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Discrimination of systolic and diastolic dysfunctions using multi-layer perceptron in heart rate variability analysis

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ABSTRACT

In this study, the heart rate variability (HRV) analysis is used to distinguish patients with systolic congestive heart failure (CHF) from patients with diastolic CHF. In the analysis performed, the best accuracy performances of short-term HRV measures are compared. These measures are calculated in four different ways with optional normalization methods of heart rate and data. The nearest neighbor and the multi-layer perceptron (MLP) are used to evaluate the performances in discriminating these two groups. The results point out that using both data and heart rate normalizations enhances the classifier performance. The maximum accuracy is obtained as 96.43% with MLP classifier.

1. Introduction

When the pumping capacity of a heart reduces, this disorder is called heart failure. As the accumulation of blood is so common in patients with heart failure, it is also named congestive heart failure (CHF). The failing heart does not manage either to pump or to fill up, which are called systolic heart failure and diastolic heart failure, respectively [1]. Although the most essential element for the success of the treatment is the reliable and exact diagnosis of CHF, systolic dysfunction was determined in only half of all cases and only 46% of physicians tried routinely distinguishing either systolic or diastolic dysfunctionality in the patients with CHF [2]. The decreased pump function (i.e. systolic CHF) can be measured by functional cardiac studies (e.g. ECG, BNP, and echocardiogram) [3–5]. On the other hand, the diastolic dysfunction is identifiable by only echocardiogram [6,7].

Almost 90% of physicians routinely performed ECG tests in patients due to its simplicity [2]. Nonetheless, physicians accepted that echocardiography is essential in diagnosis whether patient with CHF is systolic or diastolic in addition to clinical sign and symptoms [8]. Average waiting time for echocardiography was 1 month and that was 48 h for ECG [2]. Hence, simple and reliable diagnostic procedures based on ECG may be helpful for primary care physicians (PCPs) who are responsible for the early diagnosis of CHF and implementation of adequate therapy.

Analysis of heart rate variability (HRV), derived from the ECG analysis, is to analyze the variations between timings of heart beats [9]. The sinoatrial node (SAN) is the pacemaker of the heart and is responsible for the HRV. The cells of the SAN slowly but automatically depolarize; when reaching a threshold, they rapidly depolarize, followed by a repolarization, and the process repeats itself constantly. The depolarization quickly propagates to the surrounding cardiac muscle cells and the contraction of the heart begins. In healthy subjects, the SAN cells generate depolarization or action potentials at a frequency that is regulated through direct innervation of both branches of ANS: sympathetic and parasympathetic (or vagal). The parasympathetic branch releases acetylcholine (ACh) that slows the rate of SAN depolarization, while the sympathetic branch releases norepineprine that increases the rate of SAN depolarization. The SAN effectively integrates both inputs from ANS, both temporally and spatially, and this pacemaker activity is often modeled as an integrate pulse frequency modulation [40]. This is the source of HRV [41].

In 1996, standards in HRV analysis was published by proposing a number of time- and frequency-domain parameters calculated from short-term (5-min) and long-term (24-h) HRV data [9]. In order to achieve the results quickly, short-term (5-min long) HRV measures have been preferred in many studies. HRV has been used in a great number of clinical studies including prediction of sudden cardiac death after acute myocardial infarction [10], early diagnosis of diabetic neuropathy [11], dilated cardiomyopathy [12–14], CHF [15–20], fetal distress conditions [21], and obstructive sleep apnea [22].

In addition, Hallstrom et al. presented that rescaling RR

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intervals to a fixed HR reduces the variation in the measures and increases their discrimination power [23]. If these measures are calculated using heart rate normalized data, this analysis is called as “heart rate normalized heart rate variability” (HRN) analysis [20]. In a previous study, the discrimination of CHF patients who are systolic or diastolic was reached by using kNN classifier in only 12 patients as a case study [24].

In this study, it is aimed to determine whether systolic or diastolic dysfunctionality exists in CHF patients using nearest neighbor and multi-layer perceptron in both HRV and HRN measures. The following section covers brief information about the methods used in the study including data, obtaining HRV measures, normalization techniques, classification and performance assessment algorithms with the flowchart of the implementation. Section 3 gives the results. Finally, the results are discussed.

2. Methods

2.1. Experimental protocol

Patients came to the clinics after their breakfast at the morning, which took approximately 2 h from their home to clinics because of the morning traffic in Izmir, Turkey. Patients were requested to rest at least 10 min just before connecting Holter device. After the connection, patients waited for 10 min in resting position on a comfortable chair. During this time, the required paper work was also completed. Then, they left the clinics and continued their daily life. They came back to the clinics again approximately 24 h later. 30 patients from all patients were included into the study after two experts analyzed the data.

The collected data were digitized at 128 samples per second. There were 115,200 peaks in ECG by supposing 80 beats per minute during 24 h for each patient. Ectopic beats are excluded from HRV analysis in general [9]. Deciding such a big amount of beats whether normal or ectopic is very time-consuming and irritable process for experts. Moreover, this process is costly for health industry. That is the reason why the first 5-min segments of all recorded ECG data are included in this study. In addition, using only 5-min (300-s) sections of data helps us achieving the discrimination faster and not disturbing the patients longer in a clinic environment.

2.2. Data

The Holter ECG data used in this study were obtained from the Faculty of Medicine in Dokuz Eylül University [24]. Two cardiologists decided whether patients would be included into the study or not. The data included the study are as follows:

- *Systolic CHF data*: 18 patients (11 men and 7 women) with the age of 20–66 years.
- *Diastolic CHF data*: 12 patients (4 women and 8 unknown) with the age of 39–65 years.

Since the gender of 8 patients were not recorded, gender was not used as a possible feature in the study.

2.3. Heart rate variability measures

HRV data is collected after determining QRS wave structure in the ECG signals because QRS wave structure is the component that has the most distinctive amplitude values in the ECG signals. After the determination of QRS using a Matlab implementation of Pan–Tompkins algorithm [38], the time difference between two consecutive R peaks is commonly called RR-interval ($T_n = t_n - t_{n-1}$) [9]. Age of the patient, time-domain, frequency-domain and non-linear methods are used in HRV studies. For further details, the studies given in the references could be examined [19,24,20].

Welch periodogram method, which uses fast Fourier transform (FFT) method, is commonly used for the evaluation of frequency domain [25]. Thanks to this method, power spectrum density (PSD) over the data that is sampled at equal interval through the time can be computed. In this study, HRV data is re-sampled by using cubic interpolation method at 4 Hz before using FFT and detrending of data is eliminated for providing stability analysis [25]. Besides, evaluation of frequency domain obtained by Lomb periodogram which is developed as an alternative to the classical PSD method is also used. Owing to this method, PSD can be computed from directly the HRV data without needing to re-sample on time domain [26–28]. HRV evaluation of conventional frequency domain for 5-min period is examined in detail by the recommended standard [9].

There are three frequency bands commonly used in HRV analysis: VLF (0–0.033 Hz), LF (0.033–0.15 Hz) and HF (0.15–0.4 Hz) [9]. In the evaluation of frequency domain, powers of these frequency bands from calculated PSD were examined. Therefore, the following frequency domain measures were computed separately for both methods of Welch periodogram and Lomb periodogram. The frequency domain analysis contributed to the understanding of autonomic background of RR interval fluctuations in the HR record [42,43].

On the other hand, wavelet analysis not only makes possible the examination of one signal for the both time and scale domains but also eliminates polynomial non-stability [29]. Wavelets are reported as very useful for analysis of the RR intervals due to this capability. Thus, Daubechies-4 main wavelet over HRV data re-sampled at 4 Hz with the 7-level wavelet transform method was also used in this analysis to calculate the standard frequency domain features of HRV analysis [19].

Furthermore, non-linear measures derived from Poincare map were used in this study. Poincare plot is a graph that each RR interval is plotted against the previous interval, which visualizes detailed beating pattern of the heart. The Poincare plot is a popular technique thanks to its simplicity and its proved clinical ability. Fitting an ellipse to the Poincare plot's shape and calculating measures from the plot is the most popular method among nonlinear interpretation methods of HRV [30–33].

As a result, 29 features were used. Those are obtained from patient information, time domain evaluation, frequency spectrum evaluation and non-linear methods with the numbers of 1, 6, 18, and 4, respectively.

2.4. Normalization

There are two optional normalization stages in the study: (1) heart rate normalization and (2) data (or feature) normalization.

- *Heart rate normalization*: Heart rate normalization process to fix the mean HR to its new value is applied as follows [23]:

$$HRN = \frac{60}{NewHR} \times \frac{HRV}{\overline{HRV}} \tag{1}$$

  where HRN is HR normalized HRV data in seconds, HRV is raw HRV data in seconds, $NewHR$ is the new value of mean HR to be fixed in bpm, $\overline{HRV}$ is the mean value of whole HRV data in seconds, and the constant 60 is used to make unit conversion from bpm (beats-per-minute) to bps (beats-per-second). $NewHR$ is selected as 75 bpm since it is recommended and applied value in [23,20].
- *Feature normalization*: The used features must be equalized on