Fingertip pulse rate variability extraction based on extreme-point symmetric mode decomposition

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Abstract. To solve shortcomings of being sensitive to noise and waveform when using threshold method to extract pulse rate variability (PRV) at this stage, a method using extreme-point symmetric mode decomposition to extract PRV signals from pulse waves with noise is proposed. A Butterworth filter is used to remove the baseline drift, the DC mode and power frequency noise, which can effectively avoid noise interference when identifying peak points. The pre-processed data is decomposed by extreme-point symmetric mode decomposition to select the corresponding mode of the main wave, thereby reducing the difficulty of feature point extraction. Compared with the threshold method, the extraction method proposed in this paper is more intuitive and can self-adaptively select the best decomposition layer. This method is suitable for the extraction of fingertip PRV under complex noise and some disease statuses.

1. Introduction
Heart rate variability (HRV) refers to the difference in time between each heartbeat [1], although HRV has become an important tool for the detection of autonomic nervous system activity[2-3], it is very inconvenient for acquisition because it needs to be obtained from the ECG signal which needs to be collected in a lead mode. Pulse rate comes from the periodic changes of pulse. Studies have shown that pulse rate and heart rate tend to be the same in some cases, and the generation of pulse also originates from the beating of the heart. PRV also contains a lot of physiological information, and pulse collection is more convenient, so PRV can be used instead of HRV for corresponding research.

At present, PRV extraction methods are mainly divided into time domain methods and frequency domain methods. The main idea of the frequency domain method is to decompose the original pulse signal into multiple frequency bands, and select the corresponding frequency band to extract the PRV signal. This method is not highly dependent on the waveform and has high accuracy. The disadvantage is that it needs to manually select the frequency band, which is very subjective. The time domain methods commonly used are the differential threshold method and the amplitude threshold method, etc. The main idea is to detect the position of the P wave peak to extract PRV. This method is faster, but the processing effect for large amounts of data and abnormal data is poor. On this basis, this paper proposes a fingertip PRV extraction method based on extreme-point symmetric mode decomposition (ESMD). While improving the efficiency, the decomposed fundamental signal can effectively reflect the periodic changes of the pulse signal with high accuracy, and suitable in a variety of complex statuses.

2. The principle of ESMD
ESMD is a new time-frequency analysis algorithm proposed by Professor Wang Jinliang on the basis of empirical mode decomposition (EMD) in 2013[4]. Based on the analysis of the vibration angle of the
signal, the signal always moves up and down around the position of its equilibrium point, and different equilibrium points usually change its vibration position, so the decomposition based on pole symmetry actually reflects the local symmetry information of the signal. ESMD can adaptively decompose the original signal into a series of modal modes and each mode is in a different frequency range.

2.1. The process of ESMD
a) Find all extreme points in the source data Y and set them as $E_i (i = 1, 2, \ldots, n)$;

b) Connect adjacent extreme points. Set the midpoint of the connecting line segment of adjacent extreme points as $F_i (i = 1, 2, \ldots, n-1)$, Where $F_i$ is the midpoint of $E_i$ and $E_{i+1}$. Supplementary boundary points $F_0$ and $F_n$;

c) Use $n+1$ extreme midpoints to construct $p$ different interpolation lines $L_i (i = 1, 2, \ldots, n)$, where $p \geq 1$, then calculate the mean curve $L^*$ of all the interpolation curves:

$$L^* = \left( \frac{L_1 + L_2 + \ldots + L_p}{p} \right)$$

(1)

d) Subtract $L^*$ from the original signal and repeat steps a)-c) until $|L^*| \leq \varepsilon$ or the maximum filtering times is greater than the preset value K, the decomposition is stopped and the mode $M_1$;

e) Let the original signal subtract $M_1$ and repeat steps a)-d), obtain the subsequent modes in turn, until only a certain number of poles remain in the remaining mode R;

f) The K value needs to take the optimal value so that it meets the minimum $\sigma/\sigma_0$ (representing the relative standard deviation of the difference between the original signal and the remaining mode and the standard deviation of the original signal).

$$\sigma_0 = \frac{1}{n} \sum_{i=1}^{n} (Y_i - \bar{Y})^2$$

(2)

$$\varepsilon = 0.001 \sigma_0$$

(3)

g) Finally, the original signal is decomposed into n modes and the remaining modes R.

$$Y = \sum_{i=1}^{n} M_i + R(t)$$

(4)

3. Experimental processes and data processing
In order to verify the method, use Fluke Prosim8 vital signs simulator which can stably output fingertip blood oxygen signals in different status to output a stable PPG. Use AFE4490 analog front end as the core part of the signal acquisition device. AFE4490 is a highly integrated analog front end with modes for driving light-emitting diodes and receiving signals from photosensitive elements developed by TI dedicated to pulse oximetry detection. The sensor uses NELLCOR’s DS100A, which has two light sources, red light and infrared light, with wavelengths of 660nm and 940nm. Use the STM32H743IIT6 MCU to drive the device to obtain data through the serial port and communicate to PC.

Figure 1. Signal acquisition device
Output parameter of the simulator is set to 60Hz and the sampling rate of the device 500Hz[5]. This paper constructs a simulated pulse wave signal with noise by artificially adding random Gaussian noise and baseline drift to verify the feasibility of extracting PRV in a noisy environment.

Figure 2. Modified analog waveform

Use Butterworth filter to pre-process the original data, and then use ESMD to decompose the signal. A clear corresponding mode (IMF2) of the dominant wave can be found.

Figure 3. Waveform processed by Butterworth filter

Extract the mode imf3 and mark the peak position on the signal waveform after filtering. The selection and calculation method of time domain indexes refer to HRV. This paper selects four indexes such as the mean interval (MEAN), the standard deviation of the interval (SDNN), the root mean square error of the interval (RMSSD) and the standard deviation of successive RR interval differences (SDSD). Since the output of the simulator is an approximately steady signal, the standard value of MEAN should be:

\[
MEAN = \frac{T}{N} = \frac{60 \times 1000}{60} = 1000ms
\]  

(5)
Figure 4. Modes obtained by ESMD decomposition (the meaning of the ordinate is amplitude)

Table 1. Indexes calculated.

| MEAN       | SDNN  | RMSSD | SDSD  |
|------------|-------|-------|-------|
| 994.4138   | 3.6739 | 3.9914 | 3.4526 |

MEAN's error is 0.56% and other indicators are also within the normal error range.

The amount of excretion varies with the body's metabolism and activity. In the case of muscle exercise, emotional agitation, pregnancy, etc., the cardiac output increases, which is reflected in pulse wave, will cause amplitude of the dicrotic wave to increase. Patients with arrhythmia often have this condition. In this case, there may even be some dicrotic waves whose amplitude is higher than the amplitude of the peak point of the nearby main wave, which makes the traditional threshold method unable to accurately find the peak point. Take a set of data as an example: (as shown in the figure below).

Figure 5. The situation when the dynamic difference threshold method cannot identify the crest point
4. Data processing
Then use this method to analyze the real human data. The main information of the PPG signal is between 0.5Hz and 10 Hz. The original signal has interferences such as power frequency noise with a frequency of 50 Hz and a DC mode with a frequency of 0 Hz. In order to facilitate the extraction of the PRV signal, a Butterworth band-pass filter is used to pre-process the PPG signal. Using the data processed by the Butterworth filter as input data, the following figure is a schematic diagram of each mode obtained by using ESMD decomposition, in which mode IMF2 contains the main wave mode required to extract PRV, and can identify the main wave peak point when the adjacent dicrotic wave peak is too high.

In order to verify the accuracy of extracting PRV using ESMD, this paper uses a model for simulating ECG and PPG signals with arrhythmia episodes from PhysioNet[6]. This model can generate and simulate PPG with atrial fibrillation, extreme bradycardia or ventricular tachycardia episodes with atrial fibrillation, extreme bradycardia or ventricular tachycardia episodes Signal[7]. PPG in the model is obtained by placing individual pulses according to the RR intervals so that a connected signal is created[8]. The model is evaluated on synchronously recorded ECG and PPG signals from the MIMIC and the University of Queensland Vital Signs Dataset databases[9]. Use ESMD to process the corresponding PPG signal and extract PRV to compare with the standard PR data provided, a total of four time domain indexes MEAN, SDNN, RMSSD, SDSD and a frequency domain indexes LF/HF (ratio of high-frequency energy between 0.15-0.4Hz and low-frequency energy between 0.04-0.15Hz) are selected[10]. Use the model to simulate a total of thirty sets of data with different numbers of PR intervals, among which five sets of data with a fixed number of PR intervals correspond to different physiological conditions. The results are shown in the table below.

![Figure 6. Modes obtained by ESMD decomposition (the meaning of the ordinate is amplitude)](image)

|       | 50    | 70    | 90    | 110   | 130   | 150   |
|-------|-------|-------|-------|-------|-------|-------|
| MEAN  | 99.86%| 99.35%| 99.83%| 99.29%| 99.97%| 99.99%|
| SDNN  | 97.58%| 96.23%| 91.53%| 98.85%| 98.06%| 97.54%|
| RMSSD | 98.08%| 98.19%| 98.15%| 98.44%| 95.20%| 98.96%|
| SDSD  | 99.02%| 96.89%| 95.55%| 97.89%| 90.85%| 98.56%|
| LF/HF | 98.34%| 98.57%| 99.36%| 96.01%| 97.31%| 96.01%|

*The data unit of the first row is the number of RR intervals set in advance*

5. Conclusion
This paper proposes a PRV signal extraction method based on the ESMD method. By decomposing and selecting modes containing the dominant wave mode for peak point identification, the purpose of...
reducing noise interference can be effectively achieved. Relative to the commonly used threshold method, this method also has a good effect in processing and extracting PRV signals under special circumstances, which lays a foundation for follow-up research on PRV under abnormal conditions.

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