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# Fast digital lock-in amplifier for dynamic spectrum extraction

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**Abstract.** An appropriate method for spectrum extraction for better signal-to-noise ratio (SNR) and lower computational cost is essential in noninvasive detection. We have first studied two existing extraction methods for dynamic spectrum (DS) comparatively: frequency domain analysis and single trial estimation; after analyzing the advantages and disadvantages theoretically, a new method based on a fast digital lock-in amplifier (FDLIA) was developed to overcome the limitations of these two existing methods. The feasibility of the new method was verified by experiments and the results demonstrated that the FDLIA method based on DS had greatly simplified the computation of frequency domain analysis without the method error; moreover, the continuous signal was cut into several short segments in FDLIA and the gross errors from an episode of pulse wave were eliminated, and thus SNR improved. Therefore, the FDLIA method utilizing the advantages of both existing methods can be effectively realized in a general embedded system in real time for its simple algorithm. © 2013 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: 10.1117/1.JBO.18.5.057003]

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## 1 Introduction

Some official statistics from International Diabetes Federation (IDF)<sup>1</sup> and World Health Organization (WHO)<sup>2</sup> show that the diseases such as diabetes, hyperlipidemia and anemia impact human mortality and mobility, which also means unaffordable medical fees for both individuals and society. Continuous monitoring of these blood components has been recognized so far as the most important part in preventing and curing these diseases. However, it can hardly play a bigger role due to the risks of invasive and minimally invasive tests<sup>3</sup> such as pain, infection, and time-consumption. A noninvasive device that can quickly and accurately measure blood components is being expected.

There are already many reports<sup>4,5</sup> about noninvasive methods for blood component measurement, especially spectral methods which seem to be the most appealing optical technology for further investigations. Among different spectral methods,<sup>6–9</sup> transmission spectroscopy based on photoplethysmography (PPG)<sup>10–14</sup> shows remarkable superiorities and is widely used for noninvasive detection of hemoglobin and glucose directly from blood. A method using the light changes of pulsatile blood could eliminate the influence of differences of other tissues such as skin, muscle, and bone to extract the pure spectra of pulsatile blood, and also has the potential to integrate with an existing pulse oximeter for upgrading the clinical service.

However, the absorption of light by pulsatile blood is far less than other tissues and there are still some other problems, especially spectral overlap and signal weakness. For a robust, reliable, and dynamic adaptable model for blood component analysis, two things need consideration: the data extraction method and the modeling method. Nowadays, many researchers

tend to pay much more attention to different regression techniques than to the effective spectrum extraction methods, neglecting the most important thing: improving the signal-to-noise ratio (SNR) of the spectral data. Kraitl et al.<sup>11</sup> adopted the ratio between the peak-to-peak pulse amplitudes for a calculation of blood parameters. Yamakoshi et al.<sup>12</sup> used the peak-to-peak magnitude of pulse waves from only 3–4 consecutive cardiac beats, picking the beats which were the most stable and had almost similar waveforms of the pulse intensity changes during a measurement period of 20 to 30 s. Similarly, Chen et al.<sup>13</sup> proposed subtracted blood volume spectrometry, but they did not demonstrate how to extract a spectrum.

Dynamic spectrum (DS),<sup>14,15</sup> proposed by our group and based on a modified Lambert Beer's Law, is used to extract the pulsatile blood absorption spectrum from the optical pulse waves at visible and near-infrared range to analyze blood components. To improve the spectral SNR, we have proposed two effective extraction methods: frequency domain analysis<sup>16</sup> and single trial estimation,<sup>17</sup> both of which are employed to extract the DS and have greatly helped to achieve accurate prediction models in clinical experiments. Two existing methods are studied comparatively in this article. With frequency domain analysis, DSs are extracted from the whole data to make full use of the sampled data; however, the method has difficulties in eliminating errors from a certain segment of pulse waves. Single trial estimation can remove the abnormal pulses by contrast; however, its algorithm is complex. After analyzing the pro and cons theoretically, we developed another DS extraction method based on a new fast digital lock-in amplifier (FDLIA)<sup>18,19</sup> to improve the SNR of spectral data and reduce computational cost. Several real-time DSs made up of equivalent amplitudes at a special frequency are calculated by the

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FDLIA, and then real-time DSs with the gross errors are eliminated. To test the feasibility and demonstrate its advantages, some experiments were performed. Taken together, the new method takes advantages of two existing methods, making maximum use of all data and removing the abnormal pulses to improve the SNR; moreover, the method can reduce a lot of complex computations.

## 2 Extraction Methods for DS

### 2.1 Existing Methods

Two existing methods for DS extraction are originally described in the previous publications.<sup>16,17</sup> Before the DS extraction, we applied logarithmic transformations to the pulse waves at all the wavelengths. The transformed pulse waves were called logarithmic pulse waves. Frequency domain analysis extracts the fundamental frequency amplitude of a logarithmic pulse wave by fast Fourier transform (FFT) instead of the peak-to-peak value which is difficult to sample. The logarithmic pulse waves at all the wavelengths are similar and FFT is a linear transform, so the fundamental frequency amplitude is proportional to the peak-to-peak value. Therefore, the fundamental frequency amplitudes at all the wavelengths constitute DS.

It is well established<sup>18</sup> that pulse wave measurements are quite sensitive to probe tissue movement artifacts, such as an episode of gross movement artifact, hand or finger tremor, a bout of coughing, and marked changes in the breathing pattern. Single trial estimation firstly removes the abnormal segments of a logarithmic pulse wave by a model, the summation of all the logarithmic pulse waves. Then a slope is obtained by fitting a rising or falling edge at every wavelength with the corresponding edge of the pulse wave model, so the DS is made up of these slopes at all the wavelengths. For a continuous pulse wave, there are several rising or falling edges, from which we can obtain several DSs. At last, a  $3\sigma$  principle is used to eliminate some DSs with gross errors and the average of the remainder DSs is reserved.

The two methods are essentially the same, both of which, based on the statistical principle can extract a DS with high SNR from a stable pulse wave. However, it is impossible for frequency domain analysis to reduce noise that has the same frequency as the fundamental frequency. Frequency domain analysis is less efficient than single trial estimation to remove the abnormal pulse wave. From the standpoint of the algorithm complexity, frequency domain analysis is simpler than single trial estimation. Frequency domain analysis is implemented by FFT that calculates the amplitudes at all the frequencies, but only the amplitude of one frequency component is extracted for analysis. The processing cannot make full use of all the information and causes great computation waste. Therefore, both methods can be improved.

### 2.2 New Method Based on FDLIA

According to the analysis above, to improve the SNR of DS and reduce computational cost, a new method is expected which has three advantages: removing the abnormal pulse wave, making full use of all stable data, and using a simple algorithm.

To reduce gross errors, the most effective method is to cut a long pulse wave into several short segments to extract several DSs, so the DS extracted from an abnormal segment of the pulse wave can be eliminated by a statistical method. For the

problem of computation waste in frequency domain analysis, a digital lock-in amplifier (DLIA) can be used to directly extract the amplitudes at the fundamental frequency. It is equivalent to Fourier transform in principle, but it only calculates the amplitude at a known frequency.<sup>19</sup> The pulse wave has a typical fundamental frequency around 1 Hz, depending on heart rate. It is suitable in the study to use the fundamental frequency of 1 Hz for most people. The DLIA algorithm not only makes full use of all the sampled data, but also greatly improves the speed of computation. The fast digital lock-in amplifier (FDLIA) proposed by our group<sup>20,21</sup> can further accelerate the calculation speed. The fast algorithm sets the sample frequency as a whole-number multiple of four of the extraction frequency. Then the reference signals of sine and cosine are sequences made up of 0, 1, -1 and phase sensitive demodulation is simplified to addition and subtraction operations. As such, a lot of arithmetic in DLIA is reduced. Moreover, the fast algorithm combines the oversampling technology to improve the accuracy. Above all, the new method based on FDLIA was developed, which cut the pulse waves into several segments in time domain, extracted the DS by FDLIA for each segment, and then calculated the average value of the remainder DSs after eliminating DSs with noise.

The steps of the new method are detailed as follows. (1) The sample frequency and the data length are set appropriately based on the extraction frequency of 1 Hz. To use a FDLIA, the sample frequency should be a whole number multiple of four. (2) The sampled data is preprocessed by the down-sampling technology. For example, when the sample frequency ( $f_s$ ) is set to 120 Hz, the summation of every continuous thirty sampled points is seen as a new point, so the sample frequency is changed to 4 Hz that is four times of the extraction frequency. (3) The in-phase cross-correlation signal  $I$  and the quadrature cross-correlation signal  $Q$  can be calculated mainly by addition and subtraction. (4) The amplitude  $A$  of the extracted frequency at each wavelength can be calculated using Eq. (1). These amplitudes constitute a real-time DS. (5) When several DSs are extracted, a statistical method can be used to eliminate the DSs with gross errors and the average of the remained DSs is reserved.

$$A = 2 \cdot \sqrt{I^2 + Q^2}. \quad (1)$$

## 3 Materials and Methods

Experimental studies were undertaken to accomplish the following objectives: (1) to verify the correctness of frequency domain analysis to support the new method; (2) to test the new method and evaluate it by comparison. To fulfill objective (1), a feasibility study was performed. Simulation pulse waves were designed to demonstrate the substance of the method that the amplitude at the fundamental or harmonic frequency can replace the peak-to-peak value in DS extraction. To accomplish objective (2), DS extraction was implemented on both simulation and actual pulse waves to practically test the new method. We compared the DS extracted by three methods (frequency domain analysis, single trial estimation, and FDLIA) to evaluate the new method. In addition, the computation cost was compared among frequency domain analysis, classical DLIA, and FDLIA.

### 3.1 Feasibility Study

The simulation logarithmic pulse waves were generated according to Eq. (2) so they were similar waveforms:

**Table 1** Parameter setting of four simulation pulse waves.

Pulse wave	Parameter $a$	Parameter $dc$
pulse 1	0.05	8
pulse 2	0.09	11
pulse 3	0.07	10
pulse 4	0.04	9

$$y = a[|\sin(2\pi 0.5t)| + |0.3 \sin(2\pi t - \pi/4)|] + dc, \quad (2)$$

where the parameters  $a$  and  $dc$  are the amplitude of the wave and the direct component, respectively. According to the actual situation, the parameters  $a$  and  $dc$  were set differently to simulate four kinds of waves at different wavelengths. Table 1 shows the different parameters for four simulation waves. It also shows the perfusion variability index (PVI). The simulation waves were sampled. The sample frequency,  $f_s$ , was set to 120 Hz. The data length was set to 5 s. Then Fourier transform was performed on each pulse wave in MATLAB (Version 7.7.0, The MathWorks, Inc.) to extract the fundamental frequency component and two harmonic frequency components. The peak-to-peak values of these waves were accurately calculated by derivation. After normalization by dividing by the maximum, these peak-to-peak values were compared with the amplitudes of fundamental and harmonic frequency, respectively.

### 3.2 Simulation Study

To test the new method, it was fully implemented on the simulation pulse waves generated above. Two frequency components at 1 Hz and 2 Hz were chosen as the special extraction frequencies according to Eq. (2). The amplitudes at these two frequencies for all the waves were calculated by FDLIA. The difference between the two frequencies in the extraction process lay in down-sampling. One was down-sampled to 4 Hz, and the other was 8 Hz. Then these amplitudes at each frequency were

normalized and compared with the respective normalized peak-to-peak values.

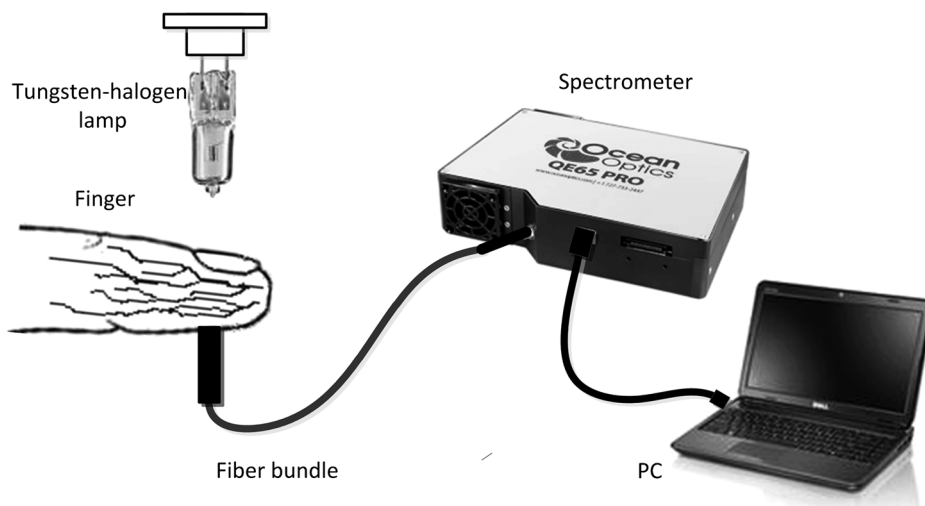
### 3.3 Application and Evaluation

To further test the new method in application, real DS extraction was also performed in the study. The pulse waves were collected using an instrument consisting of a broadband source, a fiber optic bundle, a spectrometer, and a laptop computer. Figure 1 shows the schematic diagram of the measurement system. The broadband source was a 30 W tungsten-halogen lamp (Philips). The fiber bundle as a probe consisted of several fibers with numerical aperture (NA) of 0.22, which was connected to the spectrometer (QE65000, Ocean Optics, USA). The spectrometer was connected to a laptop computer by a USB interface. The wavelength of the spectrometer ranged from 349.7 to 1147.5 nm with 0.81 nm increments. However, it was insensitive for the pulse wave under 600 nm. We chose the wavelength range 600.29 to 1147.50 nm in the experiments. The integration time per data point was 50 ms for all measurements, so the sample frequency was 20 Hz.

The instrument was allowed to warm up for at least 15 min prior to the measurement. Two healthy volunteers were enrolled in the study. They were requested to sit quietly in a chair during the test, except one was told to move her finger slightly. The data was continuously acquired for about 30 s and the total number of spectral data sets was 600.

For DS extraction, stage extraction was implemented by FDLIA to obtain several real-time DSs. With the extraction frequency being 1 Hz, two kinds of data length (5 and 3 s) were respectively adopted on the relatively stable data from the volunteer without moving her finger. Six or ten real-time DSs for different data lengths were extracted. The real-time DSs with the same data length were compared with each other, and the real-time DSs with the different data length were also compared. The remainder real-time DSs, made by removing the comparative noisy DSs with the data length 3 s, were averaged as the final DS. Moreover, the final DS extracted by the new method was compared with that extracted by the two existing methods accordingly.

To show that the stage extraction can reduce the gross errors because of the abnormal pulse waves, the data from the

**Fig. 1** The schematic diagram of the measurement system.

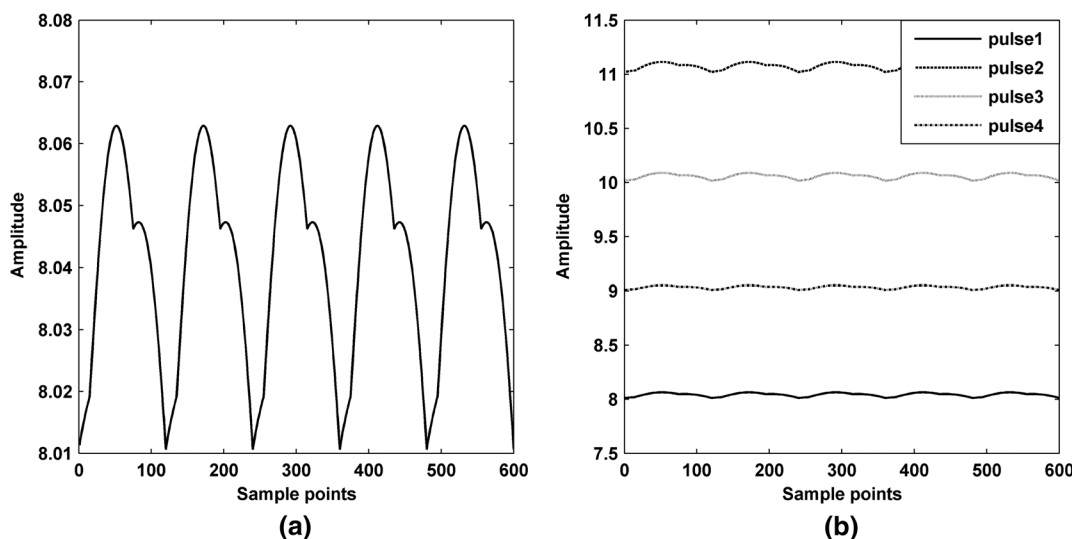


Fig. 2 (a) One of four simulation logarithmic pulse waves. (b) Four simulation logarithmic pulse waves.

volunteer with a slight finger movement was extracted by the new method and frequency domain analysis, respectively. Finally, we compared the two DSs to evaluate the new method.

### 3.4 Comparison of Computation Cost

The computational costs of frequency domain analysis, a classical DLIA, and a FDLIA were compared with each other. The computational types included multiplication, addition, subtraction, and extraction of roots. Frequency domain analysis was discussed according to the number of the sampled points. If the number of points was the exponent of 2, FFT can be performed; if not, discrete Fourier transform (DFT) can be used. The comparison was done under the conditions that the number of wavelengths was  $N$ , the sample frequency was  $4M$  times of the signal frequency, and the number of sample periods was  $q$ , so the total number of sampled points was  $4Mq$ .

## 4 Results and Analysis

### 4.1 Feasibility Study

Figure 2 shows the simulation logarithmic pulse waves. The waveform of pulse 1 is shown in Fig. 2(a), and the waveforms of pulse 1 to pulse 4 are shown together in Fig. 2(b). The frequency of the pulse waves is 1 Hz. The peak-to-peak values of the four waveforms pulse 1 to pulse 4 calculated by derivation are as follows: 0.052305, 0.094149, 0.073227, 0.041844 (six significant figures are shown for the data in simulation tests without error).

The four waves pulse 1 to pulse 4 were processed by Fourier transform. One part of the amplitude frequency response of pulse 1 by eliminating the  $dc$  component is shown in Fig. 3. The fundamental frequency component extracted is of the maximum value, and the frequency is equivalent to the frequency of the pulse wave. The amplitudes at two harmonic frequencies were also extracted. Table 2 shows the values of the amplitudes at the fundamental and harmonic frequencies. The values are all the product of the true amplitude and the number of input data points in the Fourier transform.

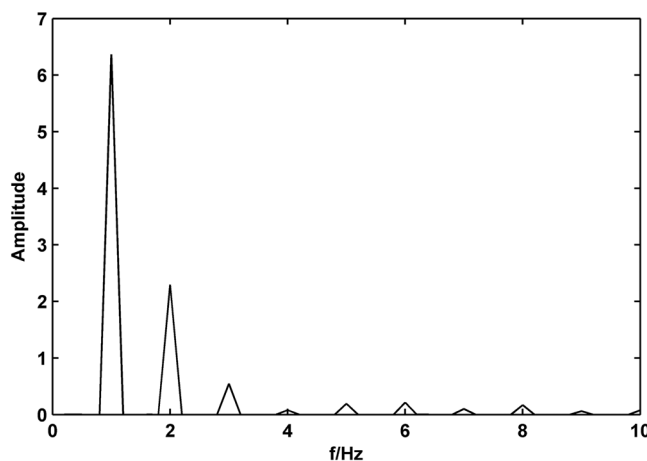


Fig. 3 Part of the amplitude frequency response of pulse 1 by Fourier transform.

Table 2 Amplitudes of four waves pulse 1 to pulse 4 at fundamental and harmonic frequencies.

	Fundamental frequency	Second harmonic	Third harmonic
pulse 1	6.367289	2.297060	0.546766
pulse 2	11.461120	4.134708	0.984179
pulse 3	8.914204	3.215885	0.765472
pulse 4	5.093831	1.837648	0.437413

The normalized peak-to-peak values of four waves were 0.555556, 1.000000, 0.777778, and 0.444444, correspondingly, which was equal to the values of each column in Table 2 after normalization, respectively. Therefore, the amplitudes at both the fundamental and harmonic frequency can take the place of the peak-to-peak values to form DS. The result verifies the feasibility of frequency domain analysis as well as the new method in theory.

**Table 3** Amplitudes at 1 Hz and 2 Hz extracted by FDLIA and FFT.

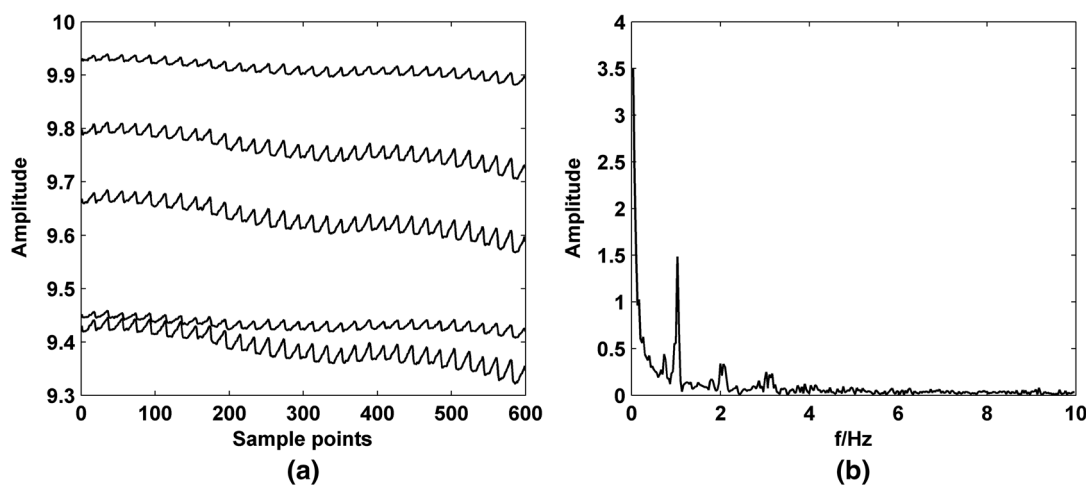
	1 Hz (FDLIA)	Fundamental frequency	2 Hz (FDLIA)	Second harmonic
Pulse 1	0.019234	0.021224	0.001286	0.007656
Pulse 2	0.034622	0.038204	0.002315	0.013782
Pulse 3	0.026928	0.029714	0.001801	0.010720
Pulse 4	0.015387	0.016980	0.001029	0.006125

## 4.2 Simulation Study

Table 3 shows the amplitudes at the frequencies 1 and 2 Hz of four waves extracted by FDLIA and FFT. The values calculated by FFT are the amplitudes at the fundamental and second harmonic frequency in Table 2, but they were simplified to the actual amplitudes. The normalized values extracted by the new method are also 0.555556, 1.000000, 0.777778, and 0.444444, which were equal to the normalized peak-to-peak values. The results demonstrate the feasibility of the new method in extracting DS preliminarily. It should be noted that the amplitudes calculated by FDLIA are attenuated greatly compared with the actual amplitudes for the down-sampling processing and spectrum leakage. Fortunately, the attenuation has no influence on these pulse waves with the same proportion.

## 4.3 Application and Evaluation

Figure 4(a) shows the pulse waves at the wavelengths of 660.21, 727.31, 808.21, 840.77, and 905.43 nm, with the data being acquired from the volunteer without movement. The waves are still disturbed by low frequency drift and high frequency noise. Figure 4(b), which is very similar to the amplitude frequency response of the simulation wave in Fig. 3, shows the amplitude frequency response of the logarithmic pulse wave at the wavelength of 727.31 nm in Fig. 4(a). The main frequency component is concentrated in the frequency of 1 Hz, and we can also see the noise spectrum distribution in Fig. 4(b).



**Fig. 4** (a) Actual pulse waves at five wavelengths of 727.31, 808.21, 840.77, 660.21, and 905.43 nm, from top to bottom. (b) The amplitude frequency response of one pulse wave at the wavelength of 727.31 nm.

For the stable data, the continuous pulse wave was firstly cut into six segments with the data length of 5 s, and the equivalent amplitudes at the frequency 1 Hz were extracted, respectively by FDLIA for each wavelength and each segment. Figure 5 shows six calculated DSs of the human finger with a constant oxygenation level (about 98%). The spectra are original without normalization. The amplitudes in Fig. 5(a) and 5(e) are relatively small with a high noise level; the amplitudes in Fig. 5(d) and 5(f) are higher than in Fig. 5(b) and 5(c). Compared with the corresponding pulse wave, the main reasons for the abnormal real-time amplitude are that the frequency and the amplitude of the pulse wave are unstable and the pulse wave is subject to noise.

Figure 6 shows ten real-time DSs without normalization when the data length is 3 s. Figure 6(a), 6(c), and 6(h) which are respectively embodied in the Fig. 5(a), 5(b), and 5(e) have higher noise than the others. The smaller segment time helps to precisely locate the pulse wave with high noise.

The real-time DSs shown in Fig. 6(a), 6(c), and 6(h) were eliminated, and then the remainder real-time DSs with the data length of 3 s were averaged and normalized as the final DS shown in Fig. 7(a). We can be sure that the more effective information can be reserved in the final DS. Figure 7(b) shows the DSs extracted by three methods: frequency domain analysis, single trial estimation and FDLIA in the same coordinate. It is found that there is hardly any difference among the shapes of three DSs. For the unknown true spectra, it is difficult to determine the best one from their shape. The correlation between the DSs extracted by FDLIA and frequency domain analysis is 0.9997, and the correlation with single trial estimation is almost the same. Therefore, we demonstrate that two existing methods and the new method can all extract DS with a high SNR for a stable pulse wave.

The logarithmic pulse wave at the wavelength of 727.31 nm from the other volunteer is shown in the Fig. 8(a). The baseline fluctuates strongly due to the movement of her finger. The DSs extracted by the new method and frequency domain analysis are shown in Fig. 8(b) and 8(c), respectively. The noise in Fig. 8(b) is less than in Fig. 8(c). The result demonstrates that the new method can enhance the SNR by cutting the continuous wave into several short segments and removing the real-time DSs with higher noise.

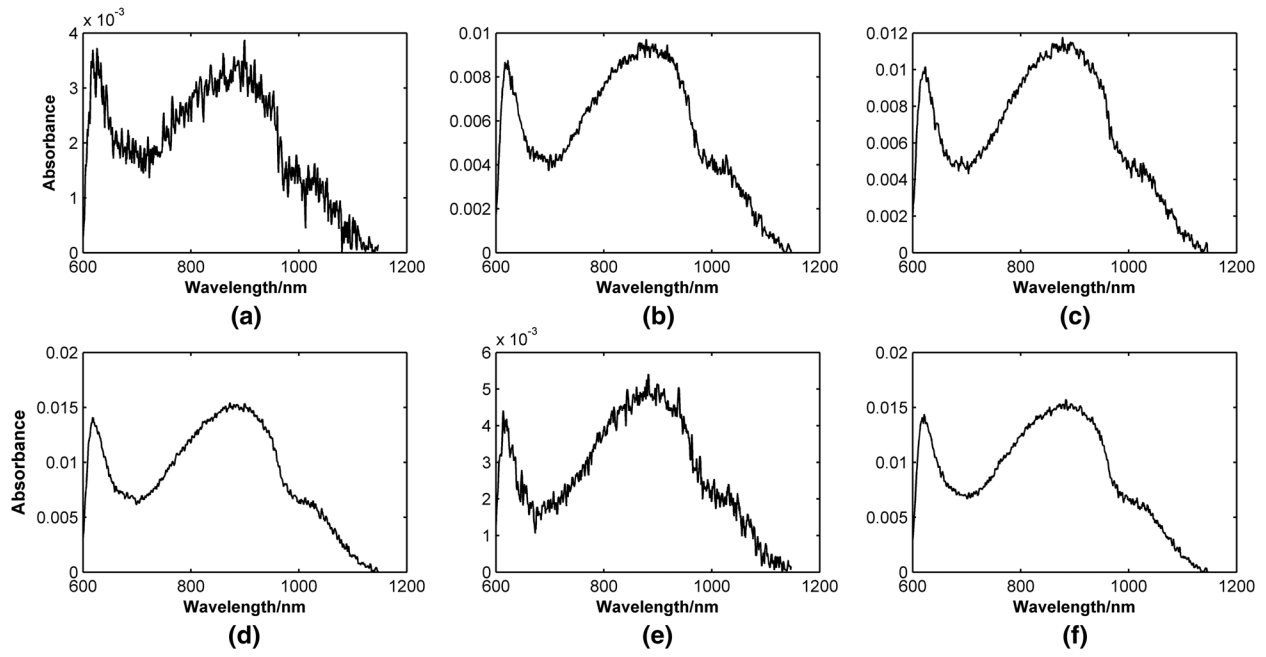


Fig. 5 Six real-time DSs with the data length of 5 s.

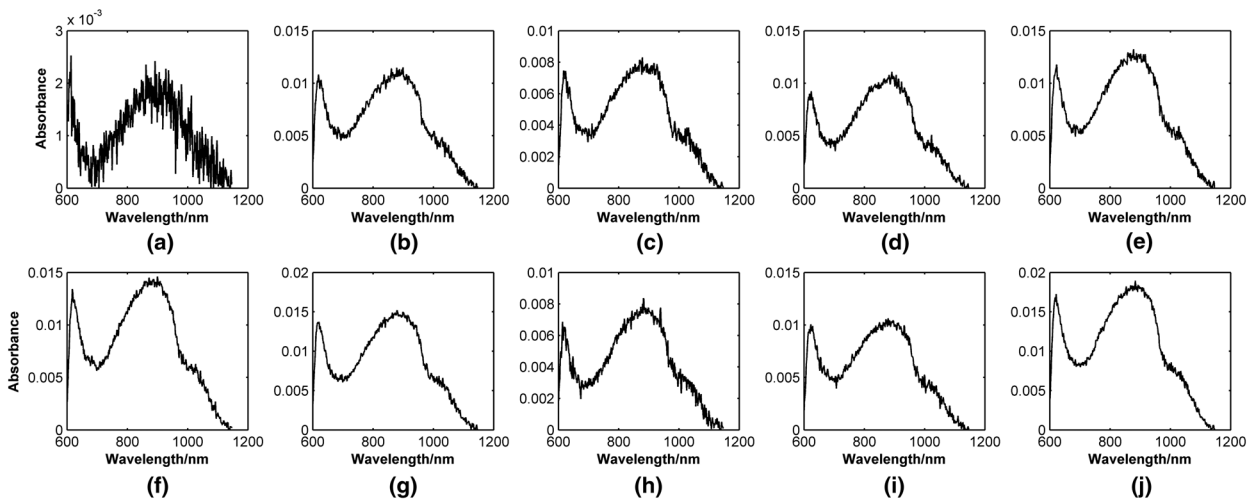


Fig. 6 Ten real-time DSs with the data length of 3 s.

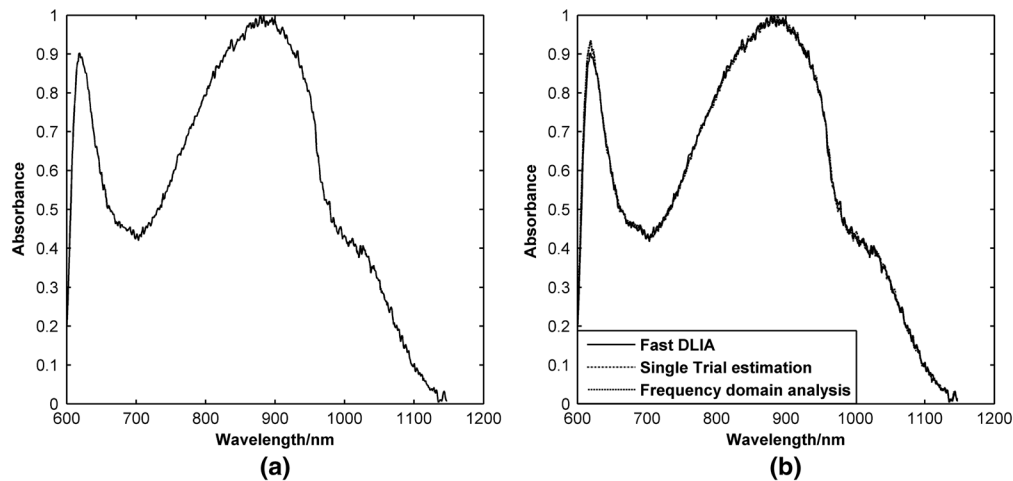
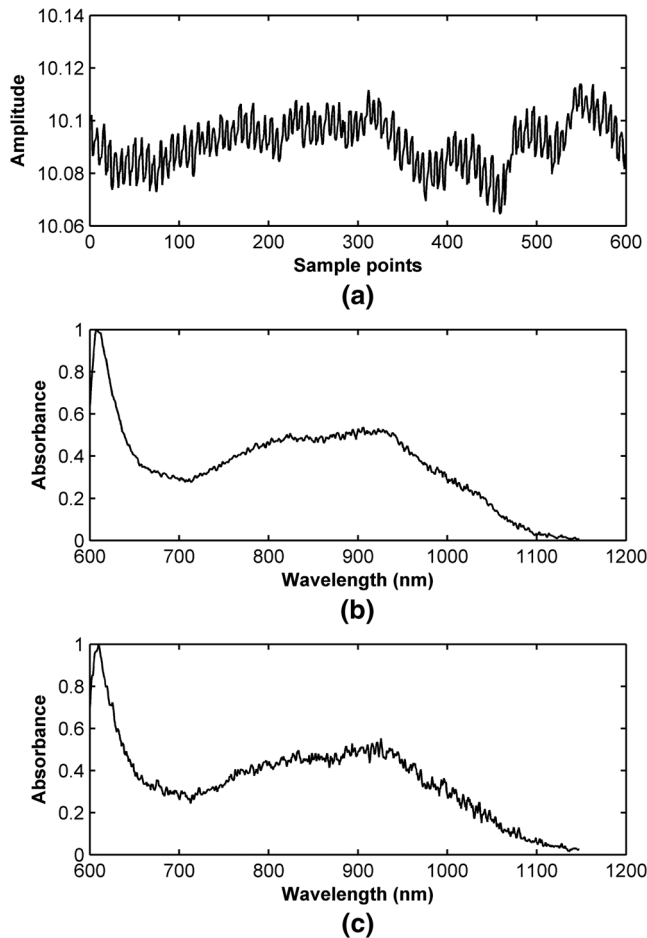


Fig. 7 (a) The average DS extracted by the new method. (b) Comparison of DSs extracted by two existing methods and the new one.



**Fig. 8** (a) Actual pulse wave at the wavelength of 727.31 nm with the finger movement. (b) Dynamic Spectrum extracted by the FDLIA. (c) Dynamic Spectrum extracted by the frequency domain analysis.

#### 4.4 Comparison of Computation Cost

Table 4 shows computation costs of three methods. Fourier transform is divided into two types: DFT and FFT. The variable  $N$  in Table 4 is the number of wavelengths, and  $4Mq$  is the number of sample points.

The FDLIA can reduce a lot of computation by comparison, especially multiplication operations compared with the other three methods in Table 4. The result means that the new method can effectively lower the computation demands of DS extraction and extract the spectrum in real time.

## 5 Discussion

DS, based on the absorption of the pulsatile blood at multiple wavelengths, can greatly reduce the influence of individual differences because of the constant absorption of other tissues in a short time and of measuring conditions such as the light intensity. In spite of this, we should pay much attention to the effective spectral extraction method when the SNR of transmission signal cannot be optimal. The two existing methods, frequency domain analysis and single trial estimation, extract the equivalence values of the peak-to-peak values at each wavelength. One is based on frequency domain, the other is on time domain, and all of them depend on the statistical average method to solve some practical problems such as data acquisition and removing movement artifacts. Although they have made good clinical research progress, there is still plenty of room for improvement in our work. In this paper, we improved the spectral extraction for noninvasive blood component measurement, and especially overcame the disadvantages of two existing methods to provide more reliable data for a calibration model and to realize the data acquisition in real time.

The simulation experimental result showed that the fundamental and harmonic frequency components of pulse waves at every wavelength are in proportion to the peak-to-peak values. The result directly verified the feasibility of frequency domain analysis. While the new method was derived from frequency domain analysis, the result can fully support the new method. Moreover, when the number of the sample periods is not an integer for the extraction frequency and the data length is short such as 3 s, the conditions will not influence the DS extraction because of the same attenuation at all the wavelengths for similar waveforms. We can also infer that spectrum leakage and barrier effects can be neglected in the new method. The results in the application to simulation and actual pulse waves showed that the new method is feasible. The comparison among three methods for a stable pulse wave showed that all these methods are in accordance with the theory of DS. However, for a pulse wave with a movement artifact, the new method, compared with frequency domain analysis, can get a higher accuracy. It takes advantage of single trial estimation. In addition, the new method can greatly reduce a lot of complex computation. Two advantages of the new method are detailed as follows: (1) It uses FDLIA to extract a given frequency component instead of all the frequency components. Obviously the new method reduces a lot of arithmetic, and FDLIA can further reduce the computational complexity, especially eliminating multiplication operations. As a result, the real-time implementation of spectrum extraction in a general embedded system is more possible. (2) For an abnormal episode of pulse wave with

**Table 4** Comparison of each operation cost among the methods.

Operation types	Multiplication	Extraction of root	Addition and subtraction
Discrete Fourier transform	$N(64 M^2 q^2 + 8 Mq)$	$4 NMq$	$N(64 M^2 q^2 - 4 Mq)$
Fast Fourier transform	$N(8 Mq \log_2(4 Mq) + 8 Mq)$	$4 NMq$	$N(8 Mq \log_2(4 Mq) + 8 Mq)$
Classical digital lock-in amplifier	$N(8 Mq + 2)$	$N$	$N(8 Mq - 1)$
Fast digital lock-in amplifier	$2 N$	$N$	$N(8 Mq - 4q - 1)$



gross errors, the stage extraction can eliminate the DSs influenced by noise and interference like single trial analysis, so that the average of remainder DSs is more accurate.

The new method can not only be used for a blood component measurement but also for existing pulse oximeters. With the potential of the new method a few problems are to be discussed. The scattering of blood has been neglected in both frequency domain analysis and the new method, for which the logarithmic pulse waves at all the wavelengths are similar. In fact, the scattering still has a little effect on the spectra. Fortunately, given the effects, a nonlinear regression method such as support vector machines (SVM) can be used to enhance the measurement accuracy. Besides, the raw *dc*-spectra from the finger showed also the typical water peak at 965 nm of finger tissue and some other components, and it is different from the DS. For further investigation, it is a worthwhile attempt to set both the DS and *dc*-spectra as input variables in the calibration regression. Moreover, we chose the frequency of 1 Hz as the fundamental frequency to extract the DS. The heart rate has a typical frequency around 1 Hz. It is suitable in the study to set up 1 Hz as the fundamental frequency for most people. By the simulation tests, we know that we can extract the DS by the new method at the fundamental or harmonic frequency. Moreover, the fundamental frequency of pulse wave in the Fig. 8(a) is far greater than 1 Hz, but the method can still be implemented well. We can conclude that it has little to do with the DS extraction if the extraction frequency doesn't conform to the heart rate. If we want to extract the DS at the fundamental frequency component, the commonly used methods can be adopted to calculate the accurate frequency of the pulse wave in real time. Then, the sample frequency and the sample length are adjusted automatically.

We believe that the improvements shown in this article open up the possibility of developing an accurate calibration model and a real-time implementation of DS extraction. We expect that the new method would also be beneficial in a variety of other spectral and biological applications.

## 6 Conclusion

A new method based on the FDLIA for DS extraction is proposed in this paper. In simulation tests and the application of two volunteers, the results verified the feasibility of the method. It can eliminate the gross error from an abnormal episode of pulse wave by cutting the continuous signal into several short segments, so the new method has higher SNR than frequency domain analysis. Additionally, it greatly reduces the complex computation, especially almost all the multiplication operations, without the method errors. The new method promises a real-time implementation of accurate DS extraction for noninvasive blood measurement in a general embedded system. To apply the method, we have initiated a clinical study and simultaneously set up a portable instrument based on the LEDs and a general embedded system to realize it in real time. We will fully evaluate the benefits of the new method in performing blood component measurement on humans in our future research.

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