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Combined effects of PPG preprocess and dynamic spectrum extraction on predictive performance of non-invasive detection of blood components based on dynamic spectrum

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ABSTRACT

The non-invasive detection accuracy of blood components based on dynamic spectrum (DS) not only depends on the accuracy of each step individually, but also the proper cooperation between these steps. Therefore, combined effects of PPG preprocess and DS extraction on the non-invasive detection of hemoglobin (Hb) were investigated in this paper: DS extraction method itself has some but insufficient ability of noise suppression, and therefore PPG preprocess method should be chosen properly to complement DS extraction method's deficiency in noise suppression and further improve the detection accuracy. In this study, zero phase-shift bandpass filter, wavelet filter and Empirical Mode Decomposition (EMD) filter, were applied for PPG preprocess and single-trial estimation was applied for DS extraction. Partial Least Square Regression (PLSR) was applied for model establishment between DS and Hb content. The results showed that in comparison with non-preprocess, the root mean square error of prediction set (RMSEP) is reduced from 14.1003 g/L to 10.7270 g/L, 11.1018 g/L, 11.2768 g/L respectively with zero phase-shift bandpass filter, wavelet filter, EMD filter. As a result, zero phase-shift bandpass filter cooperates with single-trial estimation better in noise suppression to improve the prediction accuracy of Hb content. By studying the combined effects, we could know how to combine various methods of each step together to obtain the best calibration model. This study also has referential significance to quantitative analysis with NIR spectroscopy.

1. Introduction

The contents of blood components in human are key indicators of health condition and play a very important role in the prevention and diagnosis of diseases. The traditional invasive biochemical detection not only has complicated procedures and pollution, but also causes pain to the subjects, furthermore it can't achieve long-term monitoring in real time [1,2]. Therefore, non-invasive detection technology of blood components is urgently needed and has great significance. Near-infrared spectroscopy is one of the most promising techniques for blood components detection and many researchers have made lots of significant explorations. Jeon designed a device with 5 LEDs and used the ratio of the variations of optical density between systole and diastole at two different wavelengths as variables for hemoglobin concentration determination. The relative percent error and standard deviation of the prediction set are 8.5% and 1.142 g/dL [3], respectively. But the samples should extend to lower and higher hemoglobin concentration to further validate the model. Yamakoshi designed the "Pulse Glucometry" based on InGaAs multi-photo-detector with ultra-high performance, and PLSR model was established with difference spectra to predict blood glucose levels. And they have achieved clinically acceptable accuracy [4], but the device is expensive and difficult to be widespread. Then they used Support Vector Machine (SVM) instead of PLSR for model establishment [5], but superiority of SVM over PLS can't be concluded since no comparison was made between the predictive performance of SVM and PLSR with same data. Jens Kraitl developed a device with 3 LEDs for non-invasive detection of Hb content, and the mean difference was 1.058 ± 2.93 g/L [2]. However, the effectiveness and reliability of the calibration model may be difficult to justify, since they used 45 samples for calibration and 19 for prediction. Such small sample size is insufficient for non-invasive detection of blood components involving so many influence factors. Masimo company of The United States has developed a series of non-invasive instruments with 8 and 12 wavelengths [6–9] for Hb detection and they have won the

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FDA's license. Clinical trials in recent years indicated that there exist good correlation and small deviation between SpHb measurements and invasive measurements [10–12], but there are also conditions where Hb content was underestimated when Hb content is relatively low [12] and Hb content can't be measured with low perfusion [11]. Meanwhile, the company has always claimed that SpHb is not to replace the invasive measurement and blood samples should be analyzed by invasive instruments prior to clinical decision making [13]. Chen Xingdan designed a spectrophotometric system with a broadband light source composed of 9 LEDs and BP neural network combined with Principal Component Analysis (PCA) was used to predict Hb content, but some predictive values deviated largely from true values when Hb contents are relatively low [14]. Xu KeXin proposed the floating reference position theory for blood glucose measurement [15], which holds that there exists a reference position where the signal is uncorrelated with glucose concentration and by differential correction between the signals at measuring position and reference position, background interference can be weaken obviously. They have proved the existence of such position in in-vitro experiments and Monte Carlo simulations [16], but in-vivo experiments haven't seen great progress. Maybe the reason is that the anisotropy and time-variability of human body makes it very different to find a suitable position as reference. Li Gang put forward the Dynamic Spectrum (DS) theory [17], which can reduce influences of individual differences and changes of measurement conditions. They used an instrument consisting of the tungsten-halogen lamp and a spectrometer and BP neural network was applied to establish the calibration model. And the correlation coefficient of the prediction set reached 0.907 [18]. But the problem of small sample number (60) also exists, which affects the generalization ability of neural network model largely.

Although many achievements have been made in the non-invasive detection of blood components by spectroscopy, its detection accuracy can't meet demands for clinical application. Therefore, improving the non-invasive detection accuracy of blood components still requires unremitting efforts: on the one hand, improve the accuracy and stability of each step of non-invasive detection of blood components; on the other hand, ensure that each step in the system can effectively cooperate with each other.

Non-invasive detection of blood components based on DS consists of four steps in general: multi-wavelength PPG detection, PPG preprocess, DS extraction and modeling, shown as Fig. 1. So far, the existing studies mainly focused on one single step of these four mentioned above. For PPG preprocess method, Ding Haiquan compared Savitzky-Golay (SG) filter, moving average filter and EMD filter and drew the conclusion that the prediction accuracy of Hb content is better with EMD filter [19]; Lin Ling verified that wavelet filter [20], EMD filter [21] both significantly improved non-invasive detection accuracy of blood components. For DS extraction method, peak-peak value extraction [4], frequency-domain extraction [22], single-trial estimation [23], fast digital lock-in extraction [24], Independent Component Analysis (ICA) extraction combined with the dual-tree complex wavelet transform [25] were proposed successively. However, there hasn't seen research about the combined effects between PPG preprocess method and DS extraction method. Since extraction accuracy of DS is closely related to PPG preprocess, cooperation between PPG preprocess and DS extraction was investigated in this paper. Single-trial estimation was chosen as DS extraction method from about 10 kinds of DS extraction methods; prediction accuracy of Hb content with PPG signals preprocessed with zero phase-shift bandpass filter, wavelet filter and EMD filter were compared to determine which PPG preprocess method cooperates best with single-trial estimation in noise suppression.

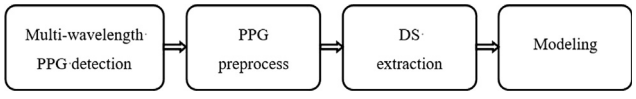

Fig. 1. Steps of non-invasive detection of blood components based on DS.

2. Theory

2.1. Single-trial estimation

Up to now, DS extraction methods based on "Dynamic Spectrum" theory are divided into two groups: time-domain extraction method, frequency-domain extraction method [22]. The frequency-domain extraction method uses the amplitude of fundamental component in frequency-domain instead of peak-peak value in time-domain. The frequency-domain extraction method itself is equivalent to a narrowband filter with high Q value, so using traditional linear filters for PPG preprocess is of little significance. Meanwhile, whether for the traditional linear filters or the frequency-domain extraction method itself, their ability to restrain motion artifacts is insufficient. As one of time-domain extraction methods, single-trial estimation [23] has good performance and it can be concluded as follows. Firstly, it obtains PPG template by superimposing PPG signals in all wavelengths and therefore white noise can be removed partly. Secondly, it makes full use of each data through 'edge' fitting, unlike the peak-peak value extraction to use only two data: the peak and the valley [4]. Therefore, it has some ability to suppress high-frequency noise and motion artifacts [26]. Finally, DS values with gross errors are eliminated according to 3σ criterion in statistics. So, single-trial estimation was chosen as the DS extraction method in this paper.

Steps of single-trial estimation are listed as follows:

1 Get logarithmic PPG signals by logarithmic operations.
2 Get the PPG template by averaging the logarithmic PPG signals of all wavelengths.
3 Perform the linear fitting between the first rising edge of the PPG template and the first rising edge of logarithmic PPG signals of each wavelength, and the obtained slope values are single-trial DS values labeled as $DS_1^{\lambda=1}$, $DS_1^{\lambda=2}$…$DS_1^{\lambda=500}$ ($\lambda$is the sequence number of wavelength).
4 All rising edges of the PPG template perform the fitting as described in step 3, and a series of single-trial DS values labeled as $DS_i^{\lambda=1,2\ldots500}$($i$ is the sequence number of rising edge) are obtained.
5 Single-trial DS values of each wavelength are averaged to obtain the averaged DS labeled as $\overline{DS_i^{\lambda}}$. Euclidean distance, shown as Eq. (1), is used for similar degree estimation between all single-trial DS values and the averaged DS, and then 3σ criterion is used to eliminate single-trial DS values including gross errors. Here, D represents the average of Euclidean distance between all single-trial DS values and the averaged DS, ν_i represents the residual error and σ represents standard deviation, expressed as Eqs. (1)–(4) respectively.

$$D_i = \sqrt{\sum_{\lambda=1}^{n} |DS_i^{\lambda} - \overline{DS^{\lambda}}|^2} \tag{1}$$

$$D = \frac{1}{n}\sum_{i=1}^{n} D_i \tag{2}$$

$$\nu_i = D_i - D \tag{3}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} \nu_i^2}{n-1}} \tag{4}$$

6 After elimination of gross errors, remaining single-trial DS values repeat step 5 until there is no gross errors. Finally, the rest DS values are averaged as the final output of DS.

2.2. PPG preprocess methods for enhancing the performance of single-trial estimation

As described in Section 2.1, single-trial estimation has some ability