Predicting Arterial Stiffness with the aid of Ensemble Empirical Mode Decomposition (EEMD) Algorithm

Hsien-Tsai Wu, Chun-Ho Lee, Chun-Erh Chen, and An-Bang Liu
Dept. of Electrical Engineering
National Dong Hwa University
Hualien, Taiwan
e-mail: dsphans@mail.ndhu.edu.tw

An-Bang Liu
Department of Neurology
Tzu-Chi General Hospital
Hualien, Taiwan
e-mail: liuab@mail.tcu.edu.tw

Abstract—In this study, we propose an easy-to-use non-invasive arterial stiffness assessment instrument that can be used to record the radial arterial pressure signals from the wrist. The system combines the ensemble empirical mode decomposition (EEMD) algorithm with the signals to derive a modified reflection index (MRI). The performance of MRI was verified based on 42 subjects (33 men and 9 women, 20 to 27 years of age). Early self-monitoring of cardiovascular dysfunction and arterial stiffness can be easily and effectively achieved by MRI because only few minutes are needed for conducting at home.

Keywords—Ensemble empirical mode decomposition; Reflection index; Arterial stiffness

I. INTRODUCTION

Increased atherosclerosis may increase cardiovascular morbidity and mortality, including hypertension, diabetes mellitus, and end-stage renal failure [1]. A digital volume pulse (DVP) can be obtained by using photoplethysmography (PPG). Recently, application of PPG has been extended to assess of arterial function including arterial stiffness and endothelial function [2-3]. The DVP exhibits a characteristic notch or inflection point (dicrotic wave) that can be expressed as percent maximal DVP amplitude, defined as reflection index (RI) [4-5]. RI is the ratio which is the amplitude of second peak was divided by amplitude of first peak.

In our recent study [6], for the radial arterial pressure signals from the air pressure system are almost identical stable, the finger micro-vascular signals from the PPG system are unstable. Air pressure sensing system and its computerized automatic procedure provide good reproducibility for measuring endothelial function. However, the dicrotic wave is not obvious in healthy subjects, shown in Fig.1.

The problem about dicrotic wave is not obvious may be solved by the ensemble empirical mode decomposition (EEMD) with Hilbert-Huang Transformation [7-8]. In this paper, EEMD algorithm was useful to develop a new arterial stiffness index defined as modified reflection index (MRI) for arterial stiffness assessment.

II. BACKGROUND OF THE EEMD ALGORITHM & SYSTEM IMPLEMENTATION

We propose a modified reflection index (MRI) with the aid of EEMD algorithm for arterial stiffness assessment.

A. Ensemble Empirical Mode Decomposition (EEMD)

In general, all data are amalgamations of signal and noise, i.e.,

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

in which \( x(t) \) is the recorded data, and \( s(t) \) and \( n(t) \) are the true signal and white noise, respectively. As given in Eq. (1), to improve the accuracy of measurements, the ensemble mean is a powerful approach, where data are collected by separate observations, each of which contains white noise. To generalize this ensemble idea, white noise is introduced to the single data set, \( x(t) \), as if separate observations were indeed being made as an analog to a physical experiment that could be repeated many times. The added white noise is treated as the possible random noise that would be encountered in the measurement process [7-8].

\[ x_j(t) = x(t) - w_j(t) \]  

The EEMD method can expand the data \( x_j(t) \) into intrinsic mode functions (IMFs), and a final residue through the sifting process. The sifting process used to estimate IMFs is listed in the following:

1. Identify the extreme (local maxima and minima) of the whole time-series \( x_j(t) \).
2. Generate the upper and lower envelopes using cubic spline method to connect the maxima and minima respectively.
3. Calculate the mean of the upper and lower envelopes, and generate the mean envelope, \( m(t) \).
4. Find an IMF candidate, \( h(t) \), through the following equation:

\[ h(t) = x_j(t) - m(t) \]  

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, designate as \( c_j(t) = h(t) \).

\( c_j \) denotes the first IMF of \( x_j(t) \)

IMF \( h(t) \) is subtracted from the input signal, and the residue
is used as the new input signal to the sifting process. This procedure is repeated until the stop criterion is met; that is, when the number of zero crossings and the number of extrema are not the same for S successive sifting steps.

6. Get the residue signal \( r(t) \) using the following equation

\[
r(t) = x_j(t) - c_k(t)
\]

where \( k = 1, 2, ..., n \).

The decomposed components \( c_k(t) \) contain the nonlinear oscillation components of the original radial arterial pressure signal.

7. Treat \( r(t) \) as a new time-series signal \( x_i(t) \), and repeat the procedure from step 1 to step 6 to get more other IMFs. Until \( r(t) \) becomes a monotonic function.

Eventually, the original signal \( x(t) \) is decomposed into a finite IMFs: \( \{c_1(t), c_2(t), ..., c_n(t)\} \) and a residue \( r(t) \) as following:

\[
x(t) = \sum_{k=1}^{n} c_k(t) + r(t)
\]

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

The EEMD 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 white noise, which populates the whole time-frequency space uniformly with the constituent components of different scales separated by a filter bank. The EEMD process is explained as follows:

1. Add white noise to the target data.
2. Decompose data containing added white noise into IMFs.
3. Repeat steps 1 and 2 with different white noise series.
4. Obtain the ensemble means of corresponding IMFs of the decompositions as the final result.

The result of EEMD is obtained when the number in the ensemble approaches infinity:

\[
c_k(t) = \lim_{N \to \infty} \frac{1}{N} \sum_{j=1}^{n} \left\{ c_{k,j}(t) + \alpha r_j(t) \right\}
\]

in which

\[
c_{k,j}(t) + \alpha r_j(t)
\]

is the \( j \)th realization of the \( k \)th IMF in the noise-added signal, \( \alpha \) is the standard deviation of the added noise, and \( r_j(t) \) is the residual after extracting the first \( k \) IMF components. The number of the trials in the ensemble, \( N \), has to be large. In this study, \( \alpha \) was set to 0.2 and \( N \) was set to 200.

B. Air Pressure Sensing System

A prototyped endothelial function measurement module board has been constructed using analog electronics for obtaining, amplifying and filtering the captured arterial pressure signal [6]. Generally, the arterial pressure signal is a variation of the pressure in the artery, the flow of blood pulsates with this variation occurring in the human body, and it is measurable at the wrist surface. The analog signal processing unit will be used to convert the pulse wave into DC and filters out the noises then amplifies it, with the purified analog signal converted into digital data by the mixed signal processing unit (MSP430F449) with a sampling rate of 500 Hz. The system entity is illustrated in Fig.2.

\[
\sum_{j=1}^{n} \left\{ c_{k,j}(t) + \alpha r_j(t) \right\}
\]

in which

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and IMF7-8 is main frequency of heart beat. The IMF9 is main frequency of respiratory. The last one mode of IMFs can be expressed as low frequency DC signals.

The reconstructed signal of pulse wave data was shown in Fig.5. The pulse wave, the dicrotic wave is obvious rendering. Clearly, radial arterial pressure pulse is consisted of systolic wave and diastolic wave. The first peak is systolic wave and the second peak is diastolic wave. According to the traditional RI definition for PPG, the reconstruction radial arterial pressure pulse by air pressure sensing system of light through the wrist, called modified reflection index (MRI) is given by:

\[
MRI = \frac{H_1}{H_2} \times 100\%
\]

The reconstructed signal of pulse wave data was shown in Fig.5. The pulse wave, the dicrotic wave is obvious rendering. Clearly, radial arterial pressure pulse is consisted of systolic wave and diastolic wave. The first peak is systolic wave and the second peak is diastolic wave.

Then the recorded data will be saved and analyzed by statistical methods such as coefficient of variation, correlation and standard deviation (via SPSS 14.0 and EXCEL 2003). Data were expressed as mean±SD. A p value < 0.05 is regarded as statistically significant. The study was approved by National Dong Hwa University Institutional Review Board (IRB), and all subjects gave written informed consent.

III. TESTING RESULTS

A. MRI with the aid of EEMD algorithm

The IMFs mode of 4th-6th were choosed to reconstruct the new radial arterial pressure signals, with corresponding to the original signal measured at wrist, as shown in Fig.4. The reconstructed signal \( x'(t) \) can be extracted as shown in Eq.(8).

\[
x'(t) = IMF4 + IMF5 + IMF6
\]

The reconstructed signal of pulse wave data was shown in Fig.5. The pulse wave, the dicrotic wave is obvious rendering. Clearly, radial arterial pressure pulse is consisted of systolic wave and diastolic wave. The first peak is systolic wave and the second peak is diastolic wave.

B. Reproducibility Analysis for MRI

To test the reproducibility of our new method, MRI was measured three times, each one day apart, in non-cardiovascular disease volunteers, 6 males and 5 females. Table 1 shows the information of the testing subjects in the study. Before any testing, all subjects rested in a supine position for 10 min in a quiet, temperature-controlled (25°C) room. Every subject will participate in the experiment for 3 days, only one measurement is performed per day, and no other constraint is required. Fig.6 is the MRI data plot after normalization of the air pressuring sensing system. For the correlation analysis, \( R=0.939 \) (P<0.01) in the first two trails, \( R=0.838 \) (P<0.01) in the second and third trials. Inaddition, \( R \) is equal to \( 0.892 \) (P<0.01) for the first and third trials. The graph shows that all 3 trials data are close to each other, which represents data that does not differ from each other. The coefficient of variation was only 5.29±2.59 (%).

TABLE 1. Characteristics of the Study Population for Comparison

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reproducibility Study</th>
<th>Correlation Study</th>
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</thead>
<tbody>
<tr>
<td>Gender, M/F</td>
<td>6/5</td>
<td>27/4</td>
</tr>
<tr>
<td>Age, year</td>
<td>24.26±2.59</td>
<td>24.26±2.59</td>
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<tr>
<td>Height, cm</td>
<td>170.63±6.16</td>
<td>171.29±6.92</td>
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<tr>
<td>Weight, kg</td>
<td>67.63±14.89</td>
<td>68.45±13.61</td>
</tr>
<tr>
<td>BMI, Kg/m2</td>
<td>22.94±4.34</td>
<td>21.84±4.34</td>
</tr>
<tr>
<td>SBP, mmHg</td>
<td>120.63±13.29</td>
<td>121.00±11.95</td>
</tr>
<tr>
<td>DBP, mmHg</td>
<td>72.09±8.32</td>
<td>72.87±8.88</td>
</tr>
<tr>
<td>HR, bpm</td>
<td>72.3±11.00</td>
<td>75.13±13.00</td>
</tr>
</tbody>
</table>

Value are expressed as mean ± SD. BMI=body mass index; SBP=systolic blood pressure; DBP=diastolic blood pressure; HR=Heart rate.
EEMD [7-8] algorithm was conducted for solving the modified for the air pressure sensing system. Hence, the system. The graph shows that all 3 trials data are close to each other, which represents data that does not differ from each other.

C. Correlation Between RI and MRI

In the correlation study, 31 non-cardiovascular disease volunteers, 27 males and 4 females, were included. Table 1 shows the information of the testing subjects in the study. Before any testing, all subjects rested in a supine position for 10 min in a quiet, temperature-controlled room. The RI was measured at fingers by the dual-channel PPG system [3]. The MRI not normalization was measured at wrist by the air pressure sensing system [6]. The MRI was high significantly correlated with RI ( r = 0.710, P<0.001), as shown in Fig.7.

IV. DISCUSSION AND CONCLUSIONS

The photoplethysmography technique deserves further consideration because of its simplicity and ease of use. In generally, that was a really good idea to define the RI using DVP signal measured at finger. In the recent study [6], changed the measuring site to wrist radial arteries instead of that were measured in previous PPG studies. However, the dicrotic wave was always not obvious in healthy subjects for the wrist radial arterial signals. In that way, RI need to be modified for the air pressure sensing system. Hence, the EEMD [7-8] algorithm was conducted for solving the problem of dicrotic wave missing.

In short, a pressure cuff was placed on subject’s wrist and a stable pressure keeping. The air pressure sensing device extracted the radial pulse signals. During examination, the pulse signal was small and distorted, which included skin noise effect from the cuff and noise from the external power supply. The analog signal processing unit was used to convert the pulse wave into DC and filtered out the noises. The analog signals converted into digital data by the mixed signal processing unit (MSP430F449) with a sampling rate of 500Hz. Then the digital data is transmitted to the PC’s analyzing software via UART (RS-232).

The digital signals were stored in a high-capacity memory unit to form a pulse signal. The proposed EEMD algorithm was used to reconstruct signals by using the sum of IMF4, IMF5 and IMF6. The reconstructed signals were used to derive a modified reflection index (MRI). MRI method with the high reproducibility was developed for arterial stiffness assessment. The coefficient of variation was 5.29±2.59 (%). This study also showed that MRI measured with air-pressure sensing system correlated very well with RI calculated from DVP. ( R=0.710, P<0.001).

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