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Original Article

Analysis of Pulse Signals Based on Array Pulse Volume*

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ABSTRACT **Objective:** To collect and analyze multi-dimensional pulse diagram features with the array sensor of a pressure profile system (PPS) and study the characteristic parameters of the new multi-dimensional pulse diagram by pulse diagram analysis technology. **Methods:** The pulse signals at the Guan position of left wrist were acquired from 105 volunteers at the Shanghai University of Traditional Chinese Medicine. We obtained the pulse data using an array sensor with 3×4 channels. Three dimensional pulse diagrams were constructed for the validated pulse data, and the array pulse volume (APV) parameter was computed by a linear interpolation algorithm. The APV differences among normal pulse (NP), wiry pulse (WP) and slippery pulse (SP) were analyzed using one-way analysis of variance. The coefficients of variation (CV) were calculated for WP, SP and NP. **Results:** The APV difference between WP and NP in the 105 volunteers was statistically significant (6.26±0.28 *vs*. 6.04±0.36, *P*=0.048), as well as the difference between WP and SP (6.26±0.28 *vs*. 6.07±0.46, *P*=0.049). However, no statistically significant difference was found between NP and SP (*P*=0.75). WP showed a similar CV (4.47%) to those of NP (5.96%) and SP (7.58%). **Conclusion:** The new parameter APV could differentiate between NP or SP and WP. Accordingly, APV could be considered an useful parameter for the analysis of array pulse diagrams in Chinese medicine.

KEYWORDS pulse signal, array pulse volume, pulse sensor, Chinese medicine

With the development of modern science and technology, the study of pulse examination objectivity has made great progress.[1] The pulse diagnosis instrument is based on Chinese medicine (CM) theory and collects information on the Cunkou arterial pulse, the position of traditional Chinese pulse diagnosis, including Cun, Guan, Chi, for the analysis of overall physiological and pathological information. The pulse sensor simulates the pulse-taking during CM diagnosis and is considered as one of the key components in pulse diagnosis instruments, transforming the pulse pressure and beats into digital signals. Initially, the pulse sensor was designed as a single point. However, CM pulse-taking is performed with 3 fingers together and can thereby examine the characteristics of the pulse with varying pressure, allowing the similarities and differences in the pulse condition to be observed using the 3 fingers together or 1 at a time.[2] Researches on the multi-probe analysis of the pulse condition at the Cun, Guan, and Chi positions have been carried out;[3] however, the existing signal acquisition and analysis technology is not yet mature and needs to be improved.

The use of an array pulse sensor to obtain multi-channel pressure signals in a small area has been extensively studied for the analysis of the pulse condition.[4] In 1986, an array pulse sensor with 63 channels was released,[5] but it has not been further developed. The flexible array pressure detector probe not only makes good contact with the skin but also simulates the way a physician feels for the pulse.[6] In Korea, 6 piezo-resistive pressure sensors (C33 series, EPCOS, Germany) have been combined into a pulse sensor instrument to measure pulse signals.[7] The 40-channel sensor made by Omron Company has been

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successfully applied in medical equipment.[8] In addition, the tactile array sensor designed by the Pressure Profile System (PPS), Inc, may be suitable for pulse wave acquisition.[9] In addition, digital image sensors[10] and flexible pulse sensors made of nano-materials[11,12] have also been designed.

Fewer analyses have been performed based on array pulse sensors than single-point sensors, and most have focused on pulse length and width.[4] Recently, a number of scientific advances have been made towards the quantification of pulse diagnosis based on array pulse sensors.[13-17] However, few reports are available on the use of the array pulse volume (APV) to assess normal pulse (NP), wiry pulse (WP) and slippery pulse (SP). In this study, we have focused mainly on APV analysis.

METHODS

Study Subjects

Pulse signals at the Guan position of the left wrists of 105 faculty and students volunteers were acquired from Shanghai University of Traditional Chinese Medicine (SHUTCM) from September 2012 to May 2014. The following inclusion criteria were used to determine eligibility: aged 18–50 years old, the volunteers had no acute or chronic diseases and had not taken any medication within the past 3 months.

The volunteers included 79 males and 26 females with an average age of 32.02±12.85 years. NP was detected in 25 volunteers, SP in 50, and WP in 30 by the DDMX-100 pulse collector (200 Hz sample frequency) developed by SHUTCM for pulse signal collection.

PPS Sensor

A 3×4-channel pressure sensor was designed by the PPS Company for this study. Its array size is 10 mm×7.5 mm, with a sensing element area of approximately 2.5 mm×2.5 mm. The sensor is approximately 0.5 mm in thickness and has a full-scale range of 300 mm Hg, a scan rate of 100 Hz and a temperature range of –20 ℃ to 100 ℃. Its sensitivity is 0.5 mm Hg (Appendix 1).

The PPS is a capacitance pressure sensor. The readings are calculated from the geometry of the conductors and the dielectric properties of the insulator between the conductors. A distinct capacitor is formed at each channel where the electrodes overlap. Scanning a single row and column selectively allows both the capacitance and the local pressure to be measured. The parallel-plate capacitor consists of 2 parallel plates separated by a distance, and the capacitance is approximately described by the following equation.[18] $C=\frac{Area}{d}$, where C is the capacitance, d is the separation between the plates, and $Area$ is the area of one parallel plate.

Data Collection

The data gatherers were trained uniformly in collection methods and standard technological procedures. We collected pulse signals from the left hand by a consistent procedure, first confirming the Guan position and the general conditions for light, medium and heavy pressure and then locating the Guan position by minor adjustments, placing the sensor on the Guan position in the best pulse position until the pulse waves were as clear as possible. Thirty seconds of pulse signals under stable conditions for all channels were collected using a DDMX-100 pulse collector and a PPS sensor, separately.

After resting for 5–10 min, the volunteers were asked to sit, breathe evenly, relax their upper arm, extend their forearm naturally forward, relax the shoulder and position the elbow with flexion of approximately 120°, and place their left wrist on the pulse pillow. Then, the PPS sensor was placed at the Guan position to obtain the signals (Appendix 1). The analysis of the pulse signals consisted of 3 steps: signal processing, signal verification and APV calculation.

Signal Processing

The original pulse data contains noise and baseline variation caused by breathing and slight movements of the volunteer's arm during pulse measurement. To remove noise and baseline variation, the pulse signals were processed using a band pass filter of 1–30 Hz. We extracted the percussion wave using the Shannon energy envelope and Hilbert transform and then located the start and end of every pulse cycle based on the percussion wave.[18,19] The pulse cycles were used to derive several parameters regarding the duration and amplitude of the 1-D pulse diagrams,[19] which were used for signal verification.

Signal Verification

To verify the position used for taking the pulse,

3-D pulse signals from 1 subject were constructed to judge whether the entire blood vessel width was covered. In Figure 1, the x-axis is the sampling time, and the z-axis represents the 12 channels in the PPS array sensor. We divided the blood vessel into 3 regions (Part 1: edge 1, Part 2: middle, and Part 3: edge 2) across its width. Each region was represented by 4-channel pulse signals. The pulse signals of all 12 channels showed the shape of the pulse, and the best signals with the highest amplitude were in Part 2. When these 2 conditions were satisfied, the signals of the subjects were transformed into pulse data.

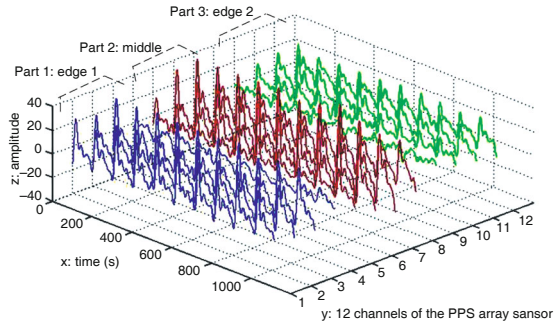

Figure 1. Three-dimension Pulse Signals from 1 Subject

In addition, to further validate the pulse signals, we referred to parameters regarding the duration and amplitude of 1-D pulse signals in the pulse data whose meanings are shown in Figure 2.[20] According to a previous study, we chose 9 parameters with physiological significance, including 6 duration parameters and 3 amplitude parameters.[20] In the structure of the PPS sensor, every region contains 4 channels. Therefore, every parameter is the average value of 4 channels over 10 cycles.

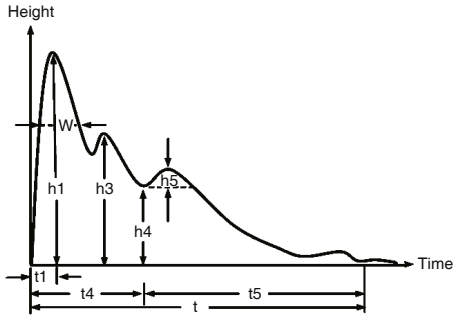

Figure 2. Meanings of Pulse Diagram Parameters

APV Calculation

After signal verification, we organized the valid pulse signals between the start and the end into a 3-dimensional array F consisting of $T \times M \times N$. T is the duration of 1 cycle. M and N are, originally, the counts of sensor units in the length and width of the PPS sensor. Because the PPS sensor has 3×4 sensor units, $M \times N$ should be 3×4. However, to accurately the trends in volume changes, we interpolate $M \times N$ to 100×100 by a linear interpolation algorithm. APV is defined as the average volume of one pulse cycle:

$$APV = \left(\sum \sum \sum (F(t,i,j) \times S) \right) / T \ (i=1,2,3...M;\ j=1,2,3...N)$$

Where $F(t,i,j)$ is the amplitude of the i^{th} and j^{th} pulse signals at time t. The y-axis represents the length of the wrist pulse, the x-axis represents the width of the wrist pulse, and the z-axis represents the relative amplitude of the pulse signals. In this study, the APV was calculated at intervals of 0.02 s in 1 pulse cycle. Meanwhile, to test the repeatability of the APV for 3 pulse conditions, WP, SP and NP, we computed the coefficient of variation (CV).

Statistical Analysis

The SPSS 18.0 statistical software (International Business Machines Corporation, USA) was used for statistical analysis. Descriptive statistics were obtained for all study variables for each study group. One-way analysis of variance (ANOVA) and Duncan's post hoc test were used to adjust for the effects of confounding factors (baseline MDA levels). A P value less than 0.05 was considered statistically significant.

RESULTS

APV

The difference between WP and NP in the 105 volunteers was statistically significant (6.26 ± 0.28 *vs*. 6.04 ± 0.36; P=0.048), as well as the difference between WP and SP (6.26 ± 0.28 *vs*. 6.07 ± 0.46, P=0.049). However, no statistically significant difference was found between NP and SP (P=0.75). WP was considerably larger, with the highest APV among the 3 pulse conditions. The change shown in Figure 3 represents a complete pulse cycle.

CV of the APV

We compared WP, SP and NP using the CV of their APVs. Regarding the repeatability of the 3 conditions, WP showed a similar CV (4.47%) to those of NP (5.96%) and SP (7.58%).

NP and SP were not significantly different in terms of the mean difference in APV. Therefore, we treated NP and SP as a group named NSP. We could observe differences between WP and NSP in the CV

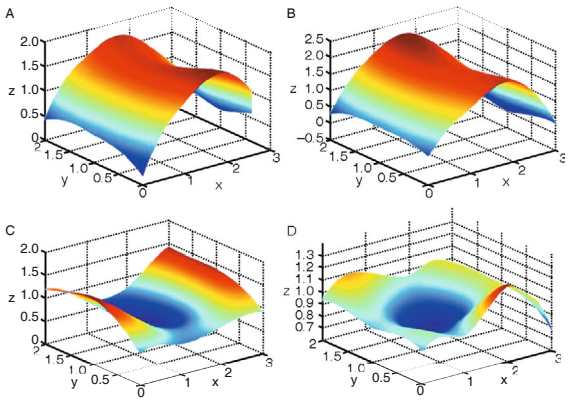

Figure 3. APV at 4 Times in 1 Pulse Cycle after Interpolation with *M*=100 and *N*=100

Notes: A represents vasoconstriction and corresponds to an increased value of the pulse signal amplitude. The average amplitude of all 12 points is increased, with the largest change in the middle; B represents the peak; C represents decreased amplitude and the appearance of a funnel with vasodilatation; D represents the minimum

of the APV. WP showed a similar CV (4.47%) to that of NSP (6.77%). A more detailed comparison between NSP and WP showed that the APV values in NSP and WP were significantly different (6.06 ± 0.42 *vs*. 6.26 ± 0.28; $P<0.05$).

DISCUSSION

Pulse diagnosis has served as important evidence for diagnosing diseases in CM for thousands of years and offers many advantages such as convenience, lack of injury, and painlessness. In the modernization of CM, scientific instruments with sensors are adopted to assist in pulse diagnosis. The parameters based on single-pulse signals represent only partial information. Integral analysis based on an array pulse sensor can obtain more information because it can more closely simulate the feeling of the pulse by physicians.

In previous studies of single-point pulse signals, *w*/*t* was usually used to distinguish among NP, SP and WP.[10,21] *W* is the width of the pulse signals in 1/3 of the percussion wave, and *t* is the time from the starting point to the ending point of a pulse cycle. The main distinctions between NP and SP are the presence of 3 waves and 2 waves, respectively, based on previous study,[20] and this distinction has been recognized in the modernization of CM. Based on the experience of the doctors involved, NP and SP both qualify as a regular pulse. Moreover, all the data in this study were from healthy individuals. We chose the best pulse signal in a 3×4-channel PPS sensor for the computation of *w*/*t*. The paired comparison between NP and SP also showed no statistical significance ($P>0.05$).

In this study, based on single-pulse analysis, we used the APV parameter of 3-dimensional pulse diagrams. This approach enables the collection of much more information on the pulse condition. We validated the pulse data by analysis with APV and compared the results in 3 pulse conditions, WP, SP and NP. Our work showed that APV could differentiate between NSP and WP. To date, despite previous studies on health assessments based on pulse signal,[21,22] APV was only now used as an actual parameter in analyzing the array pulse diagrams produced by PPS sensors.

Most researchers have focused on the relationship between parameters and pulse condition to identify regular pulse conditions in CM.[5] The problem of determining the correspondences among pulse condition, disease and body status is much more advanced, complex and difficult to understand. Our study has validated the utility of APV as a parameter for the analysis of array pulse data.

In conclusion, we suggest that APV is an important parameter for the analysis of 3-dimensional pulse diagrams. The APV can clearly distinguish between NSP and WP. However, because APV was unable to differentiate NP and SP, we adopted the combination NSP. In future work, we will conduct further data analysis based on larger datasets and focus on the range of APV in different pulse diagrams.

Conflict of Interest

The authors declare no commercial associations that might lead to conflicts of interest related to this work.

Author Contributions

Cui J, Zhang ZF, and Xu JT designed the research; Cui J, Tu LP, Zhang JF, and Zhang SL performed the research; Tu LP contributed the analytic tools; Zhang JF analyzed the data; Cui J and Tu LP wrote the paper.

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Electronic Supplementary Material: Supplementary material (Appendix 1) is available in the online version of this article at

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