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# The Research of Photoplethysmography Morphology: Distincting Preeclampsia with Hierarchical Area Ratio

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***Abstract*—The variations of photoplethysmography (PPG) morphology for the pregnancies with preeclampsia (PE) were studied in this paper. PPG data from 16 hypertensive pregnancies with PE and 26 normotensive pregnancies were acquired by the standard medical monitor. A novel hierarchical area ratio (HAR) parameter was invented to segment and quantitate the descending domain of a pulse based on the data acquired. The algorithm and features of HAR are fully explained and discussed in the paper. A rough PE distinction based on the statistics of HAR calculated from the original PPG signals was conducted with the precision of 72.7%, sensitivity of 100%, specificity of 76.9% and accuracy of 85.7%. The HAR we proposed in the paper showed favorable prospects in the quick distinction of PE.**

***Keywords-Preeclampsia,Photoplethysmography, Morphology, Feature Extraction, Hierarchical Area Ratio***

## I. INTRODUCTION

Preeclampsia (PE) is a pregnancy disorder characterized by the onset of high blood pressure and often a significant amount of protein in the urine, which often commences after 20 weeks of pregnancy. PE leads to certain changes in the hemodynamics: there is an increase in peripheral vascular resistance and stiffness, and a decrease in small artery compliance, systemic blood flow and cardiac output [1-3].Meanwhile PE can cause an increase in mean arterial pressure, systolic blood pressure and diastolic blood pressure [4-6]. It could raise an immense influence if PE could be distinguished and diagnosed earlier.

In clinical PE diagnosis, the indexes of blood pressure and albuminuria are widely used as the criterion. As albuminuria is inconvenient for real time analysis, it has been an imperious demand to evaluate the condition of the pregnancies swiftly, accurately and noninvasively.

Efforts have been made to solve the issue. Recently, researchers have found the augmentation index, pulse wave velocity and pulse pressure amplification of PE sufferers differ from the normal significantly [7-9]. These studies were carried out using the pulse wave acquired through pressure sensors, and the signals are restricted by acquisition position of the body and sensor types. Thus photoplethysmography (PPG) which is noninvasive to measure the pulse wave has drew more attentions of the researchers. Since the findings published in 2008 that the arterial stiffness of PE sufferers is higher using PPG, it's been suggested that other parameters have similar distinction in PE including reflection index, systolic blood pressure and diastolic blood pressure, pulse wave transit time and heart rate variability in subsequent researches [10-11]. In another aspect, some researchers have already explored the PPG morphology to make use of the vascular information contained in the noninvasive blood pressure estimation and the effects of aging on arterial compliance [12-13].

Thus in this paper the morphology of PPG was the focus and a novel parameter, hierarchical area ratio (HAR), was proposed to help quantitate and evaluate the vascular condition of pregnancies. The strategy and algorithm of HAR calculation was introduced in the paper, the basic characteristic of HAR was discussed as well. A rough distinction with promising result was carried out using HAR which showed favorable prospects in the distinction of PE.

## II. TYPICAL PHOTOPLETHYSMOGRAPHY FEATURES

As the PPG signals are generated by the periodic heart ejection, the process of blood flowing in vessels is also affected by the blood viscosity and vascular resistance. Abundant cardiovascular information could be obtained from PPG [14]. The typical waveform of PPG is shown in Fig.1.

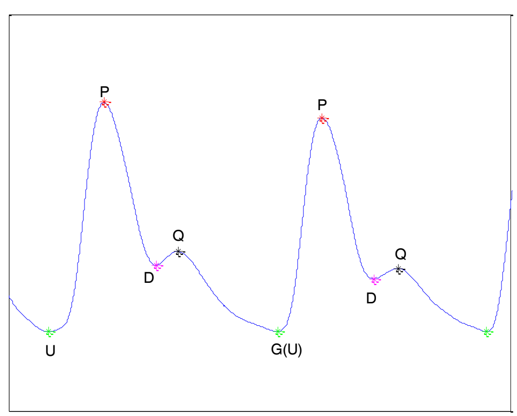


Figure 1. The typical PPG feature points

Generally the through point U/G is considered as the start/end point of current/last pulse. The point P with max amplitude is the peak of a pulse and the other crest point Q is recognized as the dicrotic wave. Point D, which maps the lowest value in the domain form P to Q, is the dicrotic notch. The domain from the U and P stands for the rapid ejection phase, domain form P to D for the late phase. Point Q conduce to comprehend the compliance of the arteriola. Traditional features are extracted on the basis of the specific points above. The heart rate could be calculated form every two peak points. The ratio of the peak value and the mean value of domain P to G has been found to be a promising index in the monitoring of certain tracheal intubation surgeries [15].

## III. METHODS

### A. Data Acquisition

The PPG data used in the paper were collected from 16 hypertensive pregnancies with PE and 26 normotensive pregnancies as a comparison in the Women's Hospital School of Medicine Zhejiang University. The CARESCAPE B650 Patient Monitor produced by the General Electric Company was used to record the PPG signals with the sample rate at 100 Hz. The acquisition methods were performed in accordance with the relevant guidelines. The PPG signals were processed by the device in arbitrary unit and exported to PC as files in comma-separated values format for further algorithm researches.

### B. Signal Preprocessing

Some basic preparations were conducted before the HAR were computed. The diagram of the signal preprocessing module is shown in Fig. 2.

The band-pass filter was generally obligatory to eliminate the noises mixed in PPG signals. Nevertheless this step was simplified with the moving average filter considering the quality of the signals acquired. Moving average filter was efficient for removing the singular value from the signal with sharp noise to make the PPG data smoother. $x_n$ represented the original signal while $y_n$ represented the filtered results. The span of the moving average filter was set 5 in the analysis, as described in

$$y_n = \frac{x_{n-5} + x_{n-4} + x_{n-3} + x_{n-2} + x_{n-1}}{5} \qquad (1)$$

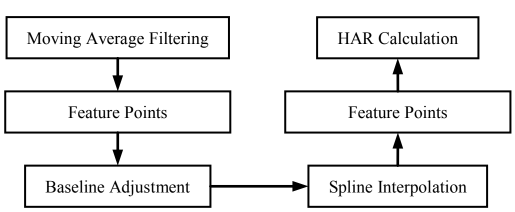


Figure 2. Diagram of the signal preprocessing

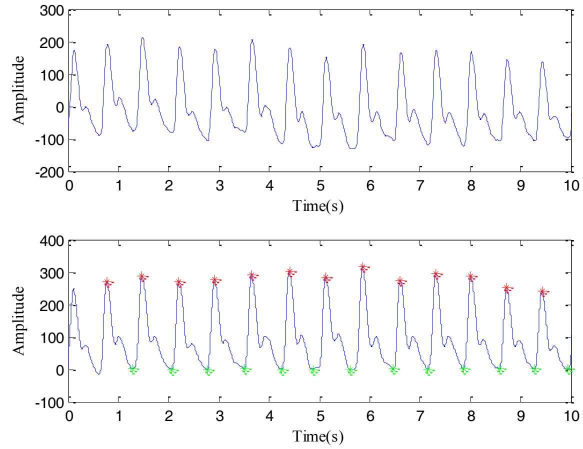


Figure 3. The contrast of original signal and processing signal

Then the feature points were extracted by dint of the differential method. The peak point was detected using the nearest zero points in the first derivation of the filtered data, and other feature points were obtained after the location of the peak point.

The procedures above were enough for the common analysis, yet inadequate for the HAR calculation. Three further procedures were conducted. As the HAR was calculated on the basis of every single pulse, the baseline of the pulse was adjusted to make the start point and end point the same amplitude. A linear transform was conducted to make arbitrary amplitude zero to the effect that the follow-up calculations could be facilitated.

Owing to the original sample rate of the original PPG data was 100 Hz which was insufficient for HAR calculation. The interpolation was used to make up this deficiency. The cubic spline interpolation method was applied in the light of that it could ensure the data after interpolation had the continuous first and second derivation. 19 new values were interpolated between every two values after the baseline adjustment.

As the cubic spline interpolation exported substantial values, the accuracy of the former feature points might be influenced. An auxiliary adjustment of the feature points was executed to reduce the deviation caused by the interpolation. The neighborhood of the old feature points were traversed to relocate the exact feature points.

The original PPG data and final results of the preprocessing were contrasted in Fig. 3. The peak point and through point were also marked for each pulse.

### C. HAR Calculation

The strategy of HAR was segmenting and quantitating the descending domain of PPG to obtain more information about vessel elasticity and blood viscosity as shown in Fig. 4.

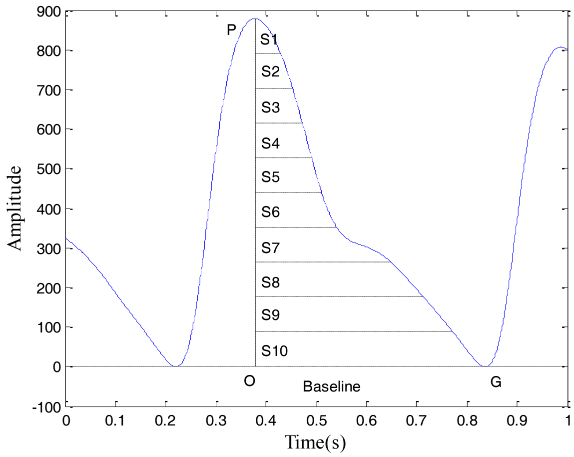


Figure 4. The schematic of HAR in a pulse

Despite the peak point and the end point, the special point mapping the abscissa of the peak point in the baseline was also detected. The line $\overline{OP}$ was drawn and divided equally into *N* pieces. *N* was named stage of HAR and set ten in the rest of our research in this paper. Thus nine points more on $\overline{OP}$ were marked and horizontal auxiliary lines were drawn through the 11 points segmenting descending domain of PPG into ten pieces. The areas between every two adjacent auxiliary lines piece were calculated and named from $S_1$ to $S_{10}$ vertical downward. The area of descending domain $S_{\frown OPU}$ was also calculated. The hierarchical area ratio (HAR) was proposed to describe how the area of pieces scattered, defined as

$$HAR_i = \frac{S_i}{S_{\frown OPU}} (1 \le i \le 10) \tag{2}$$

Equation (2) quantitated the morphologic descending process of the PPG curve, however ten dimensional vector

TABLE I. THE HARS FOR THE PULSE IN FIG. 4 WERE CALCULATED AND LISTED IN TABLE 1. DISTRIBUTION OF HAR VALUES

| Piece of PPG Curve | HAR Value |
|---|---|
| $S_1$ | 0.0178 |
| $S_2$ | 0.0342 |
| $S_3$ | 0.0457 |
| $S_4$ | 0.0558 |
| $S_5$ | 0.0659 |
| $S_6$ | 0.0786 |
| $S_7$ | 0.1149 |
| $S_8$ | 0.1638 |
| $S_9$ | 0.1965 |
| $S_{10}$ | 0.2267 |

might be nonintuitive and redundant for analysis. Thus the dimensionality reduction processing was conducted and a simplified comparatively hierarchical area ratio (CHAR) was concluded, defined as

$$CHAR_{ij} = \frac{\sum_{k=11-i}^{10} HAR_k}{\sum_{k=1}^{j} HAR_k} (1 \le i, j \le 10) \tag{3}$$

The subscript i and j were named ceiling and floor of the CHAR in (3). CHAR could also be computed with arbitrarily combination of HARs. The HARs for the pulse in Fig.4 were calculated and listed in Table 1.The $CHAR_{22}$ for the pulse was 8.139, $CHAR_{42}$ was 13.498 and $CHAR_{43}$ was 7.184.

## IV. RESULTS AND DISCUSSIONS

With the CHAR we proposed, every piece of PPG data we acquired was analyzed. CHARs with different ceilings and floors were calculated and evaluated manually in case of any unexpected errors for every pulse.

### A. Individual Consistency of CHAR

The influence of the value of ceilings and floors for CHAR was studied. For every pulse in PPG signals, three representative parameters $CHAR_{22}$ , $CHAR_{42}$ and $CHAR_{43}$ were calculated and contrasted.

Different ceiling and floor for CHAR could lead to the diversity in numerical values but similarity in the trends, as demonstrated in Fig.5. The CHAR increased/decreased as the ceiling increased/decreased when the floor stayed unchanged, and CHAR increased/decreased as the floor decreased/increased when the ceiling stayed unchanged. The correlation coefficients for the three CHARs were calculated and listed in Table 2.

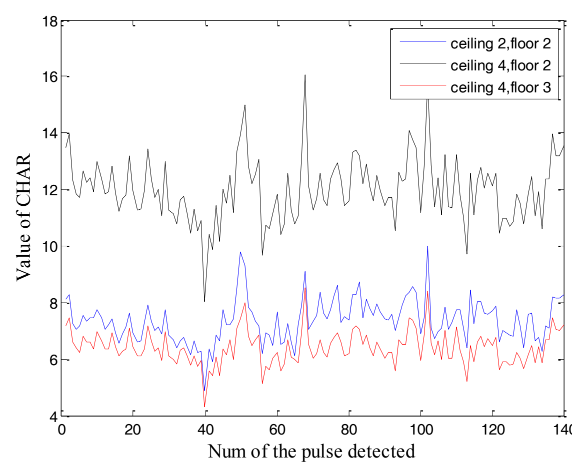


Figure 5. The trends for CHAR with different ceiling and floor based on the same piece of PPG data

TABLE II. CORRELATION COEFFICIENT OF THE CHAR PAIR

| CHAR Pair | Correlation Coefficient |
|---|---|
| $CHAR_{22}$ $CHAR_{42}$ | 0.8762 |
| $CHAR_{22}$ $CHAR_{43}$ | 0.8483 |
| $CHAR_{42}$ $CHAR_{43}$ | 0.9931 |

It's clear that there were positive correlations between HARs with different ceilings and floors. In other words, HAR possessed the feature of individual consistency.

### *B. Preeclampsia distinction*

As PE had an impact on vascular stiffness and resistance, an experiment for PE distinction was conducted using CHAR. Due to the individual consistency mentioned above, $CHAR_{22}$ was chosen for the analysis. $CHAR_{22}$ for every single piece of data were calculated and analyzed for statistics. The mean value and standard deviation of $CHAR_{22}$ were computed and depicted in Fig. 6.

Fig. 6 showed the statistics in the form of the error bar, in which the center point represented the mean value and the line stood for the variety (mean value plus/minus standard deviation). Colors and symbols were used to differ between pregnancies with PE or not. The figure displayed the distribution of the $CHAR_{22}$ from the original data. It's obvious that the $CHAR_{22}$ of pregnancies with PE had smaller mean value and standard deviation compared to those without. As the overlap of the graphs, more detailed information couldn't be picked up directly to conduct the distinction.

Thus the form was changed to display the statistics. The mean value was used as the horizontal ordinate while the standard deviation used for the vertical ordinate, finally a scatter plot was concluded as Fig. 7.

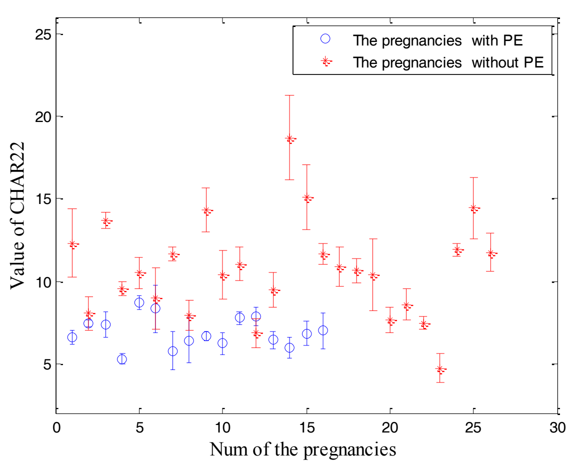


Figure 6. Original statistics of the CHAR22

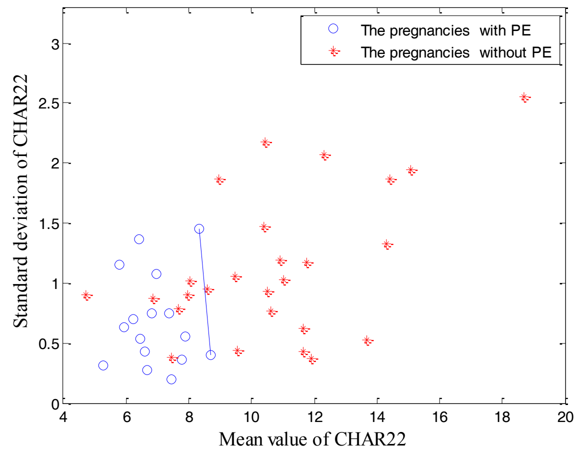


Figure 7. Improved scatter diagram for the CHAR22

It's palpable that the points represented the pregnancies with PE gathered mainly in the southwest corner of the figure. For the healthy ones, the points were more scattered in the figure and there're no points in the northwest corner. On this phenomenon, we could make a rough distinction on PE as the line separated the points in Fig. 7 for instance. The evaluations of the division were listed in Table 3.

The precision of the division was 72.7% (16/22), the sensitivity was 100% (16/ (16+0)), the specificity was 76.9% (20/ (20+6)) and the accuracy was 85.7% ((16+20)/ (22+20)), which proved CHAR might be potential in the quick distinction of PE.

The results of the division might be influenced by the limitation of our data resources, 42 pieces of PPG signals were used which was relatively small comparing to similar studies. Another impact factor might be the insufficient use of HARs. As CHAR was the ratio of certain HARs, the information it indicated about vessel elasticity and blood viscosity was attenuated. Meanwhile the middle parts of the HARs were neglected as we used $CHAR_{22}$ for analysis. The $CHAR_{42}$ and $CHAR_{43}$ were nearly linearly correlated in the last section, which indicated the $HAR_3$ barely contained useful information. Thus the HARs selected for CHAR might also influence the result with different weight coefficients. In the end, the stage set for HAR could also have a role in the results. Better methods to make the best of the HARs are in intense demand which is the focus of our research for the period ahead.

TABLE III. THE EFFECT EVALUATION OF THE DIVISION

| | True | False | Sum |
|---|---|---|---|
| Positive | 16 | 6 | 22 |
| Negative | 20 | 0 | 20 |
| Sum | 36 | 6 | 42 |

## V. CONCLUSIONS

The hierarchical area ratio and comparatively hierarchical area ratio segmented and quantitated the descending domain of PPG to obtain details about the descending velocity of the PPG curve. HAR/CHAR demonstrated the morphology of the PPG signals as well. CHAR was connected to the waveform of the pulse, different ceiling and floor for CHAR could lead to the diversity in numerical values but similarity in the trends. CHAR was adopted in the contrast between pregnancies with or without PE. Those with PE had smaller values in the mean and standard deviation of CHAR compared to those without. We succeeded in distinguishing PE with an accuracy of 85.7% and sensitivity of 100% using CHAR which showed favorable prospects in the quick distinction of PE. But there are still some limitations in our study including the insufficient data sources and inadequate exploiting of HAR parameters which need to be solved in our researches for the next stage.

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