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Ischemia detection using Isoelectric Energy Function

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ABSTRACT

A novel method has been proposed for the detection of ischemia using an isoelectric energy function (IEEF) resulting from ST segment deviations in ECG signals. The method consists of five stages: preprocessing, delineation, measurement of isoelectric energy, a beat characterization algorithm and detection of ischemia. The isoelectric energy threshold is used to differentiate ischemic beats from normal beats for ischemic episode detection. Then, ischemic episodes are classified as transmural or subendocardial. The method is validated for recordings of the annotated European ST-T database (EDB). The results show 98.12% average sensitivity (S_E) and 98.16% average specificity (S_P). These results are significantly better than those of existing methods cited in the literature. The advantage of the proposed method includes simplicity, ruggedness and automatic discarding of noisy beats.

1. Introduction

In recent years, epidemiological transition due to obesity, smoking, tobacco use, physical inactivity, an unhealthy diet and harmful use of alcohol has increased the death rate. An estimated 17.5 million people died from cardiovascular diseases (CVDs) in 2012, representing 31% of all global deaths. Of these deaths, an estimated 7.4 million were due to coronary heart disease and 6.7 million were due to stroke. Out of the 16 million deaths under the age of 70 due to non-communicable diseases, 82% for low and middle-income countries and 37% are caused by CVDs. As per prediction of the world health organization (WHO), 75% of world deaths will be due to non-communicable and coronary heart diseases (CHD) by 2030 [1]. These diseases mainly result from atherosclerosis and thrombosis, which can manifest as a coronary ischemic syndrome [2]. CVDs can be prevented by addressing behavioral risk and through management using medicine and early detection. So, currently, the attention of researchers is on establishing the timely and reliable detection of ischemia. An electrocardiogram (ECG) is one of the non-invasive techniques to diagnose the ischemia. An ECG is representative of the P wave (depolarization of the atria), QRS complex (depolarization of the ventricles) and T wave (ventricular repolarisation). Under normal conditions, an ECG carries a predictable duration, direction and amplitude of characteristic points. However, an ischemic ECG has a peculiar appearance, which is indicative of a decrease in terms of the availability of oxygen for cardiac tissues. ST-segment changes are produced by the flow of injury currents that are generated by the voltage gradients between the ischemic and non-ischemic myocardium during the plateau and resting phases of the ventricular action potential. This is manifested as an elevated or depressed ST segment in an ECG [3]. ST elevation usually appears in patients with transmural ischemia or prinzmetal angina while ST depression appears in subendocardal ischemia or stable or unstable angina [4]. A number of methods have been proposed in the last 10–15 years for the detection of ischemic beats and episodes based on digital signal analysis, rule based wavelet transforms and soft computing based algorithms. These include wavelet based entropy [5,6], a network self-organizing map (sNet-SOM) model [7], neural network (NN) and nonlinear principal component analysis (NLPCA) [8], a back propagation algorithm [9], Karhunen–Loeve transform (KLT) [10], a genetic algorithm [11], hidden Markov models (HMM) [12], machine learning techniques [13], decision tree rules using fuzzy models [14], vectorcardiographic ST-T [15] methods etc. These methods have the potential of a decision support system that can provide good advice for diagnosis. Other methods based on wavelets [16], an ant-miner algorithm [17], kernel density estimation (KDE) and support vector machine (SVM) [18], statistical features [19] and a fuzzy expert system through stochastic global optimization [20] are reported. These methods have a major advantage of interpretation of decisions as compared to black box approaches like neural networks. A Real-time system for the detection of myocardial infarction [21] is implemented. Similarly, one study identifies the ECG morphologies for normal and abnormal beats based on wavelet power spectra using statistical significance [22]. Likewise, a survey of ischemia detection techniques [23] has been performed. During recording of an ECG, the artifacts, i.e. anything other than the

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muscular activity of the heart, are contaminated on ECG. Critical problems contributing to poor detection and classification of the ST segment in an ECG include baseline wanders, varying ST-T patterns, muscle tremors, high frequency noises, power line interference, etc. The reasons may be the interference of alternating current, a loose electrode connection, patient movements, malfunctioning of the machine etc. [24]. These artifacts have an adverse effect on an ECG and make the automatic delineation of characteristic points more difficult. Besides these problems, it is necessary to detect ischemic episodes when a patient is in a critical care unit (CCU). An experienced cardiologist could easily diagnose the ischemia by just looking at the ECG, even with the presence of artifacts. However, the elimination of artifacts is primarily required to facilitate easy, accurate and automatic detection of the ST segment and classification of ischemic episodes in pathological cases. The recommendation of the American Heart Association (AHA) is to preserve the linear phase, and high pass filters can be designed with a cut-off frequency equal to the fundamental frequency of a heart rate of or lower than a certain threshold, i.e. 0.8 Hz. A number of filters have been designed for the correction of baseline wandering, including FIR and IIR filters. But these filters have the disadvantage that the ECG signal is deformed as the cut-off frequency increases. Cubic spline filters overcome this without the effect of deformation, but these filters make several errors when the sampling rate is low or when the baseline changes suddenly. Adaptive filters determine the signal and adaptively remove the noise uncorrelated with the deterministic signal. The disadvantage of these filters is the distortion of the ST segment [25]. Similarly, for ECG enhancement, the most widely used algorithm is the least mean square adaptive algorithm (LMS). But this algorithm is not able to track the rapidly varying non-stationary ECG signal within each heart beat. Using the method presented in this paper, all the listed problems can be avoided because a wavelet transform is found to be more suitable for a non-stationary ECG signal [26]. Due to the time–frequency resolution capability of wavelet transforms (WT), they were found to be more suitable for removal of noises and artifacts and for the delineation process in ECG records as compared to Fourier transform (FT) and short time Fourier transform methods (STFT) [27]. The general objective of this paper is to propose and validate a simple method for the detection of ischemia based on an isoelectric energy function through accurate pre-processing and detection of basic ECG characteristic points. Our contribution towards the diagnosis of ischemia is twofold. First, the proposed method could provide an interpretation of the results. This is of great importance while designing a device for medical decision support for patients in a critical care unit (CCU) without knowing past references. Second, it involves a direct analysis based on isoelectric energy without the involvement of any complicated calculations. The paper is organized in six sections: Section 1 introduces the ECG, ischemia and related work, Section 2 deals with resources and methods, Section 3 presents the methodology, Section 4 discusses the results, Section 5 makes a comparison with existing methods and Section 6 covers conclusions and the future scope.

2. Resources and methods

2.1. European ST-T database

Normal and ischemic (elevated and depressed) ECG records have been taken from the European ST-T database (EDB). EDB records are well characterized digital recordings of ECGs, which are used by most biomedical researchers for validation of their algorithms. The EDB contains 90 ECG signals for two hour recordings with a sampling frequency of 250 Hz per channel over a 10 mV range with 11-bit resolution [28]. The database contains records of two leads acquired from V_1, V_2, V_3, V_4 and V_5 and MLI and MLIII positions. The database records have been annotated by three expert cardiologists. The experts have diagnosed and marked the beginning and ending of ischemic episodes in the database itself. The present research work has been carried out on 43,876 ST segments from e0103, e0104, e0105, e0108, e0113, e0114, e0147, e0159, e0162 and e0206 recordings of this database.

2.2. Wavelet transform

The wavelet transform (WT) of a function $f(t)\ \varepsilon\ L^2\ (R)$ [29] at scale 'a' and position 'b' is represented by

$$\mathrm{Wf}(a,b)=\int_{-\infty}^{+\infty} f(t)\psi^*\left(\frac{t-b}{a}\right)(t)dt \tag{1}$$

Eq. (1) realizes that the signal to be analyzed $f(t)$, is convolved with a dilated version of the mother wavelet $\psi(t)$. WT is a linear operator that decomposes a signal $x(t)$ into frequency components appearing at different scales. Higher scales contain low frequency components while lower scales have higher frequency components of a decomposed signal. In a discrete time decomposition system, the wavelet coefficients are obtained by passing a vector x (n) through a bank of filters, namely approximation coefficients (CA) and detail coefficients (CD) [30]. For $a=2^J$, the wavelet transform is called a dyadic digital wavelet transform (DWT). In our case, it is a digitized ECG signal in the form of samples. The mallet algorithm [29] is used to compute DWT of a digital signal $f(n)$, as expressed in Eq. (2) and (3).

$$S_{2^j}f(n)=\sum h_k S_{2^{j-1}}f\left(n-2^{J-1}k\right) \tag{2}$$

$$W_{2^j}f(n)=\sum g_k W_{2^{j-1}}f\left(n-2^{J-1}k\right) \tag{3}$$

where $S_{2^0}f(n)=d(n), S_{2^j}$ is a smoothing operator and $W_{2^j}f(n)$ is the wavelet transform of the digital signal $f(n)$ to be analyzed. The high pass filter $G(w)$ and low pass filter $H(w)$ are further represented by coefficients $\sum g_k$ and $\sum h_k$ respectively.

$$G(w)=\sum g_k e^{-jkw} \text{ and } H(w)=\sum h_k e^{-jkw}$$

Orthogonal and compactly supported wavelets (daubechies, symlet and coiflets) are found to be more suitable for the analysis of non-stationary ECG signals because of their high number of vanishing moments [31].

3. Methodology

A general schematic diagram is shown in Fig. 1, also representing the methodology involved in the detection of ischemia for proposed method.

3.1. Pre-processing

The main goal of pre-processing is to formalize the accurate and efficient measurement of isoelectric energy in ST segments. Also, elimination of these noises is a very important task for the measurement of a TP and ST segment with high precision. It is very significant to recognize the artifact frequencies and to discriminate these artifact changes from genuine changes to prevent misdiagnosis. A general diagram corresponding to different frequencies is shown in Fig. 2. After discarding of wavelet coefficients