from these signals. Thereafter, cross-correlation, mutual information, cross-conditional entropy, coherence function, cross fuzzy entropy and cross sample entropy are studied on these constructed series for diagnosis of CAD.

The objective of present work is to develop a noninvasive methodology that can automatically diagnose the CAD using HR signals. To deal with the non-stationary nature of HR signals, Flexible Analytic Wavelet Transform (FAWT) (Bayram, 2013) is used to decompose the signals in terms of sub-band signals. Nonlinear features namely; K-Nearest Neighbour (K-NN) entropy estimator and Fuzzy Entropy (FzEn) are used to extract the nonlinear dynamics corresponding to sub-band signals obtained from HR signals. The steps performed in the present work are shown in Fig 1.

The contribution of the present study is to propose new entropy based features namely, K-NN entropy estimator and FzEn derived from sub-bands obtained from HRV signals using FAWT technique. We also propose an automated Least Squares-Support Vector Machine (LS-SVM) based classification system using these features for CAD diagnosis. The use of less number of features (only four) and 10-fold cross-validation make proposed classification system easy to implement and reliable. The proposed classification system obtained 100% classification accuracy using only four features.

Our proposed CAD diagnosis expert system is completely automated. It comprises two steps: (i) training and (ii) testing. During training step, classifier is trained using entropy features extracted from the sub-bands of FAWT. In the testing phase, unknown HR signal is fed to our system. Then same entropy features are extracted and fed to the pre-trained classifier for automated diagnosis (normal or CAD). Such an expert system will help the clinicians in their daily screening of cardiac patients. It can substantially reduce the possible human errors, screening time, and make the system robust.

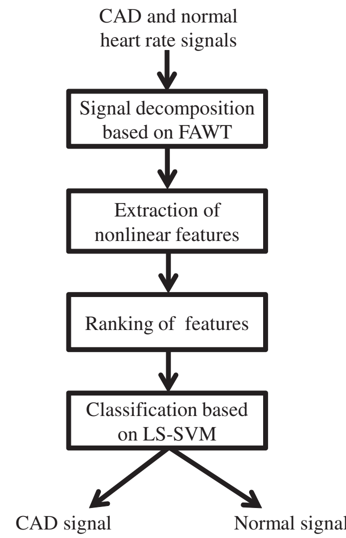

Fig. 1. The proposed automatic system for detecting CAD based on HR signals.

The organization of remaining part of this work is as follows: Section 2 describes data acquisition, preprocessing, FAWT, nonlinear features studied, feature ranking methods and LS-SVM classifier. The obtained results are provided in Section 3. Section 4 presents the discussion part. Finally, Section 5 provides the conclusion of the entire work.

2. Methodology

2.1. Process of data acquisition

ECG signals were recorded from 10 healthy subjects and 10 CAD patients at Iqraa Hospital, Calicut, Kerala, India (Acharya et al., 2014). BIOPAC^{TM} equipment was used to record the ECG signals at a sampling rate of 500 Hz (BIOPAC Systems Canada Inc., 2010). All the CAD subjects participated in the study were on similar medication. The age of all the subjects under the study ranges between 40 to 70 years. All the procedure of signal acquiring was performed under the assistance of an experienced cardiologist. The patients suffering from other heart diseases such as; myopathy, atrial fibrillation, right and left bundle branch block, and ventricular hypertrophy were not considered for the study. Finally, we have created 82 CAD files and 61 normal files with each file having 1000 samples from 10 normal and 10 CAD subjects.

2.2. Preprocessing of acquired signals

The following steps are performed to get the HR signal from the ECG signal (Acharya et al., 2014; Giri et al., 2013):

Step 1: Unwanted noise and baseline wander (Warlar & Eswaran, 1991) present in the ECG signals were eliminated by applying a band pass filter of lower and higher cut-off frequency of 0.3 Hz and 15 Hz, respectively.

Step 2: Power line interferences were eliminated, using a notch filter of 50 Hz cut off frequency.

Step 3: Pan-Tompkins algorithm (Pan & Tompkins, 1985) was used to identify the location of R peaks.

Step 4: Finally, the duration between the two consecutive R peaks (t_{RR}) was computed.