An Autocorrelation Modeling Method for Oxygen Saturation Measurement During Low Perfusion

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An autocorrelation modeling method for oxygen saturation measurement during low perfusion

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Abstract:

Background: SpO_2 is a widely used estimation of oxygen saturation owing to its convenient usage and low cost. However, SpO_2 determination under low perfusion condition is severely affected by noise.

Methods: In this paper, an autocorrelation modeling method for the oxygen saturation measurement during low perfusion is presented. The proposed method mainly contains two steps: calculating the autocorrelation of the photoplethysmography (PPG) signals and modeling for the parameter calculation. The autocorrelation of the PPG signals can suppress the noise and extract pulse waves from low perfusion signals. The model can realize the calculation of SpO_2 with the autocorrelation signals.

Results: Experiments showed that the new method had a good accuracy and stability under low perfusion condition (perfusion index (PI)<=0.2%), and it was also motion-

tolerant. Meanwhile, the new method showed a good performance for the oxygen saturation measurement under the condition of lower perfusion(PI=0.1%).
Conclusions: The new method could realize the calculation of SpO2 by little computation and high efficiency without extra hardware. It has strong potential in real-time clinical use.

Keywords: Pulse oximetry, SpO2 extraction, Low perfusion, Autocorrelation modeling method

1 Background

Saturation of peripheral oxygen (SpO_2), which reflects arterial oxygenation levels, is often used to assess the function of the respiratory system and the circulation system. Pulse oximetry is a non-invasive technique, recording from extremities such as fingers and ear lobes, to continuously monitor SpO_2. Owing to its cost-effectiveness benefits, pulse oximetry has become a regular monitoring device used in anesthesia, surgical operation, and intensive care [1,2]. However, clinical applications of pulse oximetry revealed that the measurement accuracy and precision were severely affected by motion and low peripheral perfusion caused by low ambient temperature or cardiogenic shock[3,4]. In case of low perfusion, the amplitude of photoplethysmography (PPG) signals, which is used to calculate SpO_2, become very small and hidden in noise. The signal-to-noise ratio (SNR) is too low to extract useful information with conventional methods(Fig. 1 b). In case of motion, PPG signals are contaminated by motion artifacts. The frequency spectrum overlap of PPG signals with motion artifacts makes conventional low-pass or high-pass filter techniques inapplicable. Therefore, new methods are needed to deal with the issue mentioned above.

To overcome the shortcomings of motion and low perfusion, many algorithms were developed in the past few years. For instance, Masimo Corporation proposed Discrete Saturation Transform (DST) method to adaptively filter out noise from recordings by constructing a reference noise [5]. Yan et al. proposed a robust minimum correlation discrete saturation transform (MCDST) algorithm to remove motion artifact [6]. Yousefi et al. developed a real-time adaptive algorithm to extract heart rate and SpO_2 for a wireless pulse oximeter allowing users to move freely [7]. Byung et al. proposed independent component analysis to reduce noise in PPG signals[8]. However, this method did not perform well for low perfusion interference. Foo proposed two algorithms to account for the difference between the properties of low perfusion signal and motion contaminated PPG [9]. However, Foo's method for low perfusion case was a complicated non-causal filter technique commonly used for off-line analysis. In addition, SpO_2 was not extracted in their work. Therefore, new algorithms for accurately extracting SpO_2 under low perfusion is required, especially for the anesthesia, surgical operation, and intensive care application.

Here we propose a novel autocorrelation modeling method for determining SpO_2 under low perfusion conditions. First, we characterize the properties of PPG (photoplethysmography) signals under low perfusion condition. Then, we deduce the new autocorrelation based SpO_2 extraction method. At last, validation test resutls of the method on accuracy, stability, and motion-tolerance are presented. The new SpO_2 extraction method have potential of real-time clinical use.

2 Methods

To realize the accurate measurement of SpO_2 under low perfusion condition, we designed a pulse oximetry to acquire PPG signals(generated by a SpO_2 simulator-Fluke Index 2XL) which are pre-processed and used for calculating the alternative

component(AC) and the direct component(DC). We computed autocorrelation on recorded AC signals, then calculated the SpO_2 with the autocorrelation preprocessed signals by our modeled method. The overall process is shown in Fig. 2.

2.1 PPG signal generation

Photoplethysmography (PPG) signals, which are used to extract SpO_2, can be obtained when illuminating the body with a light beam at a haemoglobin-sensitive wavelength. In the peripheral sites to be recorded, the volume of blood within the illuminating field alters periodically to the artery pulsation, thus generating fluctuating PPG signals. A PPG signal can be represented as an addition of an alternative component (AC) and a direct component (DC). The DC signals reflect lights that are absorbed or scattered by vein, base volume of artery, and other non-pulsatile tissue, while the AC signals reflect volume change in the artery and arterial blood. The parameter PI (perfusion index) is an indication of the peripheral perfusion level, which can be simply calculated by the ratio of AC to DC amplitude($PI=P_{AC}/P_{DC}$). In the low perfusion case, PI can be less than 0.2%.

To develop the new method, two kinds of PPG signals were used: 1) simulated signals, and 2) recorded signals. A way to model low perfusion condition is lowering the peripheral temperature. However, its controllability and reproducibility are relatively low. Therefore, we used simulated PPG signals generated by a SpO_2 simulator-Fluke Index 2XL (Fluke Biomedical, USA). With the simulator, we could obtain PPG signals with preset PI2 (PI for infrared case), PR (pulse rate), and SpO_2 (Fig. 1). Signal simulation is a good tool for developing and testing the new method for low perfusion case. On the other hand, motion artifacts were modeled by direct recording the PPG as the users moved their fingers. A home-made reusable dual-wavelength PPG sensors were used in this case.

2.2 Calculation of SpO_2

2.2.1 Principle of SpO_2 extraction

Oxygen saturation can be calculated by concentration of oxyhaemoglobin (HbO_2) and that of deoxyhaemoglobin (Hb). Since the absorption spectra of HbO_2 and Hb are different in the red and infra-red regions, two monochromatic lights are commonly used to illuminate peripheral vascular bed. Two PPG signals and two PIs are formed based on light transmission. Therefore, SpO_2 can be calculated according to Beer-Lambert Law as follows:

$$SpO_2 = \frac{\varepsilon_{Hb}^{\lambda_2} R - \varepsilon_{Hb}^{\lambda_1}}{\left(\varepsilon_{HbO_2}^{\lambda_1} - \varepsilon_{Hb}^{\lambda_1}\right) - \left(\varepsilon_{HbO_2}^{\lambda_2} - \varepsilon_{Hb}^{\lambda_2}\right) R} \quad (1)$$

Where, λ_1 and λ_2 are the two wavelengths (in 660 and 940 nm); R is the ratio of the two PIs (i.e., R=PI_1/PI_2); $\varepsilon_{HbO_2}^{\lambda_1}$ and $\varepsilon_{HbO_2}^{\lambda_2}$ are the extinction coefficients of HbO_2 at λ_1 and λ_2; $\varepsilon_{Hb}^{\lambda_1}$ and $\varepsilon_{Hb}^{\lambda_2}$ are the extinction coefficients of Hb at λ_1 and λ_2. All the relevant coefficients are constant[10]. Therefore, SpO_2 is determined as R is obtained from recordings. Considering individual differences in scattering effect and other uncertainty factors, Eq.1 is generally expanded in terms of second-order Taylor series in practice as follows:

$$SpO_2 = A * R^2 + B * R + C \quad (2)$$

Where the coefficients A, B, and C can be calibrated by fitting the data to a conic curve using Least Squares.

115 *2.2.2 Principle of autocorrelation modeling*

116 Autocorrelation modeling consists of 1) autocorrelation function computation, and 2)
117 relating SpO_2 and other parameters to autocorrelation signals. Before going into the
118 autocorrelation modeling details, we review the autocorrelation technique first.

119 Autocorrelation technique is a weak signal detection technique, particularly for signals
120 with cyclic properties, such as ECG. For a signal $x(t)$, and its autocorrelation function is
121 defined as

122 $$R_x(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_0^T x(t)x(t+\tau)\mathrm{d}t \qquad (3)$$

123 Now, we present a simple demonstration of noise reduction of autocorrelation
124 technique. Given a sinusoidal signal $s(t)=A\sin(\omega t+\varphi)$ and its noise $n(t)$, the signal $x(t)$ is a
125 sum of these two signals; i.e., $x(t)=s(t)+n(t)=A\sin(\omega t+\varphi)+n(t)$. Then, the autocorrelation
126 function of this signal is

127 $$\begin{aligned} R_x(\tau) &= \lim_{T\to\infty}\int_0^T \left[s(t)+n(t)\right]\left[s(t+\tau)+n(t+\tau)\right]\mathrm{d}t \\ &= \lim_{T\to\infty}\int_0^T s(t)s(t+\tau)\mathrm{d}t + \lim_{T\to\infty}\int_0^T s(t)n(t+\tau)\mathrm{d}t \\ &\quad + \lim_{T\to\infty}\int_0^T n(t)s(t+\tau)\mathrm{d}t + \lim_{T\to\infty}\int_0^T n(t)n(t+\tau)\mathrm{d}t \\ &= R_s(\tau) + R_{sn}(\tau) + R_{ns}(\tau) + R_n(\tau) \end{aligned} \qquad (4)$$

128 Since the original signal $s(t)$ and its noise $n(t)$ are independent, and if the noise is white
129 noise, the three latter terms tend to be zero as $\tau\to\infty$. Thus we have

130 $$R_x(\tau) = R_s(\tau) = \frac{A^2}{2}\cos\omega\tau \qquad (5)$$

131 The autocorrelation function has the same frequency to the original signal, and the
132 amplitude can be related to that of the original. Therefore, useful information can be
133 extracted while noises are reduced[11,12].

2.2.3 Autocorrelation modeling of SpO_2

PPG signals, are regenerative and can be regarded as cyclic in a small period of time. Suppose the resolved AC component of PPG is denoted by $p_{AC}(t)$, then we have

$$p_{AC}(t) = p_{AC}(t+mT) = P_{AC} \cdot g_{AC}(t) \qquad (6)$$

Where T is the period of $p_{AC}(t)$; m is an arbitrary constant; $g_{AC}(t)$ is normalized $p_{AC}(t)$, and P_{AC} is the amplitude of $p_{AC}(t)$. Recall that SpO_2 is calculated from R, which is the ratio of the two PIs. Since PI is defined as the ratio of AC and DC amplitude, conventional computation of R is as follows:

$$R = \frac{PI_1}{PI_2} = \frac{P_{AC1}/P_{DC1}}{P_{AC2}/P_{DC2}} = \frac{P_{AC1}/P_{AC2}}{P_{DC1}/P_{DC2}} \qquad (7)$$

However, in the low perfusion case, both P_{AC1} and P_{AC2} are very weak and prone to be distorted by noise and interference, while the amplitude of DC component was less affected. To suppress noise, we compute autocorrelations on recorded AC signals. Suppose the noise in the recorded AC signal $pr_{AC}(t)$ is denoted by $n(t)$; i.e., $pr_{AC}(t)=p_{AC}(t)+n(t)$. The autocorrelation function of $pr_{AC}(t)$ can be represent as follows:

$$\begin{aligned} R_{prAC}(\tau) &= R_{pAC}(\tau) + R_{pACn}(\tau) + R_{npAC}(\tau) + R_n(\tau) \\ &= R_{pACn}(\tau) + R_n(\tau) = P'_{AC} \cdot g'_{AC}(\tau) \end{aligned} \qquad (8)$$

Where $R_{pACn}(\tau)$ and $R_{npAC}(\tau)$ are cross-correlations of $p_{AC}(t)$ and $n(t)$, which equal to zero as they are independent with each other. $g'_{AC}(\tau)$ is normalized autocorrelation signals of $pr_{AC}(t)$ and P'_{AC} is the amplitude of autocorrelation signals of $pr_{AC}(t)$. $R_n(\tau)$ is only non-zero at $\tau=0$. Therefore, the weak cyclic pulsation signal was retrieved from the stable autocorrelation function with a strongly suppressed noise. Besides, since autocorrelation does not change the periodical property of the original signal, $R_{prAC}(\tau)$ is also regenerative and has a period of T and has an amplitude proportional to the square of P_{AC}; i.e.,

$$P_{AC} = k\sqrt{P'_{AC}} \quad (9)$$

Where k is the amplitude transfer factor (Fig. 3). Unlike sinusoidal signal, k does not exactly equal to $2^{1/2}$ and, in practice, we determined it empirically through experimental trials. In this way, the amplitude of AC component of the PPG signal, i.e. P_{AC}, can be determined.

Given P_{AC}, the perfusion index (PI) can be calculated from the amplitude of DC component (P_{DC}), which is relative easy to be determined; thus we have

$$PI = P_{AC}/P_{DC} = \left(k\sqrt{P'_{AC}}\right)/P_{DC} \quad (10)$$

In the dual-wavelength method, we actually obtained two PIs corresponding to wavelength λ_1 and λ_2, respectively. Therefore, with autocorrelation modeling method, we obtained R (denoted as R' to be distinguished from R calculated with Eq. 7) as follows:

$$R' = \frac{PI_1}{PI_2} = \frac{k_1\sqrt{P'_{AC1}}/k_2\sqrt{P'_{AC2}}}{P_{DC1}/P_{DC2}} \quad (11)$$

Where k_1 and k_2 are amplitude transfer factors at the two wavelengths. Thus we compute SpO_2 as follows:

$$SpO_2 = A*R'^2 + B*R' + C \quad (12)$$

2.3 Implementation of SpO_2

To extract SpO_2 accurately, the autocorrelation modeling technique, in practice, is comprised of four steps described as follows.

(1) Signal recording and pre-processing. The dual-wavelength signals were recorded and packed in a crosswise format for the convenience of data transmission. In the pre-processing step, data from the same source would be accumulated in a dedicated data pool

for later use. After data-rearrangement, the raw data were low-pass filtered to reduce noise, notch filtered to suppress power-line interference.

(2) P_{AC} and P_{DC} computation. As for P_{DC}, the computation was relatively simple: low-pass filtering the raw data and calculating the mean value. As for P_{AC}, we high-pass filtered the original PPG AC signal and computed the difference between peak and valley.

(3) Computation of autocorrelation function and its amplitude. In practice, the summation limit to calculate autocorrelation function can never be infinite and should be truncated:

$$R_x(m) = \frac{1}{N} \sum_{n=0}^{N-1-|m|} x(n)x(n+m) \qquad (13)$$

Where, $N>>m$. The fast computation of autocorrelation is generally achieved by FFT and window technique. To make the method be adaptive to real-time use, we employed the circular autocorrelation technique (Supplementary Fig. 1). Suppose the length of the data pool is N, the length of autocorrelation function should also be N. The tail of the pool was linked to the head. In this way, when the pool was full, the algorithm turns to the head of the data pool to restore and retrieve the new data. To compute the amplitude of the autocorrelation function, we integrated one cycle of data.

(4) Computation of R' and SpO_2 according to Eqs. (9)-(12). Every 6 seconds a new set of results were generated.

2.4 Data analysis

The new algorithm--autocorrelation modeling of SpO_2--was carried out on Matlab (MathWorks, USA). Linear regression and other statistical analysis were done by OriginPro v9.0 (OriginLab, USA) and Excel (Microsoft, USA). Statistical data were represented as mean ± SD.

3 Results

3.1 Autocorrelation modeling results

The new autocorrelation modeling method was built based on two linearity assumptions: 1) the amplitude of original AC component is proportional to square root of that of autocorrelation function as denoted by Eq. (9), and 2) the substitution of R with R' in Eq. (2). Here, we test the two linearity assumptions.

First, we created PPG signals for PI2=3%, PR=75, and SpO_2 (%) ranges from 36 to 100 using Fluke Index. The simulated signal at each SpO_2 was recorded and transmitted to PC.

We calculated the magnitudes of original PPG AC component (P_{AC}) and those of the autocorrelation functions (P'_{AC}). Since values of P_{AC} under different SpO_2 settings are different, a sweep of SpO_2 (%) from 36 to 100 yielded a sufficient multi-level coverage of PPG signals. At each SpO_2 settings, we calculated P_{AC} and P'_{AC} 10 times. Linear regression was conducted on means of each pair (n = 10). It showed a nearly perfect linearity between P_{AC} and $(P'_{AC})^{1/2}$ (Pearson's r=0.99967, Fig. 4a). Further, the amplitude transfer factor k in Eq. (9) can be calculated from the slope of the regression line. In this case, the wavelength was λ_1 and k_1=1/0.348=2.874.

After computation of k_1, k_2, P'_{AC1}, P'_{AC2}, P_{DC1} and P_{DC2}, we calculated R and R' according to Eqs. (10) and (11). Linear regression of means of R' on those of R (n=10) yielded a regression line with slope of 1.004 and Pearson's r of 0.9998 (Fig. 4b).

3.2 Accuracy

To test SpO_2 extraction accuracy of the autocorrelation modeling method, we modeled the low perfusion scene by simulating PPG signals with small PI (say, PI=0.2% and 0.1%) (Fig. 5). A sweep of SpO_2 (%) from 64 to 96 was generated by Fluke Index. In PI=0.2%

cases, all the SpO_2 were accurately estimated with a high precision (SD/mean < 3%) (Fig. 6a, Table 1). In PI=0.1% cases, SpO_2 estimates were also accurate (SD/mean < 5%) (Fig. 6b, Table 1).

3.3 Stability

To test the stability of the autocorrelation modeling method, we continuously recorded the simulated PPG signal (PI=0.2%, PR=70, SpO_2=94%) for 1 hour. The mean SpO_2 fall between 92 and 96 (94.3±0.6) (Fig. 6c). Further, we calculated PR from the autocorrelation function and got a stable and accurate estimation (69.99±0.04) (Fig. 6d).

3.4 Motion-tolerance

To test the motion-tolerance of the autocorrelation modeling technique, we recorded the PPG signals of our fingers with and without shaking with our home-made dual-wavelength sensor[13]. The experiment recorded two finger shaking (about 1 to 4 seconds and 9 to 11 seconds, Fig. 7a). Apparently, the PPG signals with finger shaking were contaminated by interference (Fig. 7a). We calculated the autocorrelation function results of the PPG signals contaminated by interference. The interference was severely suppressed (Fig. 7b).

4 Discussion

In this paper, we have described a new SpO_2 extraction method called autocorrelation modeling. It involved computation of the autocorrelation function and relating its magnitude to that of the original PPG signals. Autocorrelation strongly suppressed the noise and picked out the weak PPG signals under low perfusion condition. We demonstrated a good linearity between the magnitude of PPG signals and the square root of that of the autocorrelation function, upon which SpO_2 could be accurately extracted.

The validation experiments using SpO_2 simulator demonstrated the high-accuracy of the method in case of low perfusion(PI=0.2%）. Besides, the application of autocorrelation technique also strengthened the ability of motion-tolerance.

In the clinical use of pulse oximetry, the SpO_2 determination under low perfusion condition caused by low ambient temperature or cardiogenic shock[2,3] is severely affected by noise. This brings a lot of trouble to clinical work, such as false decreasing of SpO_2, making it important to improve the accuracy of SpO_2. Compared with the adaptive method using extra hardware, like accelerators to sense the motion, the new method enhances PPG signals by using its inherent cyclic properties. Since the computation of autocorrelation function could be achieved by Fast Fourier Transformation (FFT), the new method is suitable for real-time application with little computation and high efficiency. In the future, the method needs to be further improved to adapt to the accurate measurement under the condition of lower perfusion(PI=0.1%) and lower SNR, especially under the condition of large motion interference.

5 Conclusions

We introduced a method named autocorrelation modeling to solve the issue of inaccurate SpO_2 measurement under low perfusion in the clinical use. The validation experiments showed the autocorrelation modeling method can strongly suppress the noise and pick out the weak PPG signals under low perfusion condition. The autocorrelation modeling technique showed a high accuracy of the method in case of low perfusion (PI=0.2%), and also strengthened the ability of motion-tolerance. The validation experiments showed a strong potential in real-time clinical use for the autocorrelation modeling method.

Declarations

Declarations

Ethics approval and consent to participate:

All authors and participants declare that we have read and have abided by the statement of ethical standards.

Consent for publication:

None of the material related to this manuscript has been published or is under consideration for publication elsewhere, including the internet. All authors and participants understand that the information will be published, have read this manuscript and approve to have it considered exclusively for publication in BMC Medical Informatics and Decision Making.

Availability of data and materials:

All data generated and analysed during this study are included in this published article, and any further details of this study are available from the corresponding author on reasonable request.

Competing interests:

All authors declare that we have no competing interests.

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Authors' contributions:

Tan Shuangping designed the method described in this manuscript and designed the experiment to verify the method, and was the major contributor in writing the manuscript. Wei Jie and Chen Hao analyzed and interpreted the experiment data, and also contributed to the writing of the manuscript. Zhang Tong, Deng Youfeng and Zuo Hongbin provided a lot of help for the experimental method and writing of this paper. Wu Xiali analyzed and interpreted the experiment data. All authors read and approved the final manuscript.

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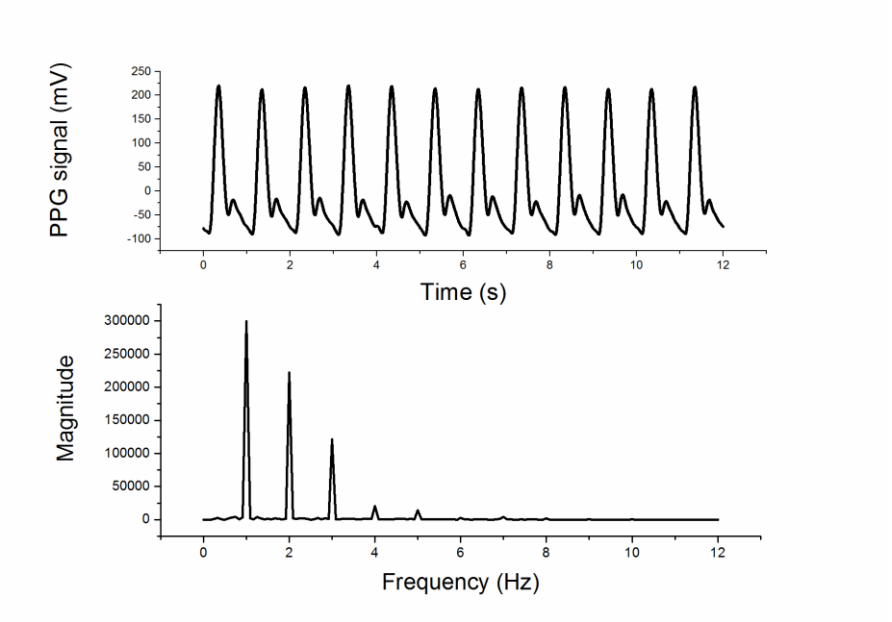
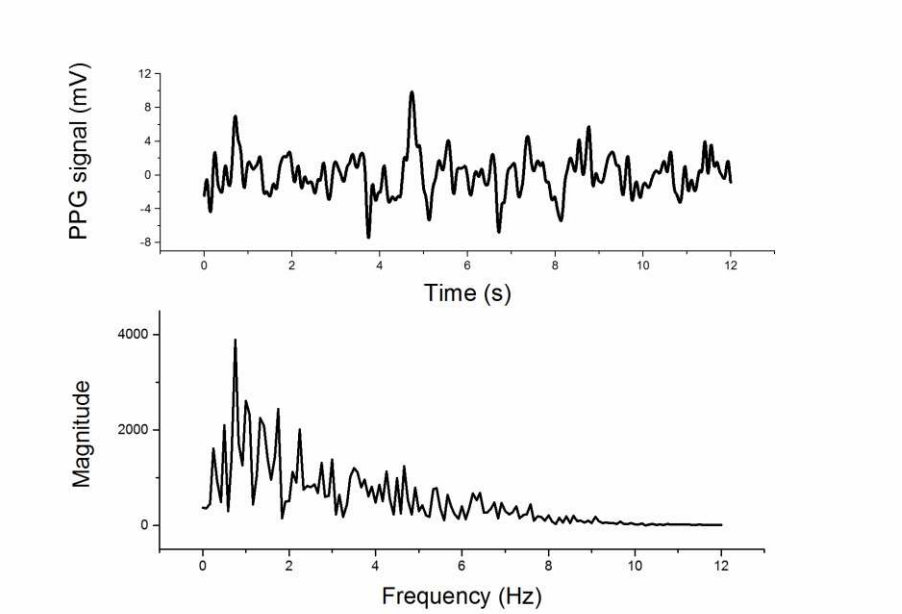
Figures:



(a)



(b)

Fig. 1 Simulated PPG signal and its Fourier spectra. (a) Normal case: PI=3%, $SpO_{2=}$96%, PR=60 times/min. (b) Low perfusion case: PI=0.075%, $SpO_{2=}$96%, PR=60 times/min

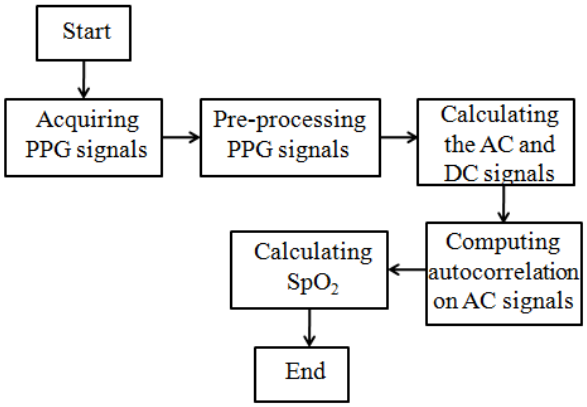


Fig. 2 Overall process of autocorrelation modeling method

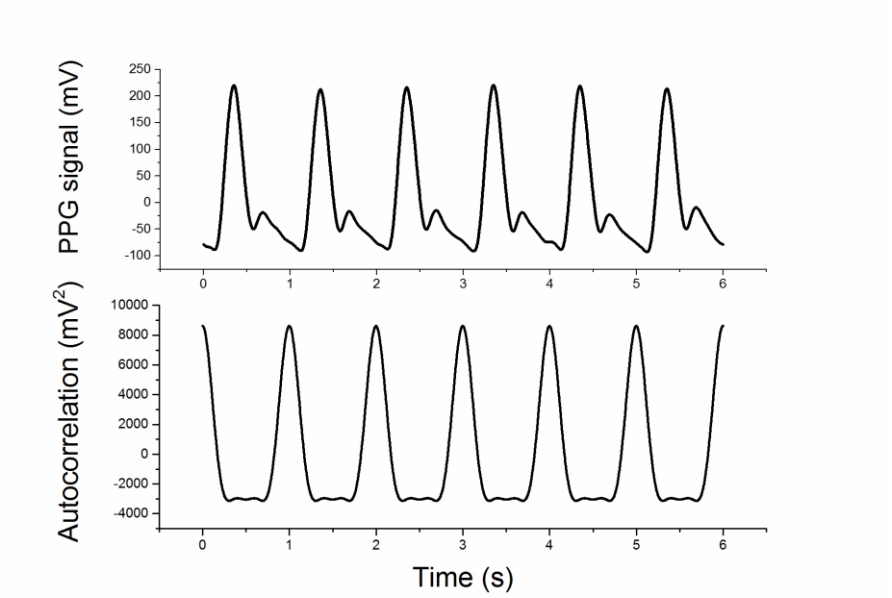
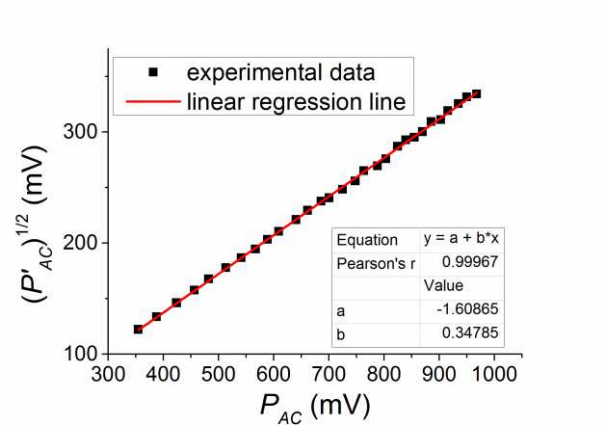
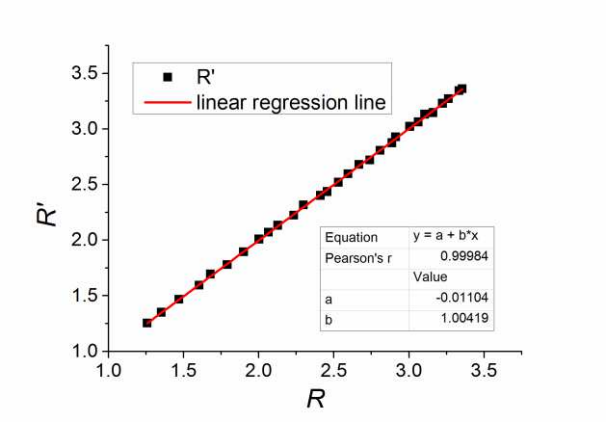


Fig. 3 Autocorrelation function of a typical normal PPG signal

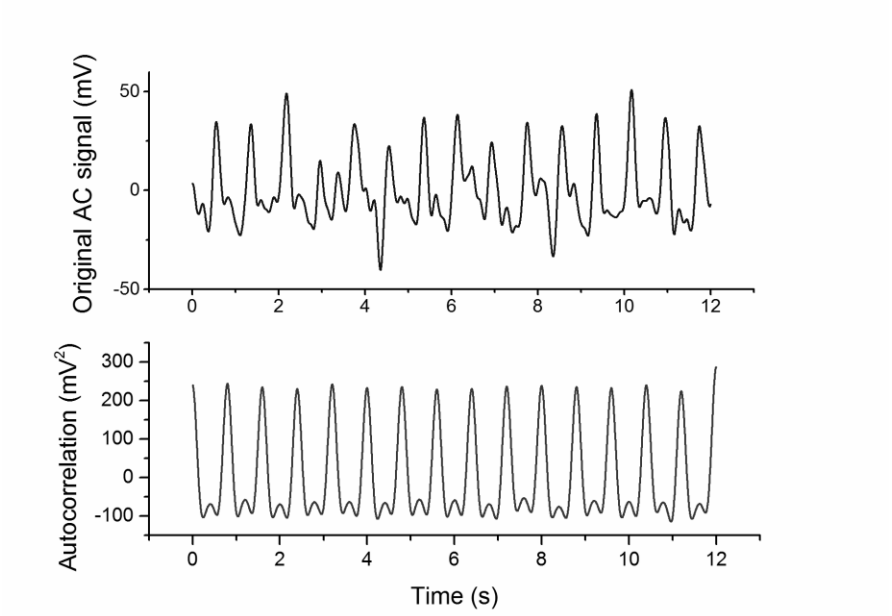


(a)



(b)

Fig. 4 Linear regression of the critical intermediate parameters. (a) Linear regression of square root of the amplitude of autocorrelation function of PPG AC component on original PPG AC amplitude; (b) Linear regression of *R'* on *R*



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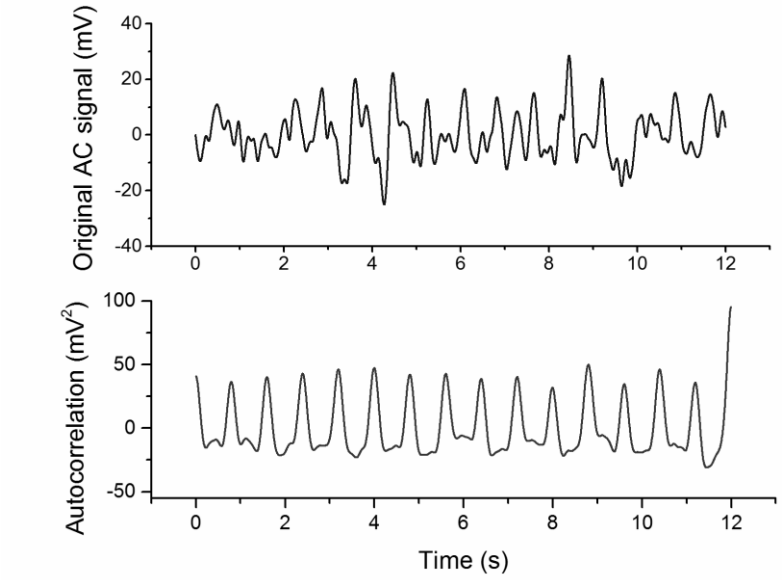
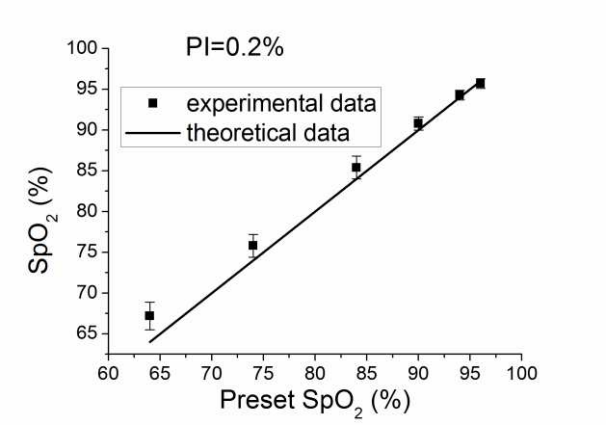


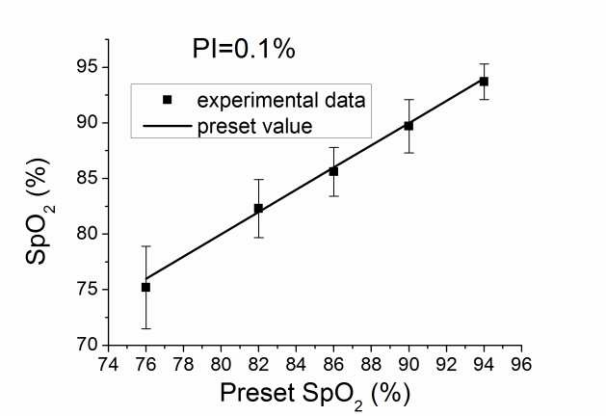
(b)

Fig. 5 Simulated PPG AC signal under low perfusion condition and its autocorrelation function. (a) PI=0.2%; (b) PI=0.1%



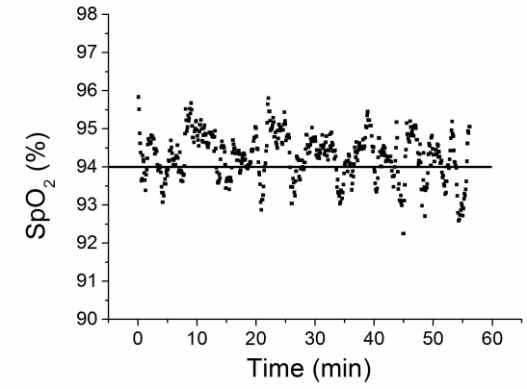
363

364 (a)



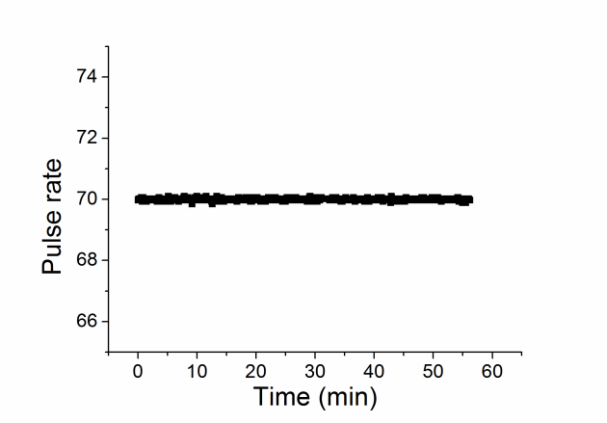
365

366 (b)



367

368 (c)



(d)

Fig. 6 SpO_2 and PR extracted using autocorrelation modeling method

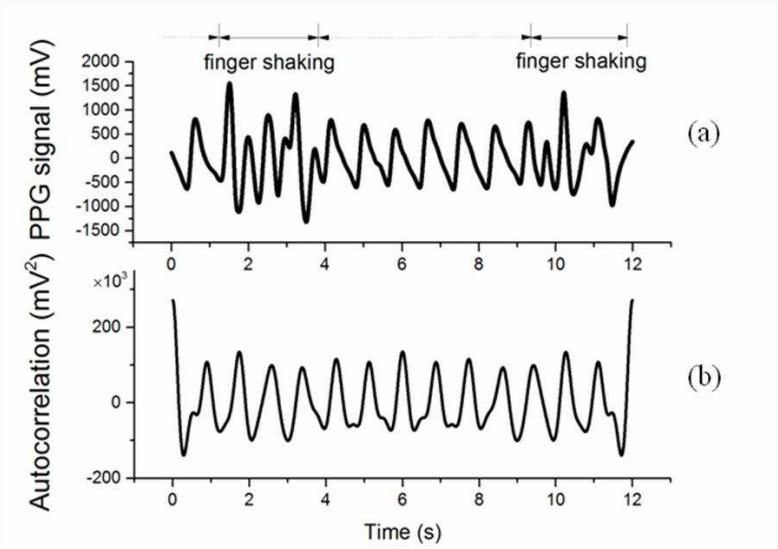
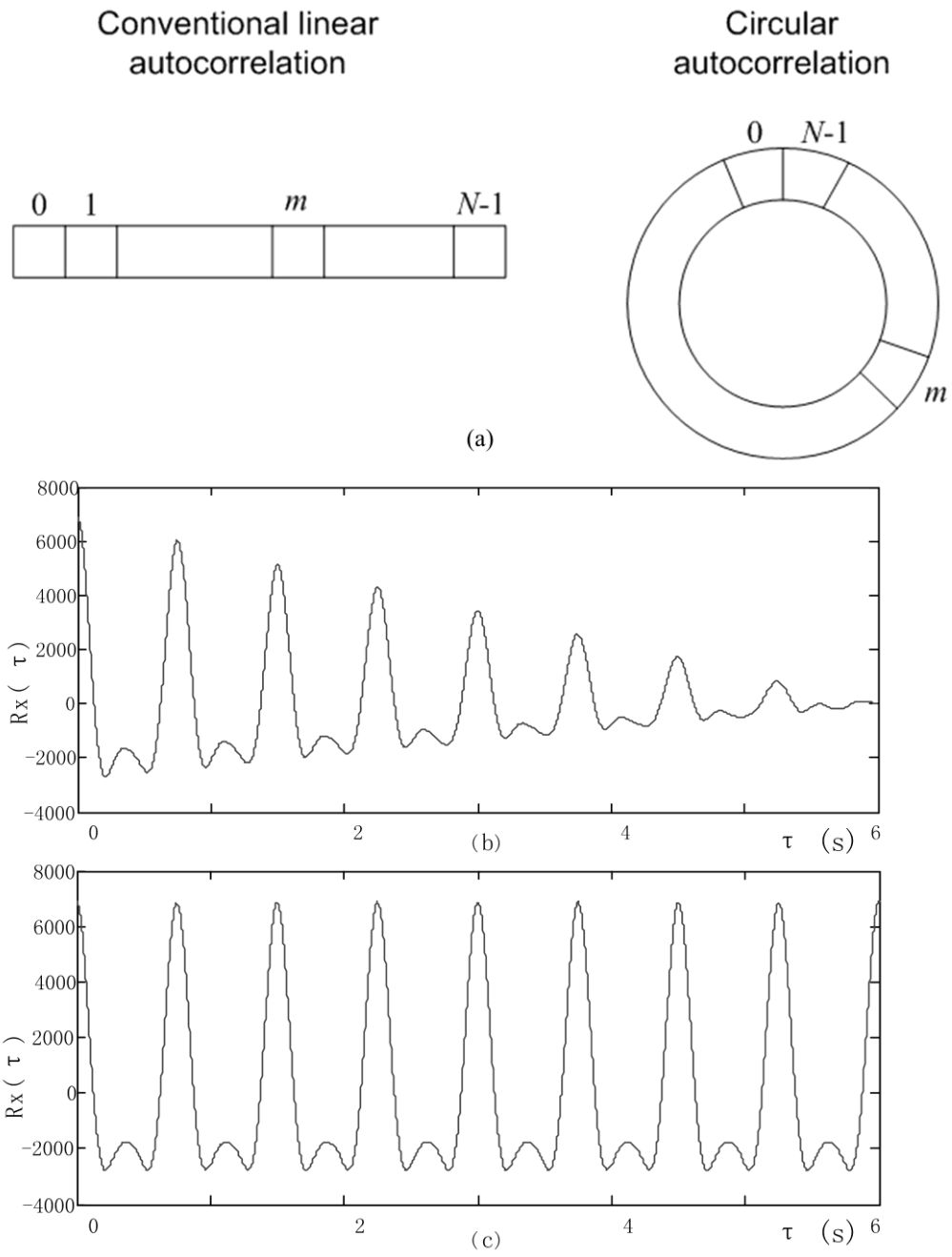


Fig. 7 Recorded PPG signal in case of body movement



Supplementary fig. 1 (a) Memory management of conventional linear autocorrelation and circular autocorrelation computation. (b) Autocorrelation function of a typical PPG signal calculated by conventional linear autocorrelation. (c) Autocorrelation function calculated by circular autocorrelation

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389 **Tables:**

390 Table 1 SpO_2 estimates under low perfusion condition

	PI=0.2%						PI=0.1%				
Preset SpO_2 (%)	64	74	84	90	94	96	76	82	86	90	94
Mean of estimates	67.2	75.8	85.4	90.8	94.3	95.7	75.2	82.3	85.6	89.7	93.7
SD of estimates	1.7	1.4	1.4	0.8	0.6	0.6	3.7	2.6	2.2	2.4	1.6

391

Figures

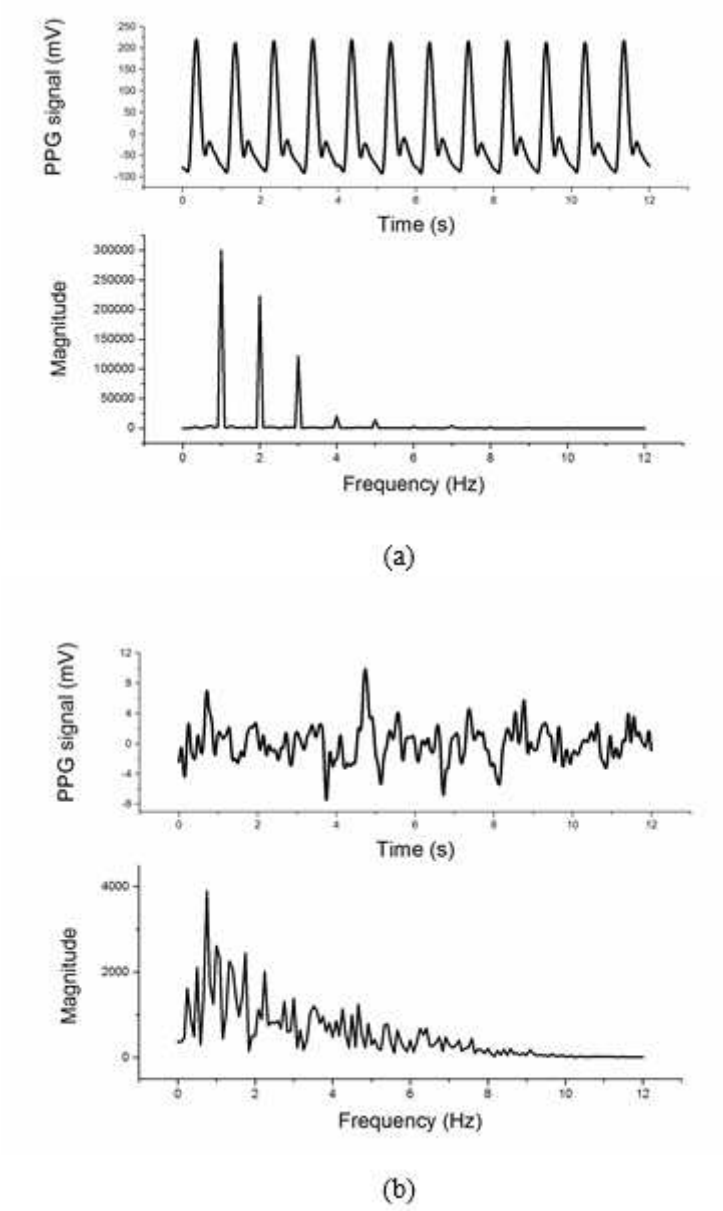


Figure 1

Simulated PPG signal and its Fourier spectra. (a) Normal case: PI=3%, SpO2=96%, PR=60 times/min. (b) Low perfusion case: PI=0.075%, SpO2=96%, PR=60 times/min

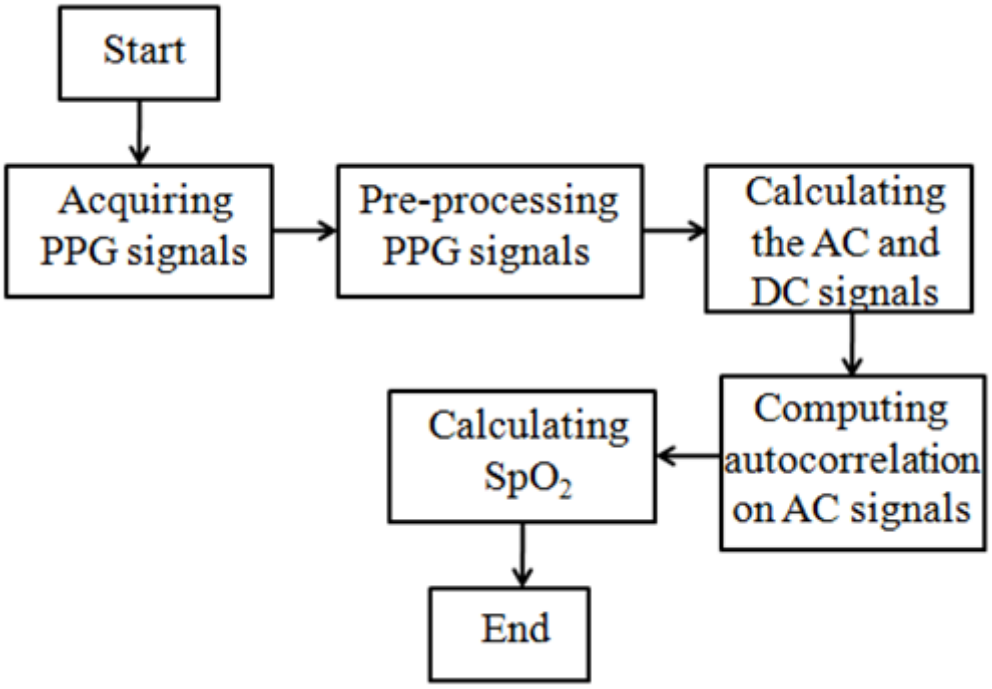


Figure 2

Overall process of autocorrelation modeling method

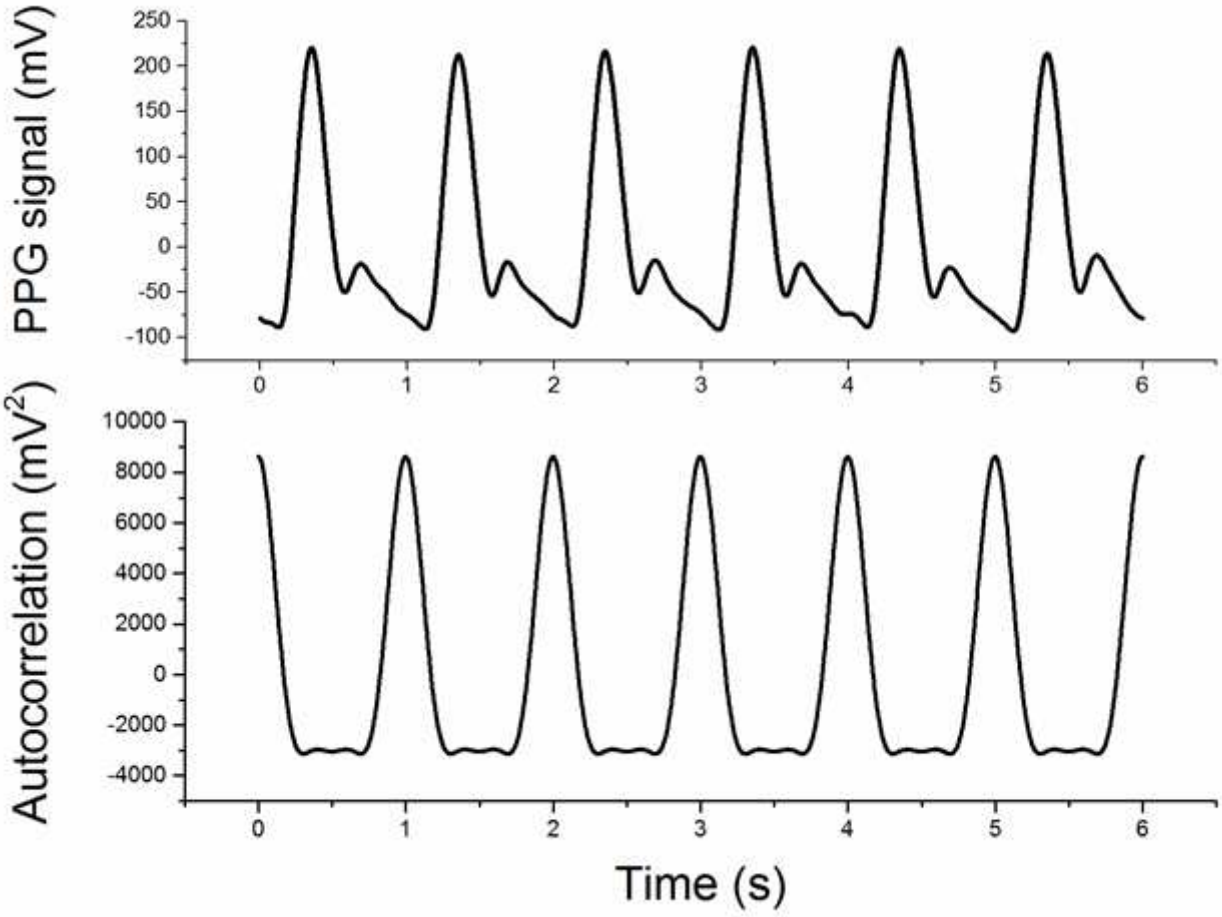


Figure 3

Autocorrelation function of a typical normal PPG signal

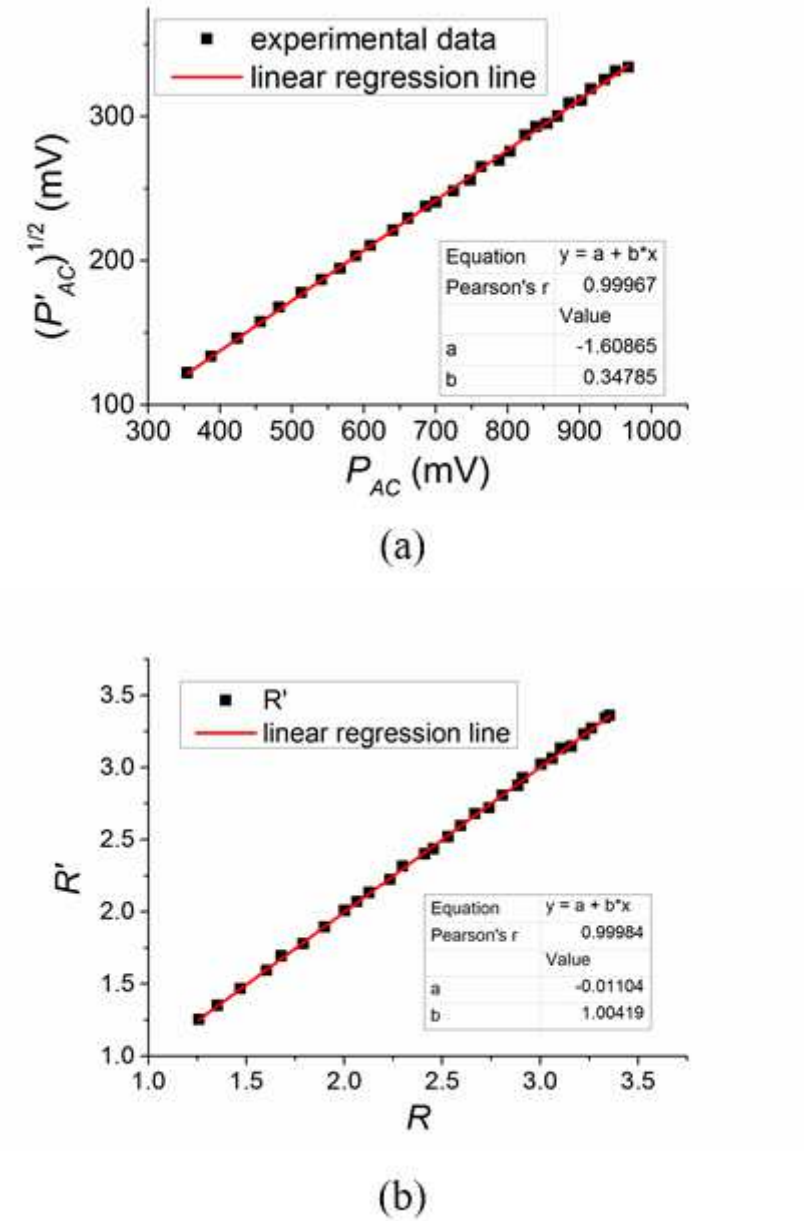


Figure 4

Linear regression of the critical intermediate parameters. (a) Linear regression of square root of the amplitude of autocorrelation function of PPG AC component on original PPG AC amplitude; (b) Linear regression of R’ on R

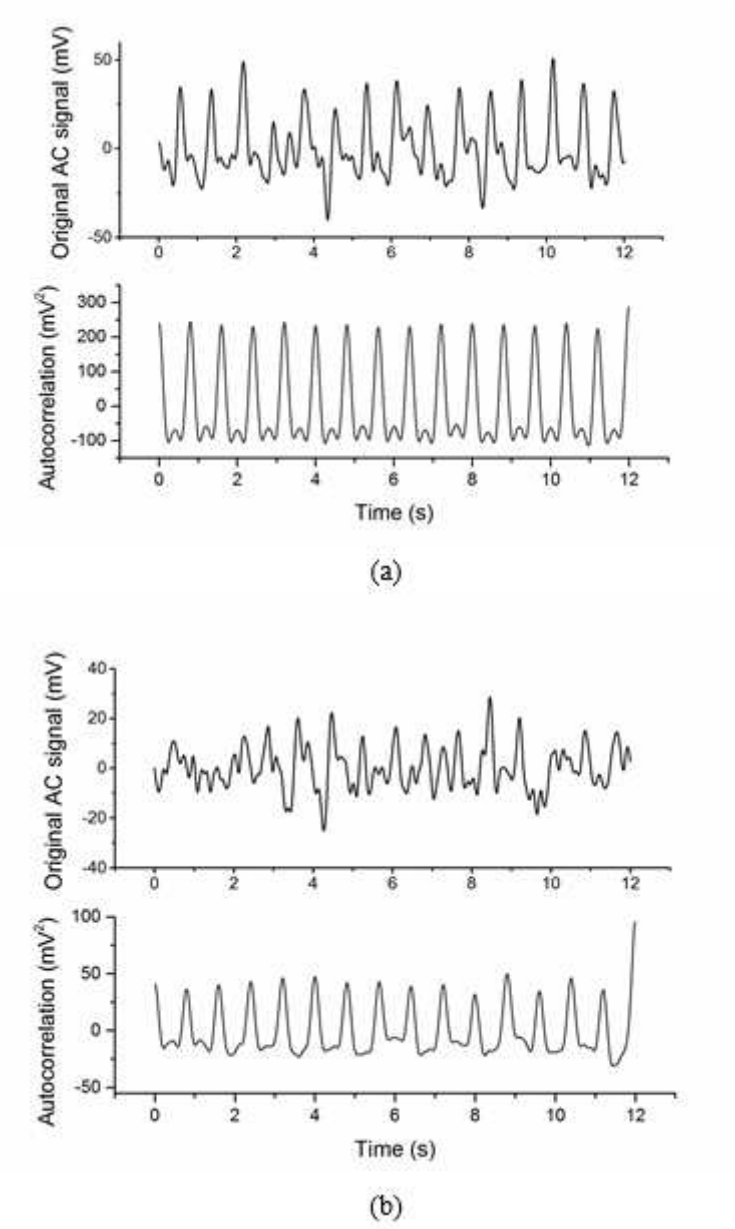
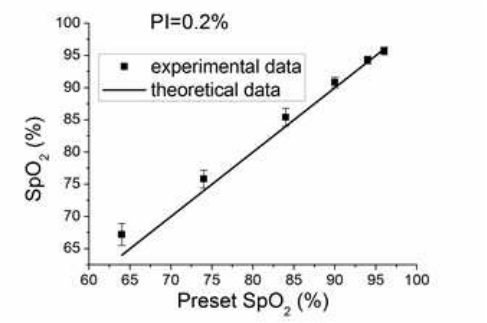
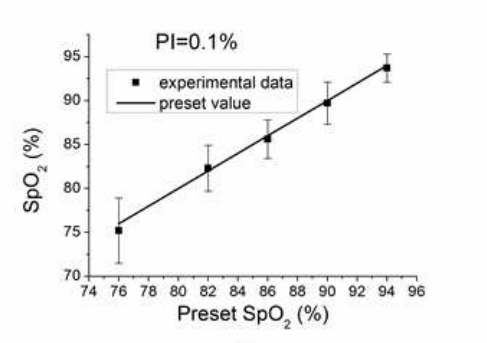


Figure 5

Simulated PPG AC signal under low perfusion condition and its autocorrelation function. (a) PI=0.2%; (b) PI=0.1%



(a)



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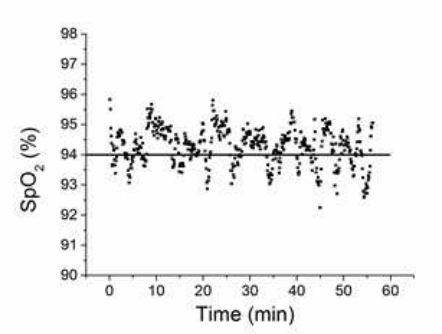
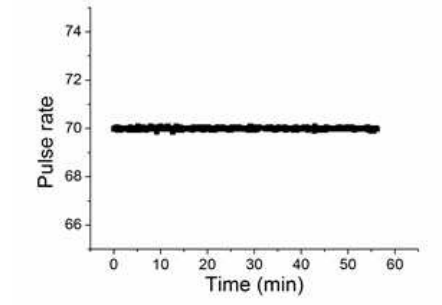


(c)



(d)

Figure 6

SpO2 and PR extracted using autocorrelation modeling method

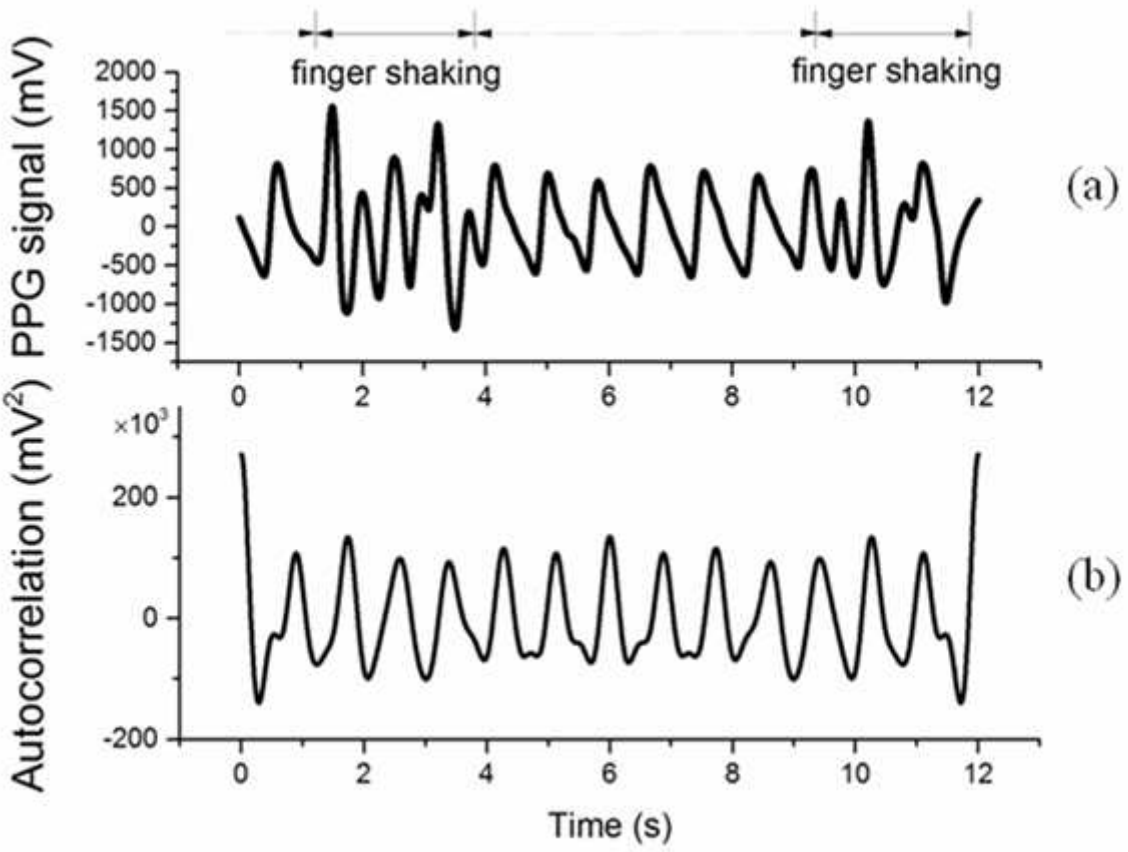


Figure 7

Recorded PPG signal in case of body movement

Supplementary Files

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- Supplementary.docx