Assessment Parameters on Array Pulse Wave Analysis and Application in Hypertensive Disorders

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Research

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Assessment Parameters on Array Pulse Wave Analysis and Application in Hypertensive Disorders

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Abstract

Background: At present, there is no effective analysis method for array pulse wave. But this is very important for promoting the development of pulse diagnosis. Hypertension is a common and easy-to-diagnosis of cardiovascular disease, which is the development foundation of other cardiovascular diseases. Our goal in the study is to establish analysis method for array pulse wave and preliminary application in hypertensive disorders.

Methods: In this study, a sensor array can be used for real-time monitoring of pulse wave twelve channels. We calculated the average pulse wave (APW) of per channel within thirty seconds. The most representative pulse wave (MRPW) and the APW matched by correlation coefficient. Feature points of the MRPW were identified by manually. These feature points corresponding to the array
pulse volume (APV) parameters were also identified by manually. Finally, clinical trial was executed to detect these feature performance indicators in hypertensive disorders.

**Results:** The raoAPV$_{h1}$, raoAPV$_{h3}$, raoAPV$_{h4}$, raoAPV$_{h3/h1}$ and raoAPV$_{h4/h}$ of hypertension group significantly increased compared with that of the healthy group ($P<0.01$, $P<0.05$). The zhongAPV$_{h4}$, zhongAPV$_{h3/h1}$, zhongAPV$_{h4/h1}$ and meanAPV$_{h3}$, meanAPV$_{h3/h1}$, meanAPV$_{h4/h1}$ were significantly increased in hypertension group compared with healthy group ($P<0.05$, $P<0.01$). The chiAPV$_{h4/h1}$ of hypertension group was obviously elevated ($P<0.05$). The results preliminarily validated novelty of APV on array pulse wave analysis. This indicator was effective in reflecting the hypertensive vascular function.

**Conclusion:** Traditional Chinese Medicine (TCM) pulse is a combination of multi-dimensional information. Array sensor could be better reduction of TCM pulse characteristics. In the study, the analysis of array pulse wave was valid, and the APV was reliable to mirror TCM pulse characteristics.

**Keywords:** Pulse diagnosis; Traditional Chinese medicine; Sensor array; Array pulse volume; Healthy persons; Hypertension persons.

**Background**

Pulse diagnosis is one of the four diagnosis methods of traditional Chinese medicine (TCM), and is the essence and inheritance summary of TCM for thousands of years. The richness and diversity of pulse also determines the difficulty of pulse diagnosis. With the development of modern science and technology, modernization of pulse diagnosis has achieved great progress, which makes the pulse wave signal convert into visual digitized pulse diagram. Morphological characteristics of
pulse wave is the track of blood pressure, vascular wall tension, the combined force of the overall displacement motion of the vessel and the phase change. This is closely related to cardiac systolic and diastolic function, the state of blood vessel wall.[1] A complete pulse beat cycle can be able to reflect heart pumping features. These characteristic parameters of pulse wave are interpreted by time domain analysis. So we can objectively know whether there is arterial stiffness and cardiac dysfunction or not. Therefore, pulse wave is of great help to clinical diagnosis of cardiovascular disease, particularly for asymptomatic population. These demand pulse wave has higher authenticity, reliability and accuracy. Pulse diagnosis is a method to detect *yin* and *yang*, *interior* and *exterior*, *cold* and *heat*, *asthenia* and *sthenia* of the system.[2] Pulse contains a wealth of physiological information, receptors are widely distributed in the finger pulp, and so we can feel different pulse. The objectivity of pulse diagnosis helps to achieve quantification of diseases. At present, the objectivity of single pulse diagnosis is relatively mature. However, the single pulse diagnosis cannot fully reflect characteristics of pulse or the stereoscopic sensation under doctors’ finger pulsation. Accordingly, in order to better reduction of pulse, modern technology has been applied to the research and development of pulse diagnosis instrument. Sensor array can reflect temporal and spatial characteristics of radial artery pulse wave, which is more in line with Chinese physicians’ pulse diagnosis method.[3-5] The principles, content and method of pulse diagnosis determined the inevitability of sensor array. Although the array pulse wave could better reflect pulse characteristics from different angles, but the analysis method of array pulse wave is still in the early stages. This allows the array pulse wave analysis based on the pulse diagnosis principle become more urgent.

Capacitive pressure sensors with good repeatability and sensitivity, this can be a good simulation of the doctor’s finger pressure. From the bionics point of view, more flexible surface
contact-type sensing model are designed, and modern computer information processing techniques were applied to the pulse wave extraction. Although sensor array has obvious advantages in reflection pulse, but it is not supported by data. Common pulse diagnosis method in TCM including floating, medium and heavy. Capacitance sensors have a wide range and convenient pressure. The advantages of capacitance sensors also reflect in the following points: firstly, the capacitance sensor can better detect the pulse wave pressure of different individuals. Secondly, it has simple structure, good temperature stability and strong adaptability. These features help the pressure sensor burden enormous temperature change, and contribute to clinical expansion and application in the future. Thirdly, Capacitance sensor has a good dynamic response, which facilitates measurement of rapidly changing parameters, such as instantaneous pressure. All of which is useful to detect subtle changes of pulse wave. Capacitance sensor requires minimal effect energy, which means that the sensor portion can be made small, thin, i.e., very light mess. This feature allows design a plurality of sensing channel, and synchronous detection of multiple channels. [6]

Though much work have been done in the research and development of sensor array, the analysis method of array pulse wave has not been established yet.[7-10] This is extremely important for its clinical application. Existing studies have shown that pulse wave abnormality is closely associated with cardiovascular disease, this provides strong evidence for the assessment of physiological and pathological status of an individual. [11, 12] In this work, we synchronously monitored multi-channel pulse wave by pressure profile system (PPS) capacitance pressure sensor to provide real-time visualization. Left wrist radial artery of “guan” position was chosen as common measurement site. By calculating the average pulse wave (APW) of every channel, we can best match the most representative pulse wave (MRPW), array pulse volume (APV) can manually
identified of the feature points corresponding to the MRPW. APV represents average volume of pulse beat in per unit time, which can be computed by linear interpolation algorithm.[13] Here, a sensor array based on pressure was applied to achieve multipoint monitoring of radial arterial pulse wave. The pulse diagram collected by sensor array has the characteristics of multi-point and multi-dimension, which is more consistent with the principles and clinical needs of TCM pulse diagnosis. Based on this, we explored the analysis of array pulse wave, and the results demonstrated APV owned tremendous potential in early cardiovascular function indication.

**Materials and Methods**

**PPS sensor array**

Time-domain analysis is commonly used in the pulse wave analysis method, and the obtained pulse wave parameters are beneficial for cardiovascular disease diagnosis.[14] A typical pulse wave (Figure 1) incorporates $h_1$, $h_2$, $h_3$, $h_4$, $h_5$, $t$, $t_1$, $t_4$, $t_5$ and $w$. A pulse period can be divided into the ascending branch and descending branch, both of which form the main wave ($h_1$). The gorge of descending branch is called dicrotic notch ($h_4$), between the main wave and dicrotic notch is predicrotic wave ($h_3$), also known as tidal wave. The trough between $h_1$ and $h_3$ is the main wave amplitude gap ($h_2$). After the dicrotic notch is dicrotic wave ($h_5$). In the study, PPS sensor array is provided by the United Stated (Pressure Profile Systems, Inc. USA), including hardware and software parts. The Chameleon software and drivers need to be installed in advance. The hardware comprises of four parts: USB Cable of FingerTPS Electronics Power, Rechargeable Wireless Bluetooth Interface Electronics Box, BlueTooth Dongle and Capsense Wrist Module. Capsense Wrist Module was placed at the “guan” position of left radial artery. Pulse wave signal was received
through Rechargeable Wireless Bluetooth Interface Electronics Box, and presented on a computer. USB Cable was used to charge the Electronics Box. (Figure 2A)

Before the Chameleon software opened, the battery needed to be fully charged and connected through USB interface with a computer. Hardware component should be connected as the following sequence: firstly, plugging the BlueTooth Dongle into an open USB port on the computer. Secondly, Turning the FingerTPS electronics power switch on prior to launching the software. When the power electronics was initialized, the LED should blink in green, means that the software ready to connect. Otherwise, electronics battery needed to be continue charging. The battery can be used continuously for four hours, two to three hours full charge. Finally, launching Chameleon software. The detailed information and illustrative diagram of PPS was shown in Table 1 and Figure 2B.

<table>
<thead>
<tr>
<th>Table 1 Performance introduction of PPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array size</td>
</tr>
<tr>
<td>Element size</td>
</tr>
<tr>
<td>Thickness</td>
</tr>
<tr>
<td>Full scan range</td>
</tr>
<tr>
<td>Scan rate</td>
</tr>
<tr>
<td>Temperature range</td>
</tr>
<tr>
<td>Power</td>
</tr>
</tbody>
</table>

APW and the MRPW

The original pulse wave signal should first remove noise by band-pass filtering, including high frequency noise and low frequency noise. The purpose of denoising is to remove interference, such as power line interference, electromagnetic signals, baseline drift, myoelectric activity, system noise, and the noise generated in the body shaking during pulse wave acquisition process. Thus, the main wave could be shown as much as possible, and the other frequency interference waves suppressed.

The pulse rate is at 60~100 beats per minute, the effective frequency is at 1~2Hz, mostly at
1~4 Hz. Since the main pulse wave occupied most of the energy in the whole pulse wave, so we chose at 1~4Hz bandpass filter for filtering original pulse wave. The bandpass filter was designed by MATLAB tool, with six order and two passband cutoff point of 1Hz and 4Hz filter respectively was a Chebyshev I type infinite response filter.[15]

In the original pulse wave, the baseline drift existed for the body and wrist movement during pulse wave acquisition process. In Figure 3A-3B, 12-channel pulse wave signal of a 26-year-old male in 30 seconds was shown. High fidelity pulse wave signals of raw data were recorded without any filtering process (Figure 3A). After band-pass filtering process, the denoised pulse wave signals showed better consistency (Figure 3B). In all of the pulse wave cycle the h₁, h₃, h₄ and h₅ were visible obviously.

For the pulse wave of every channel, we calculated the APW. The correlation coefficient (CC) was referred to find the best matched pulse wave called the MRPW by MATLAB tool. As shown in Figure 4, APW and the MRPW of one channel in a 26-year-old male. At last, we manually identified the MRPW characteristic parameters corresponding to APV.

APV

For PPS sensor array, we could get twelve-channel pulse waves at the same time, meaning twelve points at one moment. Twelve points according to the position of sensor array can be composed of two-dimensional array. F represented the amplitude of twelve points, the F value of 3*4 was interpolated into N*N by linear interpolation. N value was 1000, namely 3*4 two-dimensional array was transformed into 1000*1000 array M. M was the amplitude of multiple points aiming at forming a surface. Thus, a three-dimensional pulse map was constructed. (Figure 5A) It could reflect
the pulsation effect of the vessels at different points in the same time and comprehensively reflected characteristics of pulse. For every moment, the volume \( V \) was calculated as Equation:

\[
V = S \times \sum_{i=1}^{N} \sum_{j=1}^{N} M_{ij}
\]

Where the \( V \) represented the volume of different moments, \( S \) was the area bounded by pulse width (X axis) and pulse length (Y axis).

The fluctuation of pulse wave was periodic companied with energy change. The pulse wave motion cycle energy of a healthy person was stable. APV reflected the energy change of each pulse cycle. We defined the APV as average volume of pulse beat in unit time. A typical pulse cycle was shown in Figure 5B. When vasoconstriction, increased amplitude, the average amplitude of twelve points were increased. On the contrary, when vasodilation, lower amplitude and the average amplitude of twelve points decreased. MATLAB tool was for drawing graph of APV in a pulse cycle. Since the sampling frequency was 100Hz, the extraction frequency of APV was also set to 100Hz. For the determined characteristic parameters of the MRPW, the APV might be identified based on the particular time point by manual identification.

Experimental protocol

Twenty-six healthy volunteers were enrolled in the experimental. To keep the baseline consistent, we recruited twenty-six patients with hypertension who were matched by age and gender. Fifty-two aged from 20 to 40 years male volunteers were enrolled for the clinical experiments.
The volunteers were required to sit quietly until the respiration, HR and blood pressure were stable. The blood pressure was detected by electronic sphygmomanometer (OMRON HBP-9020). Then the sensor array (PPS SN7798) were fixed in left-hand-side “guan” site of the wrist.[16] (Figure 6) The real-time pulse waves of 30 seconds were carried out. Record the amplitude of three characteristic peaks and one valley in pulse waveform. The detailed operation step was as follows: Array pulse wave acquisition method: 1) Pulse wave collectors and volunteers were required to receive standardized training; 2) Before pulse wave acquisition, every volunteer was required 5-minute break to restore their smooth breathing. The volunteers took an upright seat facing the pulse wave collectors. The left forearm relaxed and stretched forward naturally with the elbow at 120 degrees. The left wrist was placed on the pulse diagnosis pillow with the palm up naturally. The body should be straight and breathing steadily without speech and body shaking; 3) The “guan” position of the left hand was chosen as the pulse collection site, due to the strength of the wrist pulse at “guan” is usually stronger than at “cun” and “chi”. Guan is at the radial artery inside the styloid process of the radius by the testers’ middle finger pulp. The array pulse signals from the left hand “guan” position was confirmed and optimum pressure was ascertained by general condition for light, medium, and heavy pressure, and minor adjustment was allowable for spotting.

Statistical analysis

To acquire a statistical analysis, we used SPSS 25.0 program to analyze the data. Two Independent Student T test and Mann-Whitney U test were applied for two group comparisons. \( P < 0.05 \) was considered statistic difference.
Results

The comparison of basic information between healthy group and hypertension group.

As shown in Table 2, SBP and DBP were significantly higher in the hypertension group than in the healthy group, and the hypertensive men had significantly higher weight and BMI. The other clinical characteristics did not differ between the groups.

Table 2 Basic information of volunteers in the clinical experiment

<table>
<thead>
<tr>
<th></th>
<th>Healthy group</th>
<th>Hypertension group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>30.23 (5.72)</td>
<td>32.00 (8.34)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>174.27 (6.56)</td>
<td>174.85 (7.59)</td>
</tr>
<tr>
<td>Weight (Kg)</td>
<td>73.08 (8.18)</td>
<td>80.73 (14.66)*</td>
</tr>
<tr>
<td>BMI</td>
<td>24.05 (2.28)</td>
<td>26.35 (4.08)*</td>
</tr>
<tr>
<td>SBP (mmHg)</td>
<td>124.04 (9.46)</td>
<td>147.70 (8.28)***</td>
</tr>
<tr>
<td>DBP (mmHg)</td>
<td>76.54 (5.74)</td>
<td>89.50 (10.45)***</td>
</tr>
<tr>
<td>HR (bpm)</td>
<td>84.62 (13.16)</td>
<td>83.92 (14.55)</td>
</tr>
</tbody>
</table>

BMI: Body Mass Index; SBP: Systolic Blood Pressure; DBP: Diastolic Blood Pressure; HR: Heart Rate; bpm: Beat Per Minute

*P<0.05, **P<0.01, ***P<0.001 in comparison with the healthy group.

APV characteristic parameters

Time domain analysis is commonly used method of pulse wave analysis, which is beneficial to two-dimension pulse wave. Based on the characteristic parameters of single pulse and our previous study, we explored the APV this spatial feature. We calculated the absolute value of APV at specific time, and the relative ratio of APV at different time points. These indicators were
important for health assessment.

Assessment of APV characteristics parameters

According to the pulse diagnosis direction of twelve single channel and the axila direction of vessel, the twelve single channel could be divided into three channels, i.e. radial passage (rao), intermediate passage (zhong) and ulnar passage (chi). (Figure 2B) For every passage, we calculated the average of the four channels (mean). In addition, we also calculated the average of twelve channels. In accordance with the physiological significance of the characteristics parameters of single channel pulse, we defined the APV too. The specific meanings of APV were shown in Table 3.

Table 3 The meaning of APV characteristic parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>APV_h1</td>
<td>The area under the surface formed by the set of amplitude of the main wave</td>
</tr>
<tr>
<td>APV_h3</td>
<td>The area under the surface formed by the set of amplitude of the predicrotic wave</td>
</tr>
<tr>
<td>APV_h4</td>
<td>The area under the surface formed by the set of amplitude of the dicrotic notch</td>
</tr>
<tr>
<td>APV_h5</td>
<td>The area under the surface formed by the set of amplitude of the dicrotic wave</td>
</tr>
<tr>
<td>APV_h3h1</td>
<td>The area under the surface formed by the ratio of the amplitude of the predicrotic wave amplitude to the amplitude of main wave</td>
</tr>
<tr>
<td>APV_h4h1</td>
<td>The area under the surface formed by the ratio of the amplitude of the dicrotic notch amplitude to the amplitude of main wave</td>
</tr>
<tr>
<td>APV_h5h1</td>
<td>The area under the surface formed by the ratio of the amplitude of the dicrotic wave amplitude to the amplitude of main wave</td>
</tr>
</tbody>
</table>

The changes of APV between healthy group and hypertension group

We compared the difference of APV between healthy group and hypertension group. The results showed that APV_h4/h1 in rao, zhong, chi and mean was markedly increased in hypertension group. APV_h4 and APV_h3/h1 in rao, zhong and mean were significantly elevated in hypertension group. APV_h3 in rao and mean obviously rised in hypertension group. APV_h1 in rao observably raised in hypertension group. APV_h5 and APV_h5/h1 had no significant difference between the two
groups. (Table 4, Figure 7A-7G) By analyzing the results, we could speculate that the hypertension group had increased peripheral resistance, decreased vascular compliance and reduced left ventricular compliance. This was consistent with early study.[17] And the results proved three-dimension of APV characteristic parameters were sensitive.

Table 4 Comparison of APV characteristic parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mean (SD)</th>
<th>t/Z</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Healthy group</td>
<td>Hypertension group</td>
<td></td>
</tr>
<tr>
<td>rao</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APV_h1</td>
<td>8.623 (1.349)</td>
<td>9.947 (1.192)</td>
<td>-3.220</td>
</tr>
<tr>
<td>APV_h3</td>
<td>7.219 (1.784)</td>
<td>8.729 (1.377)</td>
<td>-3.470</td>
</tr>
<tr>
<td>APV_h4</td>
<td>6.497 (1.682)</td>
<td>7.940 (1.565)</td>
<td>-3.388</td>
</tr>
<tr>
<td>APV_h5</td>
<td>-0.002 (0.188)</td>
<td>-0.022 (0.175)</td>
<td>0.714</td>
</tr>
<tr>
<td>APV_h3/h1</td>
<td>0.827 (0.090)</td>
<td>0.874 (0.058)</td>
<td>-2.714</td>
</tr>
<tr>
<td>APV_h4/h1</td>
<td>0.743 (0.089)</td>
<td>0.793 (0.091)</td>
<td>-2.512</td>
</tr>
<tr>
<td>APV_h5/h1</td>
<td>0.001 (0.022)</td>
<td>-0.002 (0.019)</td>
<td>0.934</td>
</tr>
<tr>
<td>zong</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APV_h1</td>
<td>8.840 (1.387)</td>
<td>9.715 (1.002)</td>
<td>-1.326</td>
</tr>
<tr>
<td>APV_h3</td>
<td>7.414 (1.860)</td>
<td>8.617 (1.315)</td>
<td>-1.975</td>
</tr>
<tr>
<td>APV_h4</td>
<td>6.497 (2.016)</td>
<td>7.806 (1.404)</td>
<td>2.303</td>
</tr>
<tr>
<td>APV_h5</td>
<td>0.100 (0.237)</td>
<td>0.035 (0.183)</td>
<td>-1.098</td>
</tr>
<tr>
<td>APV_h3/h1</td>
<td>0.830 (0.100)</td>
<td>0.883 (0.055)</td>
<td>-2.426</td>
</tr>
<tr>
<td>APV_h4/h1</td>
<td>0.721 (0.128)</td>
<td>0.800 (0.089)</td>
<td>-2.739</td>
</tr>
<tr>
<td>APV_h5/h1</td>
<td>0.012 (0.029)</td>
<td>0.004 (0.019)</td>
<td>-1.226</td>
</tr>
<tr>
<td>chi</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APV_h1</td>
<td>8.643 (1.760)</td>
<td>9.428 (1.037)</td>
<td>-0.918</td>
</tr>
<tr>
<td>APV_h3</td>
<td>6.974 (2.203)</td>
<td>8.182 (1.440)</td>
<td>-1.410</td>
</tr>
<tr>
<td>APV_h4</td>
<td>6.229 (2.084)</td>
<td>7.360 (1.520)</td>
<td>-1.586</td>
</tr>
<tr>
<td>APV_h5</td>
<td>0.100 (0.287)</td>
<td>0.016 (0.182)</td>
<td>-0.924</td>
</tr>
<tr>
<td>APV_h3/h1</td>
<td>0.795 (0.126)</td>
<td>0.863 (0.074)</td>
<td>-1.849</td>
</tr>
<tr>
<td>APV_h4/h1</td>
<td>0.707 (0.120)</td>
<td>0.774 (0.100)</td>
<td>-2.042</td>
</tr>
<tr>
<td>APV_h5/h1</td>
<td>0.127 (0.039)</td>
<td>0.003 (0.022)</td>
<td>0.409</td>
</tr>
<tr>
<td>mean</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>APV_h1</td>
<td>8.739 (1.213)</td>
<td>9.646 (0.763)</td>
<td>-1.558</td>
</tr>
<tr>
<td>APV_h3</td>
<td>7.275 (1.751)</td>
<td>8.460 (1.135)</td>
<td>-2.228</td>
</tr>
<tr>
<td>APV_h4</td>
<td>6.454 (1.764)</td>
<td>7.653 (1.273)</td>
<td>-2.537</td>
</tr>
<tr>
<td>APV_h5</td>
<td>0.066 (0.216)</td>
<td>0.018 (0.160)</td>
<td>-1.226</td>
</tr>
<tr>
<td>APV_h3/h1</td>
<td>0.823 (0.096)</td>
<td>0.874 (0.062)</td>
<td>-2.604</td>
</tr>
<tr>
<td>APV_h4/h1</td>
<td>0.727 (0.106)</td>
<td>0.789 (0.087)</td>
<td>-2.836</td>
</tr>
<tr>
<td>APV_h5/h1</td>
<td>0.009 (0.026)</td>
<td>0.002 (0.017)</td>
<td>-1.098</td>
</tr>
</tbody>
</table>

rao: the average of radial four channels; zong: the average of intermediate four channels; chi: the average of ulnar four channels; mean: the average of twelve channels.
Discussion

With the development of modern pulse diagnosis, many high-tech materials were applied to the research of pulse diagnosis instrument. Chinese pulse is the pulse wave characteristics and physician global impression under the fingers, including pulse rate, rhythm, floating and sinking, strength and weakness, thickness and thin, stiffness and softness and other information. Based on this, the sensors need to be as realistic as possible to feel and reflect the pulse. Single-channel pulse wave sensor is limited on pulse information acquisition, but this is essential to acquire rich information for disease diagnosis. Sensor array may compensate this disadvantage to some extent. Different types of sensors array have been developed for health monitoring. Wang et al[18] combined a pressure sensor and a photoelectric sensor array made of a multi-channel sensor fusion structure. This pulse system was demonstrated effectiveness than previous pulse acquisition platforms. Xu et al[19] validated that a piezoelectric sensor array-based device had similar accuracy and reproducibility in measuring pulse wave velocity (PWV). Park et al[20] reported a stretchable array of highly sensitive pressure sensors consisting of polyaniline nanofibers and au-coated polydimethylsiloxane micropillars, which showed great potential in wearable device. Sensor array achieve simultaneous measurement of the width, amplitude and other spatiotemporal information of dynamic pulse wave under different pressures.[21]

Compared with single-channel sensor, sensor array may be more comprehensive to response the pulse characteristics. PPS array capacitance pressure sensor can be manually pressurized, and reflect morphological characteristics of 12-channel pulse wave in real-time. Single-channel pulse parameters has been proved to be effective and reliable in clinical disease.[3, 22, 23] For better health monitoring, the devices are designed to be wearable for continuous measurement and
physiological and pathological signals.[24] Though single-channel pulse wave sensor has the advantages of low cost and flexibility, it is limited in extracting adequate pulse information. Sensor array can better simulate the rich feeling under physicians’ finger pulp. It also raises higher requirement for APW analysis.

A large amount clinical and epidemiological evidence have indicated that hypertension is one of the major risk factors for cardiovascular disease, characterized by impaired vascular structure and endothelial function, which is the early vascular lesion of hypertension.[25] In this study, both SBP and DBP in the hypertension group were significantly higher than in the healthy group (Table 2). It has been explained in the previous studies that the increase of $h_1$ and $h_3/h_1$ was associated with arterial stiffness.[26] The parameters of $h_1$ represents good ejection function of left ventricle. The left ventricle is the primary target for organ damage. In the early stage of hypertension, myocardial cell will adapt to the increased workload by ventricular remodeling.[27] This might lead to compensatory increased of $h_1$. In our work, increased APV$_{h_1}$ at rao in hypertension group agreed with previous study. The ratio of $h_3/h_1$ reflects compliance and peripheral resistance of the vascular wall.[26] Hypertension is often accompanied by arteriosclerosis performance.[28, 29] Increased PWV is observed in hypertension.[30] The vascular compliance in hypertension is reduced.[31] Increased APV$_{h_3/h_1}$ at rao, zhong and mean in hypertension group was consistent with previous reports.[32]

The existing study provided that the degree of arteriosclerosis was increased in hypertension population, and vasoconical elasticity was reduced, and the PWV was accelerated. [33, 34] In the pulse time domain analysis, $h_4$ is used to evaluate the peripheral resistance of the blood vessels, $h_3$ is used to assess the elasticity and peripheral resistance of arterial blood vessels. In this study APV$_{h_4}$,
APV_{h3} and APV_{h4/h1} were rising in hypertension group, indicating that the peripheral resistance and vascular elasticity of the hypertension was elevated, which was consistent with the previous research.

For the asymptomatic people, the proposed pulse diagnosis method by sensor array is convenient, noninvasive and propagable. This provides a safe and convenient way for the screening of cardiovascular disease. We found that it was comparable when we compared the difference between the two groups of APV parameters in the same part. There was more obvious index difference at zhong. According to the hemodynamics[35] and hydromechanics[36], the flow of blood in the blood vessel can be divided into Laminar Flow and Turbulence. Lamflow is a rule movement, in the case of laminar flow, the flow direction of the liquid per mass point is equal to the long axis of the pipeline, but the flow rate of each mass point is different, the fastest flow rate at the pipe axis, closer the tube wall The slower the flow rate of the shaft layer. So, the difference of average APV of 12-channel between the two groups was not obvious.

Further clinical experiments need to be carried out in the follow-up works. Since only twenty-six subjects of each group to analyze the array pulse wave. In the following research, the distribution of subjects should be expanded in quantity, age, sex and other health conditions. Sensor array used in this study can realize real-time monitoring of multi-channel. The proposed array pulse analysis method primarily demonstrated that APV parameters could predict health condition. It is true that this equipment is relatively high in the current stage, but it is very potential for pulse diagnosis in the medical field. Therefore, the analysis method of array pulse is very important. In this study, we proved the reliability of APV through small sample in predicting health status.

Conclusions
This study is a new attempt in analysis of array pulse wave. Single-channel pulse wave sensor is limited in obtaining pulse wave information. Sensor array helps to achieve three-dimensional pulse wave. The sensor area of sensor array used in this study is very small, and the subsequent sensor research can develop in a more convenient direction. The characteristic indicator APV mirrors the energy change of blood vessels. The parameter comparison between healthy group and hypertension group showed APV good prediction in cardiovascular function. The array pulse wave still hides a lot of information to be explored. In the future, we intend to extract more valuable multiple features of array pulse wave. We will use different pulse wave analysis, including time domain analysis and frequency domain analysis. Convolutional Neural Network and other Machine Learning and Deep Learning methods would be used to realize intelligence feature point recognition and the classification of pulse.

**List of abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>TCM</td>
<td>Traditional Chinese Medicine</td>
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<tr>
<td>PPS</td>
<td>Pressure Profile System</td>
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<tr>
<td>APW</td>
<td>Array Pulse Wave</td>
</tr>
<tr>
<td>MRPW</td>
<td>Most Representative Pulse Wave</td>
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<tr>
<td>APV</td>
<td>Array Pulse Volume</td>
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<td>CC</td>
<td>Correlation Coefficient</td>
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<tr>
<td>PWV</td>
<td>Pulse Wave Velocity</td>
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**Ethics approval and consent to participate**
The study was fully approved the Ethics Committee of Shuguang Hospital affiliated to Shanghai University of Traditional Chinese Medicine. All patients provided written informed consent.

**Consent to publish**

Written informed consent for publication was obtained from all participants.

**Availability of data and materials**

The data and materials used to support the findings of this study were available from the corresponding author upon request.

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**Authors' Contributions**

In the paper, Zijuan Bi and Xinghua Yao carried out all the experiments, analyzed data and wrote the paper, and contributed equally to this study; Xiaojuan Hu provided technical support; Pei Yuan, Xiaojing Guo, Zhiling Guo, Sihan Wang, Jun Li, Yulin Shi and Jiacai Li Performed manual
identification of data feature points; Ji Cui and Jiatuo Xu designed the experiments and revised the paper, and contributed equally to this study. All authors have read and approved the final manuscript.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Legends

Fig. 1 A complete pulse wave period. h, amplitude/height; h_1, amplitude of main wave; h_3, amplitude of predicrotic wave; h_4, amplitude of dicrotic notch; h_5, amplitude of dicrotic wave; t_1, time between the start point of pulse wave and main wave; t_4, time between start point of pulse wave and dicrotic notch; t_5, time between dicrotic notch and the end point of pulse wave; t, time of the enteric pulse wave; w, width of main wave in its one-third amplitude position.

Fig. 2 The introduction of PPS. a, Schematic of PPS capacitance pressure sensor. 1, USB Cable of Rechargeable Wireless Bluetooth Interface Electronics Box; 2, Rechargeable Wireless Bluetooth Interface Electronics Box; 3, BlueTooth Dongle; 4, Capsense Wrist Module. b, The distribution of 12 channel.

Fig. 3 The pulse waveform in 30 seconds. a, Raw data of 12 channel in a 26-year-old male. b, Filtered data of 12 channel in a 26-year-old male.

Fig. 4 The comparison of APW and MRPW. a, An APW of 26-year-old male. b, The MRPW of 26-year-old male.

Fig. 5 The three-dimensional pulse diagram. a, Simulated three-dimension pulse diagram. a, The variation of APV in a pulse period. 1, The radial artery vasoconstricted and the points amplitude
increased; 2, When the average amplitude of 12-points reached its maximum, an expansive change occurred in the middle; 3, Radial artery vasodilation and the points amplitude decreased; 4, The average amplitude of 12-points reached its minimum, an funnel-like variation occurred in the middle.

Fig. 6 Photograph of array pulse wave signal acquisition system and direct view of 12-channel pulse wave.

Fig. 7 Comparison of APV parameters between healthy and hypertension groups. a, Comparison of APV_{h1} between healthy and hypertension groups. b, Comparison of APV_{h3} between healthy and hypertension groups. c, Comparison of APV_{h4} between healthy and hypertension groups. d, Comparison of APV_{h5} between healthy and hypertension groups. e, Comparison of APV_{h3/h1} between healthy and hypertension groups. f, Comparison of APV_{h4/h1} between healthy and hypertension groups. g, Comparison of APV_{h5/h1} between healthy and hypertension groups.
Figures

Figure 1

A complete pulse wave period. $h$, amplitude/height; $h_1$, amplitude of main wave; $h_3$, amplitude of predicrotic wave; $h_4$, amplitude of dicrotic notch; $h_5$, amplitude of dicrotic wave; $t_1$, time between the start point of pulse wave and main wave; $t_4$, time between start point of pulse wave and dicrotic notch; $t_5$, time between dicrotic notch and the end point of pulse wave; $t$, time of the enteric pulse wave; $w$, width of main wave in its one-third amplitude position.
Figure 2

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Figure 7

Comparison of APV parameters between healthy and hypertension groups. a, Comparison of APVh1 between healthy and hypertension groups. b, Comparison of APVh3 between healthy and hypertension groups. c, Comparison of APVh4 between healthy and hypertension groups. d, Comparison of APVh5 between healthy and hypertension groups. e, Comparison of APVh3/h1 between healthy and
hypertension groups. f, Comparison of APVh4/h1 between healthy and hypertension groups. g, Comparison of APVh5/h1 between healthy and hypertension groups.