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Original Research Article

Early Detection of Sudden Cardiac Death Using Nonlinear Analysis of Heart Rate Variability

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ABSTRACT

Background and Objective: Sudden cardiac death (SCD) is one of the most widespread reasons for death around the world. A precise and early prediction of SCD can improve the chance of survival by administering cardiopulmonary resuscitation (CPR). Hence, there is a vital need for an SCD prediction system.
Methods: In this work, a novel and efficient algorithm for automated detection of SCD six minutes before its onset is proposed. This algorithm uses features based on the nonlinear modeling of heart rate variability (HRV). In fact, after the extraction of the HRV signals, increment entropy and recurrence quantification analysis-based features are extracted. The one-way ANOVA is applied for the dimension reduction of feature space—this results in lower computational cost. Finally, the distinguishing features are fed to classifiers such as the decision tree, K-nearest neighbor, naive Bayes, and the support vector machine.
Results: By using the decision tree classifier we have achieved SCD detection six minutes before its onset with an accuracy, specificity, and sensitivity of 95%. These results demonstrate the superiority of the presented algorithm compared to the existing ones in performance.
Conclusions: This study shows that a combination of features based on the nonlinear modeling of HRV, such as laminarity (based on recurrence quantification analysis), and increment entropy leads to early detection of sudden cardiac death. Choosing the decision tree improves the performance of the algorithm. The results could help in the development of a tool that would allow the detection of cardiac arrest six minutes before its onset.

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1. Introduction

Sudden cardiac arrest (SCA) is known as a critical cardiovascular condition in which sudden cardiac death (SCD) of an individual with or without preexisting cardiac disease is expected [1–5]. In most times, cardiac arrhythmias, such as ventricular fibrillation (VF), ventricular tachycardia (VT), and ventricular flutter (VFL), initiate the occurrence of SCD. A primary bradyarrhythmia is associated with a smaller number of SCD events [6]. SCA immediately causes circulatory failure across the body, resulting in oxygen deprivation and subsequent loss of consciousness within one minute [7]. When SCA occurs, the electrical ventricular defibrillator is mainly utilized to stimulate the heart and reinstate its function. The mortality rate caused by cardiac diseases has decreased in the last few decades, but SCD is still reported as the pioneer of cause of death in the USA as well as other countries [8]. Since the onset of symptoms appears approximately an hour before sudden death, early prediction of SCD is a critical issue for clinicians to perform successful restoration of heart activity [9].

Many research works have developed non-invasive techniques for automated SCD detection based on signal-processing approaches. For this aim, electrocardiogram (ECG) and heart rate variability (HRV) are useful signals [10]. The HRV signal, which can be derived from the ECG signal, is the physiological phenomenon of variation in the time interval between heartbeats. It is measured by the variation in the beat-to-beat interval. There are several linear, nonlinear, time-domain, and frequency-domain approaches for the analysis of ECG and HRV signals [11–13].

Shen et al. [6] performed a study on ECG signals in which the results of performing the modified zero-crossing approach and wavelet-based methods for SCD detection before its onset was reported. For this aim, 4-minute ECG signals—two minutes before and after the VF onset time of SCD occurrence—were analyzed. The results indicated that the correct detection rates using wavelet and modified zero-crossing methods were 92.31% and 98.48% respectively. In another attempt to predict SCD using ECG signals, Kora [14] applied fast conjugate symmetric sequency-ordered complex Hadamard transform (CS-SCHT) coefficients to four minutes of ECG signals prior to the SCD onset. The classification accuracy was 99.3% for the detection of SCD. Acharya et al. [15] also proposed an ECG-based SCD detection algorithm; they explored the feasibility of developing an integrated index for SCD detection by ECG signal analysis. Nonlinear features, including fractal dimension, Hurst's exponent, detrended fluctuation analysis, approximate entropy, sample entropy, and correlation dimension from the second-level discrete wavelet transform (DWT) of decomposed ECG signal were extracted. Next, SCD was detected using the combination of DWT and nonlinear features. The accuracy of SCD detection was 92.11% for fourth minutes before its occurrence. The ECG-based studies on SCD detection show that the methods used in these studies need more data samples and they would not detect the occurrence of SCD early enough.

Commonly, nonlinear heart rate dynamics, such as rapid spectral alterations and low frequency heart rate oscillations, are appeared in patients at high risk of SCD [16–18]. The paper in which Donald and his colleagues analyzed HRV signal to investigate the effects of SCD were one of the first ones in this field [18]. Their results are same as those reached by a recently published paper [17] in which the authors reported that low HRV is linked with increased risk of SCD in the general population. Subsequently, many researchers used HRV-based features to detect SCD.

Ebrahimzadeh et al. [19] extracted time, frequency, and time-frequency features of the HRV signal and assessed them to detect SCD events. The accuracy of the employed classifier was 99.16% by using ECG signals just one minute prior to the SCD event. This research group also presented the detection of the SCD algorithm using the combination of the time-frequency and nonlinear features of HRV signals. The experimental results showed that the accuracy of their algorithm for the fourth one-minute ECG interval prior to SCD onset was 83.96% [20]. Murukesan et al. [7] showed how the combination of time, time-frequency, and nonlinear features from five-minute HRV signal (two minutes before SCD onset) provided satisfying performance with a detection rate of 96.36%. As another example of using HRV as a SCD detector, we can point to a study carried out by Acharya et al. [21], who detected cardiac death four minutes prior to its onset using recurrence quantification analysis (RQA) and Kolmogorov complexity parameters. The accuracy of their algorithm was 86.8%. In another work, they [10] also extracted various nonlinear features such as Hjorth's parameters, fuzzy entropy, Tsallis entropy, Renyi entropy, and energy features of DWT coefficients for the classification of HRV signals into normal and at the risk of SCD. They reached the accuracy of 94.7% in this recent research. Murugappan et al. [22] detected SCD events six minutes before its onset by exploiting time-domain features. The results proved that an accuracy of 93.71% was obtained using fuzzy classifier. In an effort to find out how recurrence plot-based features and Poincare plots can be helpful for SCD detection, Houshyarifar and his colleagues [23] reported SCD detection four minutes before its onset with the accuracy of 92%. In another study, they also proposed the SCD detection method using bispectrum and linear features of the HRV signal. An accuracy of 91% for the detection of SCD six minutes before its onset was achieved by this research team [24]. In the previously mentioned research works, which are based on HRV processing, the MIT-BIH SCD Holter and MIT/BIH Normal Sinus Rhythm databases [29] were utilized by the researchers to evaluate their proposed methods. The main drawbacks of time and frequency domain techniques are inadequate representation of data and inaccurate time resolution respectively [25–28]. As ECG or HRV signals have nonlinear and non-stationary characteristics, linear algorithms will not provide enough information for accurate SCD detection [19].

This work focuses on SCD detection using nonlinear methods to address the above-mentioned drawbacks and decipher the hidden information relating to SCD in the HRV signals. The vital importance of development and improvement of the existing algorithms is not deniable. To summarize, the goal of our study was to achieve a robust automated algorithm with the three following fundamental features: high accuracy, low computational complexity due to reduction of

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