ARTICLE IN PRESS

Neurocomputing (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

Age-related alterations in the sign series entropy of short-term pulse rate variability☆

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A R T I C L E I N F O

Communicated by D.-S. Huang

Keywords:
Short-term pulse rate variability
Sign series entropy
Sliding window iterative sign series entropy analysis
Probabilistic neural network
Age classification

A B S T R A C T

Pulse rate variability (PRV) has been certified as a substitute for heart rate variability (HRV) to diagnose and predict some diseases. Sign series entropy analysis (SSEA), a kind of nonlinear method, has been used to analyze HRV signal effectively. However, the time consumption of SSEA is too long, and it is unknown whether SSEA is suitable for analyzing short-term PRV signals. Therefore, an improved SSEA method named sliding window iterative SSEA (SWISSEA) is proposed to analyze short-term PRV signal and derive some age-related alterations. Moreover, a radial basis probabilistic neural network (RBPNN) based algorithm is proposed to classify subjects according to their ages. Continuous non-invasive blood pressure signals from the MIT-BIH database are chosen to generate short-term PRV signals as the experimental data, and their time domain and frequency domain parameters are extracted and selected for classifying. The experimental results show that the pulse beats are more uniform as the increase of the age, the sign series entropy (SSE) increases with aging and has a significant difference between young and old subjects even if the PRV signal is corrupted by heavy noises, the approach based on RBPNN can accurately classify subjects according their ages. In addition, the SWISSEA reduces the time consumption of SSEA, is more suitable for analyzing short-term PRV signals in real time, and has a potential in portable medical devices.

1. Introduction

Heart rate variability (HRV), generated from heart beat to beat fluctuations, is the result of balance between sympathetic system and parasympathetic system. Various studies have shown that HRV signal contains abundant physiological and pathological information on cardiovascular neural and humoral regulation systems [1–3]. HRV signal is derived from ECG signal. However, during ECG signal recording, multiple electrode attachments and cable connections are not convenient for portable medical devices.

Pulse rate variability (PRV) is also generated from heart beat to beat fluctuations. Compared with HRV signal, PRV signal can be derived either from pressure pulse signal, or from continuous non-invasive blood pressure signal, or from photoplethysmogram signal, and the above signals are easily collected [4,5]. In addition, a wide range of studies have shown that PRV can be a surrogate of HRV when the subjects are sleeping or resting, as well as in some non-stationary states [6,7]. Short-term PRV signal, is the PRV signal whose length is shorter than 10 min, and is more useful for portable medical devices in home health care or clinical applications.

At present, there are many HRV signal analysis methods, either in the time domain, or in the frequency domain, or geometric, or nonlinear, are employed directly to analyze PRV [8–10]. Among these methods, the nonlinear approaches, beneficial for mining underlying rules and pathological information of autonomic nervous system, have shown that aging has a profound impact on HRV [11,12]. However, most nonlinear methods need long-term signals, some even over 24 h. The sign series entropy analysis (SSEA), a nonlinear method, is employed to analyze short-term HRV signal [13,14], and the experimental results show that the sign series entropy (SSE) of short-term HRV signal evidently changed along with aging. However, because of the long time consumption, it is difficult to analyze PRV signal with SSEA in real time, and up to present, it is unknown whether SSEA is suitable for analyzing short-term PRV signals in aging.

In this study, a rapid SSEA based method named sliding window iterative sign series entropy analysis (SWISSEA) has been proposed to

☆ Preliminary version of this manuscript has been selected in International Conference on Intelligent Computing(ICIC), 2015 (Paper ID: 112, Title:Age-Related Alterations in the Sign Series Entropy of Short-Term Pulse Rate Variability) and its extended version is sub-selected for the Neurocomputing journal.

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http://dx.doi.org/10.1016/j.neucom.2016.09.094
Received 24 December 2015; Received in revised form 18 July 2016; Accepted 3 September 2016

analyze short-term PRV signals of young and old subjects. The proposed method is tested over the largest publicly available MIT-BIH database [15] and its performance is analyzed. Then, a radial basis probabilistic neural network (RBPNN) based algorithm is proposed to classify subjects based on SSE, the time and the frequency domain parameters.

The paper is organized as follows: in Section 2, the data we used are first introduced, then the theory of SSEA and SWISSEA and the process of the RBPNN based algorithm are presented. The results of experiment are shown in Section 3. Next section discusses the experimental results. The conclusion is given in last section.

2. Materials and methods

2.1. Data

The PRV signals for experiments are extracted from the continuous non-invasive blood pressure signals that are from the MIMIC/Fantasia database [15]. Two groups of rigorously-screened healthy subjects, 20 young (21–34 years) and 20 old (68–85 years) subjects undergo 120 min of continuous supine resting while continuous ECG and respiration signals are collected. All subjects remain the resting state in sinus rhythm when watching the movie, Fantasia (Disney, 1940), to maintain wakefulness, and all signals are digitized at 250 Hz.

However, only a half of subjects in each group (Records f2y01-f2y10, f2o01-f2o10, with equal number of female and male) are investigated to record continuous non-invasive blood pressure signals with the duration of 66 min(min).

Compared to ECG signals, the pulse beats in blood pressure signals are uncalibrated. So in this paper, the dynamic difference threshold detection algorithm [16,17] is used to calibrate the pulse beats, and each beat annotation is verified by visual inspection. Then the PRV signals are obtained from continuous pulse beat intervals.

2.2. Sign series entropy analysis

Denote PRV signal as $\{PP(i)\}$, i=1, 2, ⋯, N, where $PP(i)$ is the interval between the i-th and the $(i+1)$-th pulse beat, and N is the number of pulse beat intervals. In practice, the pulse beat intervals are not well uniform, and have three variation directions. Here, three symbols are employed to represent the variation directions of pulse beat intervals:

$$s(i)=\begin{cases}0, & PP(i+1)<PP(i)\\ 1, & PP(i+1)=PP(i) \quad i=1,2,\ldots,N-1\\ 2, & PP(i+1)>PP(i)\end{cases} \tag{1}$$

where, $s(i)$=0, 1, 2 indicates the pulse beat interval which is descendant, invariant, and ascendant, respectively. From Eq. (1), the magnitude of PRV signal is coarse-grained, and only the change direction is remained. The details are shown in Fig. 1.

In order to seek for the changing rule of the signal $s(i)$, a vector series with the size of $(N-m)\times m$ is defined as:

$$S(i)=[s(i),s(i+1),\ldots,s(i+(m-1))],\quad i=1,2,\ldots,N-m \tag{2}$$

Fig. 1 gives an example to show the process of generating $S(i)$. As can be seen that the changing modes of PRV signals can be easily observed (i.e. let the length of $S(i)$ as m and get $M=3^m$, which indicates the number of continuous modes). The probability of each mode is:

$$p(j)=\frac{n(j)}{n-m},\quad j=1,2,\ldots,M \tag{3}$$

where $n(j)$ is the number of the j-th mode in $S(i)$.

Then the information entropy represents as:

$$SSE(m)=-\sum_{j=1}^{M}p(j)\log_2 p(j) \tag{4}$$

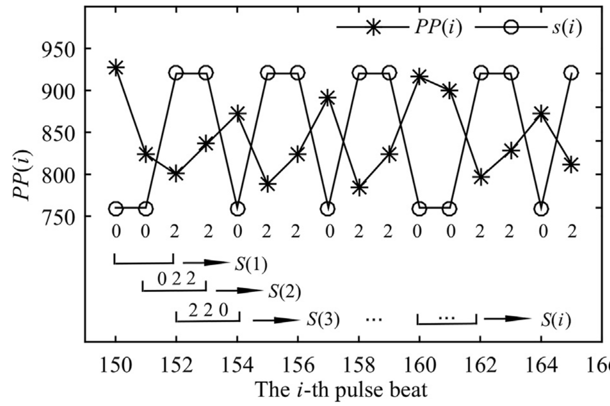

Fig. 1. The process of generating construct vector $S(i)$, when m=3.

Here, we rename the above information entropy as the sign series entropy, and its value indicates the average irregularity of $S(i)$. If $S(i)$ only has one mode, the value of SSE is 0; if the number of each mode in $S(i)$ is equal, the value of SSE is maximal.

The SSE value of PRV signal reflects the rules of pulse beat, and SSEA is an efficient nonlinear method to analyze PRV signals. However, if the old data are all engaged to the calculation of SSE in the dynamical signal processing, it will lead to the significantly decrease of computational efficiency. In order to overcome this problem, we propose an improved SSEA method with high computations efficient to analyze PRV signals in real time.

2.3. Sliding window iterative sign series entropy analysis

In microsystems, the new collected data are often stored in the buffer cache and only 512 bits, 1024 bits or 2048 bits data (which are necessary in data processing) are buffered to save the cache space. Here, the buffer length is set as 1024 bits. Besides, A sliding window with the length of N_w is used in SWISSEA to speed the computation of SSEA and save the cache space. The length of vector $S(i)$ is m, in order to ensure that the data in the sliding window are enough to form a vector but not overflow the buffer, the N_w ranges from m to 1024. In each sliding of the window, only updating the parameters of the newest and the oldest PRV data, can we get the value of SSE. The full procedure is as follows:• Step 1: Symbolization of PRV Signal

The process of symbolization is the same as SSEA (as Eq. (2)), but different from SSEA, it need not to save and signify all PRV data in buffer cache. In Fig. 2, the new PRV datum $(pp(N_c))$ and the old PRV

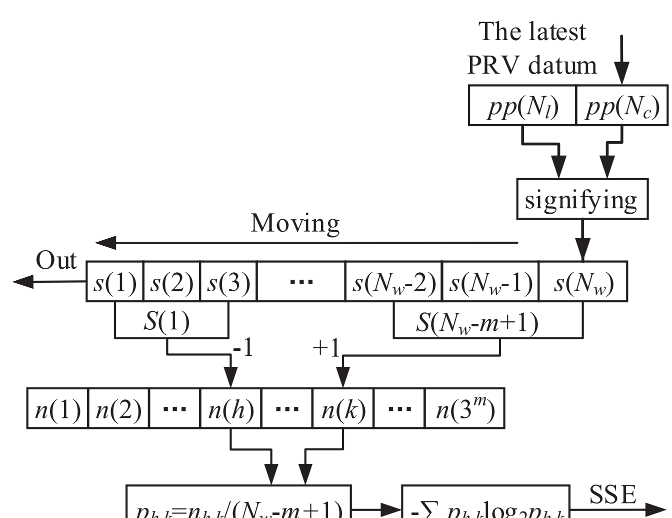

Fig. 2. The process of SWISSEA (m=3).