
PPG Signal Processing with Ensemble Empirical Mode Decomposition for Small Animals
Yu-Cheng Lin1, Cyuan-Cin Liu1, An-Bang Liu1,2, Chun-Cheng Yang1 and Hsien-Tsai Wu1,*
1Dept. of Electrical Engineering, National Dong Hwa University, Hualien, Taiwan
E-mail: dsphans@email.ndhu.edu.tw Tel: +886-3-8634098
2Department of Neurology, Tzu-Chi General Hospital, Hualien, Taiwan
E-mail: liuab@mail.tcu.edu.tw

Abstract—Photoplethysmography (PPG) is a simple and useful optical technique. It is widely used to assess arterial stiffness in human. Although the PPG applying widely used, there are only few studies investigated to use PPG in small animals. It may be due to the PPG signal drift. In this study, we proposed a simple and easily operated system which is consisted of acquisition of PPG signal and the signal processing with ensemble empirical mode decomposition method, in order to solve the drift of pulse wave in small animals via our system.

I. INTRODUCTION

Photoplethysmography (PPG) was developed by Hertzman [1]. It was a non-invasively, simple and useful optical measurement technique that could be used to detect digital volume change in the microvascular bed of peripheral vessels [2]. The PPG waveform contained two components [3]; one, attributed to the pulsatile component in the vessels, i.e. the arterial pulse, was caused by the heartbeat, and gave a rapidly alternating signal (AC component). The other was due to the blood volume, respiration, vasomotor activity, vasoconstrictor waves, Traube Hering Mayer (THM) waves, thermoregulation and gives a steady signal that changes very slowly (DC component) [2].

In the previous studies, [4-8] the research workers usually used tonometry or ultrasound Doppler to assess arterial stiffness in small animals. These techniques required professionals to operate and are very expensive. In comparison, PPG was a simple and useful optical technique to measure the signals in human. Hence, we applied the PPG technique to measure the pulse wave and to assess arterial stiffness in small animals. However the PPG signal presented drift phenomenon in small animals (Fig. 1); it might be caused by other physiological signals and unknown signals. The drift phenomenon of the PPG signal might cause inaccuracy for assessing arterial stiffness in small animals. Therefore, we used a new signal process method, known as the ensemble empirical mode decomposition (EEMD) with Hilbert-Huang Transform (HHT). The EEMD could decompose a signal into finite components which were called intrinsic mode functions (IMFs) [9-11].

In this study, we followed the previous study to assess endothelial function in small animals [12] by using that we proposed an easy operation, cheap and non-invasive system which was included of self-developed instrument to capture biological signal. We used EEMD to decompose signal, and verified accuracy of our system.

Fig. 1 Drift phenomenon of pulse wave signals in rats, recorded by infrared sensors and PPG.

II. BACKGROUND OF ENSEMBLE EMPIRICAL MODE DECOMPOSITION (EEMD)

The EEMD is a noise assisted data analysis method of which the main part is the empirical mode decomposition (EMD). In general, all data are amalgamations of signal and noise, i.e.,

\[ x(t) = s(t) + n(t) \]

(1)

in which \( x(t) \) is the recorded data, and \( s(t) \) and \( n(t) \) are the true signal and noise, respectively. As given in (1), To single data set, \( x(t) \), as if separate observations were indeed being made as an analog to physical experiment that could be repeated many times. The EMD technique decomposes the data \( x(t) \) into a number of IMFs and a final residue through the sifting processing. The IMFs are meant to be monotonic function, orthogonal to each other and a set of IMF’s should be complete.

The EMD sifting process based on the following observations:
1. Identify the extreme (local maxima and minima) of the whole time-series \( x(t) \).
2. Generate the upper and lower envelopes using cubic spline method to connect the maxima and minima respectively. The upper-envelope \( u(t) \) and lower-envelope \( v(t) \) of the signals \( x(t) \).
3. Calculate the mean of the upper and lower envelopes, and generate the mean envelope, \( m(t) \).

\[m(t) = \frac{u(t) + v(t)}{2}\]  
\[(2)\]

4. Find IMF candidate, \(h(t)\), through the following equation:
\[h(t) = x(t) - m(t)\]  
\[(3)\]

5. Check if \(h(t)\) is an IMF using the conditions defining\((1)\). If \(h(t)\) is not an IMF, repeat the process steps 1-5. (2). If \(h(t)\) is an IMF, then calculate the stopped or the residue, \(r(t)\), becomes a monotonic function from which no more IMFs can be extracted, the sifting process end. It was designate as \(B_i(t) = h(t)\), IMF; denotes the first IMF of \(x(t)\).

6. Get the residue signal \(r(t)\) using the following equation:
\[r(t) = x(t) - B_J(t)\]  
\[(4)\]

7. Treat \(r(t)\) as a new time-series signal \(x(t)\) is decomposed into a finite IMFs: \((B_1(t), B_2(t), \ldots, B_J(t))\) and a residue \(r(t)\) as following
\[x(t) = \sum_{j=1}^{n} B_j(t) + r(t)\]  
\[(5)\]

, where \(n\) is the number of IMFs of \(x(t)\).

The EEMD is a noise assisted data analysis method consists of an ensemble of data decompositions with added white noise and then treats the resultant mean as the final true result. The principle of EEMD is to add adequate of white noise \(w_m(t)\) to original signal \(x(t)\), let can clearly separate the scale of data and eliminates mode mixing \([13]\) on frequency problem. As shown in \([9-11]\). Given a signal \(x_m(t)\) the procedure begins by giving an ensemble members \(N\) and an added noise amplitude \(\sigma\).

The EEMD sifting process as follows:
1. Add a different white noise series \(\sigma w_m(t)\) to \(x(t)\), the \(m^{th}\) “artificial” observation will be
\[x_m(t) = x(t) + \sigma w_m(t)\]  
\[(6)\]

2. Decompose \(x_m(t)\) into a number of IMFs with EMD sifting process
3. Obtain the ensemble means of corresponding IMFs of the decompositions as the final result.

A signal \(x_m(t)\) can be decomposed into a sum of ensemble mean IMFs and residues as the following form:
\[x_m(t) = \lim_{N \to \infty} \frac{1}{N} \sum_{m=1}^{n} \left\{ c_{j,m}(t) + \alpha r_m(t) \right\}\]  
\[(7)\]

in which
\[c_{j,m}(t) + \alpha r_m(t)\]  
\[(8)\]

is the \(j^{th}\) realization of the \(m^{th}\) IMF in the noise-added signal.

In this study, \(\sigma\) was set to 0.2 and \(N\) was set to 200.

III. MATERIAL AND METHODS

A. Acquisition of Photoplethysmography (PPG) signal and count of vasodilatation index (DI)

The rat’s pulse wave signal was measured by photoplethysmography. This detection device consists of two infrared sensors emitting a wavelength of 940 nm wavelength. The sensors was placed on rat’s footpads, signals were detected by infrared sensors were transmitted analogy processing to amplify and filter. The analog signal converted into digital signal by a USB-6009 DAQ (National Instruments, Austin, TX, USA) with 200 Hz sample rate. Finally these digital signals are sent to a personal computer for storage and analysis. Vasodilatation index (DI) represented the degree of endothelial function; it was calculated as following the previous study. The DI index can be expressed as
\[DI = \frac{Amp_{RH}}{Amp_{Baseline}}\]  
\[(9)\]

, where \(Amp_{RH}\) is the maximal amplitude of the PPG signals after cuff deflation, \(Amp_{Baseline}\) is the amplitude of the PPG signals before cuff inflation. In this study, we used two indices to represent the DI which was calculated by different methods. One was \(DI_1\) represented that DI was calculated by the raw data without any procedure. The other one was the DI was calculated by the raw data were dealt with EEMD, defined as \(DI_2\).

B. Animals

All the animal procedures were approved by the Institutional Animal Care and Use Committee of the Tzu Chi General Hospital. Seven Male WKY rats (6-9 weeks old, weighted from 250g to 330g) were purchased from the National Laboratory Animal Breeding and Research Center, Taipei, Taiwan.

C. Experimental procedures

First, these animals were anesthetized with intraperitoneal injection of pentobarbital (50 mg/kg), and they would be fixed in the supine position before measuring the PPG signals. The infrared sensors were taped on the footpads. Before a vaso-clip was placed at the proximal part of the left common femoral artery, we measured and recorded the rats’ PPG signals as the baseline signals for two minutes. After measuring the baseline signals, we would cutoff the blood flow of rats’ left common femoral artery by a vaso-clip for 5 minutes. After 5 minutes, the vaso-clip would be removed. We measured and recorded the rats’ PPG signal for two minutes. Whole experimental processes would be implemented twice in one week for every rat.

D. Statistical analysis

All the results were represented as mean ± standard deviation. Associations among \(DI_1\) and \(DI_2\) were evaluated by the Pearson correlation test. The present of the coefficient of variation (CV\%) was used to calculate reproducibility of DIs. The statistical analysis was performed with SPSS 14.0 package software. The statistical significance was accepted at \(P < 0.05\).

IV. Results

The all recorded pulse wave are shown in Fig. 2. There was a drift phenomenon in either baseline period or hyperemic period.
There is a drift phenomenon in either baseline period or hyperemic period, which may contribute to the uncertainty of our measurement.

In order to solve the drift problem, the recorded pulse wave signals were decomposed by EEMD. There were several IMFs after decomposition of the original pulse signals (Fig. 3). The third IMF was proposed to be a pulse signal.

In comparison, the pulse wave (IMF3) dealt with EEMD was more stable than that without EEMD processing (Fig. 4).

We used a well established model, reactive hyperemic vasodilatation to evaluate the advantage of application of EEMD in managing pulse signals of small animals. It was proposed that removal of drift phenomenon in the pulse signals can improve the accuracy and reproducibility of the measurement. We took the pulse wave signals before occlusion of the artery as baseline data, and the maximal signals after releasing of the vaso-clip as RH data. The DI was defined as the ratio of RH data to baseline data. DI_N was the DI calculated by original pulse amplitudes. DI_E was the DI assessed by the decomposed pulse signals. We used correlation between the first and second measurements to estimate reproducibility of these two DIs. From Table I, we found that the reproducibility of DI_E was better than that of DI_N (r=0.897 vs. r=0.582; CV=0.283% vs. 0.351%). Therefore, EEMD indeed removes drift phenomenon and improves the accuracy of measurement in small animals.

Table 1

<table>
<thead>
<tr>
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<th>DI_N</th>
<th>DI_E</th>
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<tbody>
<tr>
<td>Measurement1</td>
<td>1.68±0.42</td>
<td>1.66±0.42</td>
</tr>
<tr>
<td>Measurement2</td>
<td>1.93±0.98</td>
<td>1.76±0.58</td>
</tr>
<tr>
<td>Correlation</td>
<td>r=0.582</td>
<td>r=0.897</td>
</tr>
<tr>
<td>CV</td>
<td>0.351%</td>
<td>0.283%</td>
</tr>
</tbody>
</table>

Although PPG has wildly been used to assess physiological signals inhuman beings, it is rarely to be applied on small animals due to drifting of pulse signals. This phenomenon causes uncertainty of measurement in small animals. In this study, we used EEMD to decompose the original pulse signals from WKY rats, and then we could get steady signals at IMF3 after decomposition. We also found low-frequency signals, at IMF4, which may contribute drifting of the original signals; and other unknown signals at IMF 5, IMF 6 and IMF 7. The last three low-frequency signals may consist of unknown physiological significance.
In conclusion, PPG is a simple and cheap method to detect physical signals including digital flow volume in human. Because of the unreliability, PPG has never been used in small animals. We found that to remove signal which caused pulse wave drift can improve accuracy by measuring DIs in rats. Hyperemic vasodilatation, a well-established model, is addressed in this study to assess the reproducibility. Our platform can offer a useful and reliable tool to assess the changes of atherosclerosis in small animals in the near future.

ACKNOWLEDGEMENT

We acknowledge the expert technical assistance of Miss Szu-Hsuan Chen. This work was supported by grant from the National Science Council, Taiwan (NSC98-2221-E-259-017) and by a part of an intramural research grant of the Buddhist Tzu Chi General Hospital (TCRD 97-26).

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