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PQR signal quality indexes: A method for real-time photoplethysmogram signal quality estimation based on noise interferences

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ABSTRACT

The photoplethysmograph (PPG) acquired from pulse oximeters has been extensively used to estimate the heart rate and blood oxygen saturation. However, how to improve the accuracy of these parameters is always a challenging work as PPG is susceptible to be contaminated by noises especially motion artifacts (MAs). This study presents an algorithm called PQR to calculate three indexes (P/Q/R) for estimation the signal quality based on noise interferences and rSQI index for comparison of any two signals. P/Q/R indicates the influencing degree of high-frequency noise, baseline wandering and motion artifacts on PPG respectively. And a relative signal quality estimation index rSQI is designed to compare the quality of any two signals. When the value of rSQI is greater than zero, it illustrates that the quality of the former signal is better than the latter, and vice versa. Lower P/Q/R scores could be obtained from the algorithm if PPG is contaminated by strong artifacts or with an irregular signal morphology. The algorithm put a complete successive signal into consideration instead of signal segmentation beat by beat. Experiment results using MIMIC (Multi-parameter Intelligent Monitoring for Intensive care) database indicates the availability of PQR algorithm. And the real-time PPG signal quality estimation system could be realized to help estimating heart rate online by applying PQR algorithm to the dataset of IEEE Signal Processing Society. Moreover, the experiments using our lab hardware platform show the corresponding preliminary results of application on the comparison of different signal processing methods. The novel PQR algorithm generates significantly lower rSQI values with the comparison of reference signal when PPG signals are contaminated by strong noise. The chosen threshold could be established once an application has been defined derived from the collected data. The PQR algorithm maybe could help to guide the choice of PPG signal in real-time for the physical information extraction such as heart rate.

1. Introduction

Photoplethysmography is a simple, low-cost and noninvasive optical detection technique. It has been widely used in wearable devices to measure vital physiological parameters including heart rate, oxygen saturation and blood pressure. The PPG waveform is very feeble and it can be easily interfered when signals are collected. There are three main noise interferences: high-frequency noise, baseline wandering and motion artifacts. Removing these noises to obtain the clean signal is still a challenging work [1]. On the one hand, signal quality can differ because of different influencing degree of noise, and it can impact the accuracy of measuring. A signal quality estimation system is needed to evaluate the quality of different original signals. On the other hand, signal processing algorithms are necessarily applied to the contaminated signals in order to reconstruct clean PPG signals. So signal quality estimation system can also give the evaluation results of signal processing algorithms.

Hjorth parameters can be used to evaluate the signal quality and then this algorithm was improved by Deshmane [2–5]. He put forward an adaptive artifact detection algorithm to suppress the false electrocardiogram (ECG) alarms. Signal quality assessment algorithms are highly dependent on specific statistics and waveform morphology characteristics. Photoplethysmogram signal quality estimation using repeated Gaussian filters and cross-correlation is developed [6]. This algorithm designs index “0-100″ to estimate the signal quality of the segmentations. It can only apply to the signals which have good waveform morphology and the algo-

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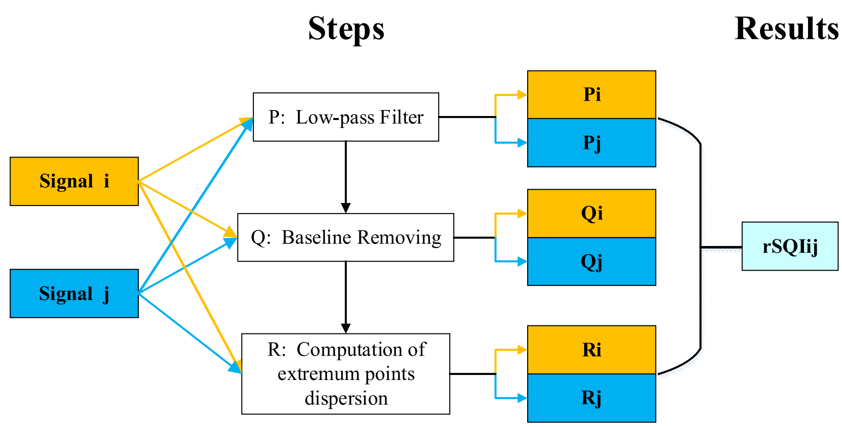

Fig. 1. The signal quality assessment system flow diagram.

rithm needs to select standard waveforms as reference signals. Some waveform morphology features related with signal quality can be extracted from the PPG signals using beat-by-beat segmentation then compare to the corresponding thresholds. Finally the signal quality has three ratings including good, poor and bad [7,8]. Its limitation is also obvious, especially the beat-by-beat segmentation algorithm which is not applicable for noisy signals. There is no ideal PPG waveform to refer to so that the choice of these thresholds is a challenging work. There are other PPG signal quality estimation methods using bispectral analysis [9,10], dynamic time warping and machine learning [11]. These developments demonstrate that PPG signal estimation algorithms now mostly base on the segmentation of beat-by-beat and they cannot be applied to all signals, especially the signals which are contaminated by high-frequency noise and motion artifacts seriously. And when the frequency of motion artifacts is very close to the frequency of real PPG pulse signal, these algorithms can influence the function of wrong arrhythmia alarms.

PPG signals vary from person to person in the real data collection procedure so that there is no standard original signal to refer to. In addition, it is difficult to obtain the signal with high quality from devices in the intensive physical exercise state and the design of signal quality estimation algorithms still need to be based on the waveform morphology characteristics. Through the analysis of large amounts of signal, we found that the noise interferences are not completely useless as we can research influencing degree of different noises on PPG for designing signal quality estimation system.

To sum up, this paper presents a kind of PPG signal quality estimation algorithm based on noise interference—PQR algorithm. Three evaluation indexes P/Q/R are designed for describing the characteristic of PPG signal and relative signal quality index rSQI is designed in order to compare quality of any two PPG signals. It should be noted that the P index indicates the influence of high frequency noise on PPG signal. The Q index indicates the influence of baseline wandering noise on PPG signal. The R index indicates the influence of motion artifacts noise on PPG signal. This paper performs two groups of experiments to verify the effectiveness of the PQR algorithm. Firstly, we apply our algorithm to the PPG data collected by our lab to estimate the signal quality in different motion states for the comparison of different signal processing algorithm performance. This experiment is designed to illustrate the availability of PQR algorithm. Secondly, we apply PQR algorithm to the real-time PPG signal quality estimation system for heart rate monitoring online. It indicates the signals with bad quality could not provide correct HR information so that these signals need deeper signal processing to remove the corresponding noise or need to be discarded. Of course, the proposed algorithm also has its limitations. On the one hand, PQR algorithm is only applied on the PPG signals. On the other hand, the algorithm can be used in the procedure of vital signs monitoring including heart rate, oxygen saturation and so on from wearable device which collects PPG signals.

This paper is organized as follows: the proposed PQR algorithm is introduced in Section 2. The experiments and results are presented in Section 3. Then the discussion is in Section 4. Finally, the conclusion is summarized in Section 5.

2. PQR algorithm design

The evaluation algorithm designs three indexes P/Q/R for the representation of signal quality firstly. “P” characterizes the influencing degree of high-frequency noise on signal. “Q” characterizes the influencing degree of baseline wandering on signal. “P” characterizes the influencing degree of motion artifacts on signal. According to P/Q/R indexes, the relative quality evaluation index—rSQI is designed to compare the quality of different two signals so that we can judge which signal has better quality. The signal quality assessment system flow diagram is shown in Fig. 1 below.

In the section of PQR algorithm introduction, we use the reference “PLETH data” from MIMIC ((Multi-parameter Intelligent Monitoring for Intensive care)) Database (available at physionet.org). The database was the product of mutlti-parameter recordings of ICU patients. The reference data number used in this paper is “411/411″ and its sampling rate is 125 Hz. We select two signals with the same length from the same reference data and the two original signals is shown in Fig. 2.

2.1. Step 1: designing “P”

From the beginning to the end of signal sampling sequence, we define the difference operator Δ, and ΔPPG_n are obtained from

$$\Delta PPG_n = PPG_{n+1} - PPG_n \quad (2.1)$$

The difference operator is used to determine the number of local maximum points and local minimum points. We define the sampling point as the local maximum point when Δ changes from positive to negative and define the sampling point as the local minimum point when Δ changes from negative to positive. The local maximum points and the local minimum points are all called local extremum points. As we all known, high-frequency noise will increase the number of local extremum points. After removing the high-frequency noise, if the number of local extremum points does not change, it indicates that the signal is not impacted by the high-frequency noise. Larger number of reduced local extremum points denotes greater impact of high-frequency on PPG signal. In