A High-Efficiency and Real-Time Method for Quality Evaluation of PPG Signals

Hongxing Li1, a, Shizhao Huang2, b*

1Electronic communication engineering college, Anhui Xinhua University, Hefei, Anhui, 230088, China;
2Electronic communication engineering college, Anhui Xinhua University, Hefei, Anhui, 230088, China;
acapricorn_1@qq.com, b735426836@qq.com

Abstract. The pulse oximeter (POM) is a device for real-time detection of HR and SpO2 based on PPG (Photo Plethymo Graphy) signals, and its detection accuracy varies with diverse interferences. Therefore, it is presented in the paper a method for quality evaluation of PPG signals to detect wavebands of interference signals. Firstly, features of PPG signals are acquired by slope weighted sum function (SSF). Then, the normalized cross-correlation coefficient of each signal and its reference signal is calculated. Finally, signal quality index (SQI) is calculated based on nonlinear scaling function. In the research, 20 PPG signals with 1469 beats are chosen from the CB database to make the experiments of signal quality evaluation. The experimental results show that the method included can effectively identify useful signals from the mixed signals. The sensitivity and positive prediction value are 94.66% and 96.78%, respectively. Consequently, the method proposed has high recognition accuracy with key significance in clinical applications.

1. Introduction

SpO2 refers to the percentage of the capacity of HbO2 in the total capacity of Hb, that is, the concentration of blood oxygen in the blood, which is a key physiological parameter of respiratory and vascular system. The amount of light absorbed during arterial pulses is related to the amount of oxygen in the blood. The ratio of the two spectra (visible red spectrum (660 nm) and infrared spectrum (940 nm) absorbed is calculated to acquire the value of SpO2, which is the principles of POM[1]. Nowadays, POM has been a standard monitoring tool in many clinical applications. However, the accuracy of POM is easily attacked by such interferences in practical applications as ambient light, physiological movements of test subjects, and low perfusion which reduces signal quality and parameter accuracy, thus resulting in false alarm[2]. Therefore, real-time calculation of PPG signal quality with high accuracy has a key significance in clinical blood oxygen monitoring.

At present, there are few algorithms for direct PPG signal quality (SQI) calculation. Most algorithms aim at removing bands of interference signals or minimizing the influence of interference on signals and they can be classified into the following categories.

(1) Statistical Method

ICA[3] or PCA[4] is adopted to separate the useful signals from the interfering signals. Due to high similarity between some interfering signals and the original pulse signals, the detection results often
do not meet the expectation.

(2) Frequency Analysis Method
The method includes FFT [5], DST [6], and so on. It has strong robustness that the useful signals can be accurately extracted with strong interference. But it requires too large amount of calculation.

(3) Evaluation Method Based on Wave Forms [7] [8]
Signal quality evaluation is obtained by feature recognition of wave forms and template matching. The method can receive good detection effect with a large amount of threshold detections.

The methods above have certain anti-interference performance, but they all require large computation. Real-time detection may be unavailable in dual-wavelength POM. Therefore, to improve calculation efficiency of detection with movement interferences, it is presented a new method for quality evaluation of PPG signals. Firstly, features of PPG signals are acquired by slope weighted sum function (SSF) to obtain the band of each beat. Then, the normalized cross-correlation coefficient of the signal band of each beat and its reference signal is calculated. Signal quality index (SQI) is calculated by nonlinear scaling function based on the cross-correlation coefficient obtained. Finally, the sensitivity (Se) and positive prediction value (+P) are applied to verify accuracy of the method. SQI ranges from 0 to 100, where 0 indicates poorest signal quality and 100 indicates best signal quality.

2. Method Design
Fig. 1 shows the algorithm flow of the signal quality evaluation system. Firstly, the acquisition and preprocessing of original signals are implemented. Then, the SSF method is adopted to acquire the features of PPG signal in each wave band. Finally, signal quality evaluation algorithm is applied to calculate SQI value of each band.

2.1 Low-Pass Filter
Low-pass filter aims at filtering out the high frequency noises mixed in signals so as to improve the accuracy of signal features extracted. In the method, moving average filter is adopted to implement signal preprocessing. The moving average filter uses the mean value of the input signal values of a fixed time window as the output signal. A special case of FIR filter, moving average filter has the advantages of small calculation and easy implementation [9]. It can be expressed as equation (1), where, \( y(n) \) is output signal, \( x(n+L) \) stands for input signal, and \( L \) represents the width of time windows.

\[
y(n) = \frac{1}{L} \sum_{n=0}^{L-1} x(n+L)
\]

2.2 SSF Algorithm
The principle of SSF algorithm [10] is to sum up the rising slope values of signal within a fixed time window, while the rest of the signal return to zero, so as to enhance the information of the rising slope parts of the PPG signal and to suppress the rest parts of the signal. It has been expressed as equation
(2), where $w$ is the width of analysis window, $\Delta y_k = y_k - y_{k-1}$, and $y_k$ refers to the signal obtained by low-pass filtering processing of PPG signal. To maximize the enhancement effect of the parts of PPG signal in rising slopes by SSF, $w$ should be as close as possible to the duration of contraction period of PPG signal. In the method, $w$ is 128ms.

$$z_i = \sum_{k=-w}^{w} \Delta u_k, \Delta u_k = \begin{cases} \Delta y_k, \Delta y_k < 0 \\ 0, \Delta y_k \geq 0 \end{cases}$$ (2)

Fig.2 corresponding relation of PPG signal and SSF signal

Fig.2 shows the corresponding relation of PPG signal and SSF signal. Firstly, seek the points with the largest value in enhanced SSF signal which correspond to those points with largest rising slope in PPG signal. Then, seek the nearest zeros around the points with the largest value, and they are the origins and peaks of the pulse wave. The origins of original PPG signal are shown as dotted lines in Fig.2.

2.3 Calculation of SQI Value

PPG signal is collected by photoelectric sensors. Besides interferences from electronic devices, blood perfusion indexes, breathing and movement interferences, and spatial offset of sensors can all affect the wave form of PPG signal, reduce signal quality, and finally influence evaluation results. Therefore, separating the high-quality PPG signal from mixed signals has great clinical significance.

High-quality PPG signal refers to the signal stable within a period of time and containing no external interference factors that may change the subsequent processing results. Generally, there are two methods for evaluating signal quality: (1) making comparison with features of the former wave; (2) applying extra static evaluation algorithm \[11\]. Because the former method has the characteristics of self-adaptation and can completely show the variation trend of signal quality, it is adopted to calculated signal quality index (SQI) in the method of the paper.

Firstly, evaluation of PPG signal within a certain time is implemented to acquire the reference signal. The evaluation method is calculating normalized correlation number $C$ between each beat signal and its former beat signal, where $C \in [-1,1]$. The calculation of $C$ is shown in equation (3), where $x(n)$ and $y(n)$ respectively stand for two sets of PPG signals with the length of $N$ to be analyzed \[12\]. It can be derived by Schwartz Inequality that $|C| \leq 1$. When $x(n)$ equals $y(n)$, $C$ gets its maximum value. Conversely, when $x(n)$ is completely independent of $y(n)$, $C=0$. When there is a certain similarity between $x(n)$ and $y(n)$, $C$ has its value between 0 and 1. Therefore, when $C$ tends to be stable, the current signal is considered to be stable in this recording and chosen as a reference signal for subsequent analysis.

$$C = \sum_{n=1}^{N} x(n)y(n) / \sqrt{\sum_{n=1}^{N} x(n)^2 \sum_{n=1}^{N} y(n)^2}$$ (3)

Then, the normalized cross-correlation number between each heart beat signal subsequently recorded and the reference signal is calculated (Notice that, the reference signal is also updated in real time in the process of cross-correlation calculation of each band).

Finally, is applied to calculate the SQI value. Equation (4) shows the nonlinear scaling function, where $e$ has the coefficient of 8 to ensure SQI value in the range of 0-100.
When SQI value approaches 0, it indicates that the current signal is greatly interfered and the signal quality is poor. When SQI value approaches 100, it indicates that the current signal quality is good and can be used for analysis and calculation. In addition, when there is an irregular transformation in heart rate, or when there is no signal for a long time or even cardiac arrest, the system automatically returns 0 for SQI.

3. Performance Evaluation Method

A set of standard biological signal databases recorded by the complex systems laboratory (CSL), Capnobase (CB) database is maintained by the school of electrical and computer engineering, Columbia University[13]. The subjects are aged 1-74 years old and data are acquired with all general anesthesia. Although the signal sampling rate was 100Hz, all of them were derived with 300Hz oversampling frequency. Moreover, CB database contained 124 data records of 120s and 42 data records of longer than 480s with all the dc components removed. Therefore, PPG signals of 1469 beats are chosen from CB data to verify the performance of the method in the paper. The performance of the signal quality evaluation method was qualitatively implemented by calculating the sensitivity $Se$ and the positive prediction $+P$. The expressions are shown in equation (5) and Equation (6), where $TP$ refers to the amount of true positive results, $FN$ stands for the amount of false negative results, and $FP$ represents the amount of false positive results.

$$
Se = \frac{TP}{TP + FN} \quad (5)
$$

$$
+P = \frac{TP}{TP + FP} \quad (6)
$$

4. Experimental Results

The signal quality evaluation uses the PPG signal data of 20 sets with a total of 1469 beats in CB database including normal PPG signals, signals with movement interferences, and signals with asystole. The accuracy of SQI calculation was verified by manual identification. The criterion is that when SQI > 50, it indicates that the current signal band is acceptable; otherwise, it indicates that the current signal band has no analytical significance. As is shown in table.1, the quality evaluation method has a good detection performance with the sensitivity and positive prediction values respectively to be 94.66% and 96.78%.

| Count | TP   | FP   | FN   | Se (%) | +P (%) |
|-------|------|------|------|--------|--------|
| 1469  | 1348 | 45   | 76   | 94.66  | 96.78  |

Fig.3, Fig.4 and Fig.5 respectively show the effects of SQI evaluation method on three types of PPG signals (normal signal, signal with motion interferences and signal with asystole). The left coordinate represents the amplitude level of PPG signal, and the right one stands for the SQI value.
5. Conclusion
It is proposed a new method for quality evaluation of PPG signals. Preprocessing is first implemented to PPG signals collected. Then, SSF method is applied to extract features thus realizing signal segments. Finally, the effective quality evaluation method is adopted to calculate the SQI value of each band. Experimental results show that the method can effectively calculate the SQI level of each band, so as to objectively reflect the variation trend of the signal, such as the occurrence of motion interferences and asystole, thus having great significance in clinical monitoring. On the other hand, since the cross-correlation processing on two complete heart beat bands should be implemented in the quality evaluation method and a period of training process is required to obtain the reference signal, the calculation amount has been increased, thus affecting the real-time performance of signal detection.

To solve this problem, spline interpolation can be performed on the peak and valley points of the known standard signal to construct a standard reference signal, so as to reduce the time of updating the reference signal.

Above all, the method can effectively make signal segmentation, evaluate the signal quality of each band, and effectively identify abnormal wavebands caused by movement interferences, asystole, and sensor loss, thus acquiring the overall variation trend of the PPG signal. Therefore, the method has a good application prospect both in clinical care and in quality evaluation of periodic signals with distinct characteristics.

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References
[1] Zhang Genxuan, Shi Bo, Cao Yang. A New Method for Calculating Pulse Oxygen Saturation[J]. Journal of Biomedical Engineering, 2017, (01): 62-65.
[2] Edward D. Chan, Michael M, Chan, et al. Pulse oximetry: understanding its basic principles facilitates appreciation of its limitations. Respiratory Medicine (2013) 107, 789-799.
[3] Spurek P, Tabor J, Rola P, et al. ICA based on asymmetry[J]. Pattern Recognition, 2017, 67:230-244.
[4] Wang W T, Huang H C. Regularized Principal Component Analysis for Spatial Data[J]. Statistics, 2016.
[5] Tian He, Zhu Huanyan, Zhang Wei. Research on Multi-functional Fitness Detector Based on FFT
and Photoelectric Sensor[J]. Chinese Journal of Medical Instrumentation, 2013, 37(1): 23-26.

[6] Latour M, Piluso V, Rizzano G. Free from damage beam-to-column joints: Testing and design of DST connections with friction pads[J]. Engineering Structures, 2015, 85:219-233.

[7] Grill W M, Wongsampigoon A. Waveform shapes for treating neurological disorders optimized for energy efficiency: US, US9089708[P]. 2015.

[8] Cole S R, Voytek B. Brain Oscillations and the Importance of Waveform Shape[J]. Trends in Cognitive Sciences, 2017, 21(2):137.

[9] Wang Guowei, Mei Zhaomin, Zeng Ruili, et al. Extraction of gearbox early fault features based on segmenting with Features of a curve and multilevel fractional Fourier transformation filtering [J]. Journal of Vibration and Shock, 2016, 35(11):161-166.

[10] Li Q, Li P, Su Z, et al. Effect of a novel motion correction algorithm (SSF) on the image quality of coronary CTA with intermediate heart rates: Segment-based and vessel-based analyses[J]. European Journal of Radiology, 2014, 83(11):2024-32.

[11] Saeh I, Mustafa M W, Al-Geelani N A. New classifier design for static security evaluation using artificial intelligence techniques[J]. International Journal of Electrical & Computer Engineering, (2088), 2016.

[12] Zhang Mei, Wen Jinghua. Point Cloud Registration Method of Normalized Correlation Number and Iterative Recent Surface [J]. Computer Engineering, 2016, 42(10):271-276.

[13] Zhu T, Pimentel M A, Clifford G D, et al. Bayesian fusion of algorithms for the robust estimation of respiratory rate from the photoplethysmogram[C]// Engineering in Medicine and Biology Society. IEEE, 2015:6138-6141.