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Age and blood pressure associated changes in the Gaussian modelling characteristics of the photoplethysmographic pulse

Original Research

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Abstract. Gaussian modelling has been reported as a useful method to analyze arterial pulse waveform changes. This study aimed to determine the effects of age and blood pressure on Gaussian modelling characteristics of the photoplethysmographic (PPG) pulse. Finger PPG signals were recorded from 300 normal subjects. For each subject, finger PPG pulses were normalized beat-by-beat for both width and amplitude and then averaged to obtain a normalized reference pulse waveform. This reference waveform from each subject was modelled using three Gaussian functions, with nine parameters determined, including the peak amplitude, peak time and half-width from each Gaussian function. The effect of age and mean arterial pressure (MAP) on the nine parameters were analyzed using regression analysis, with the mean values of the nine parameters compared between groups (for age: <50 vs≥50 years old; for MAP: <93 vs≥93 mmHg). The results showed that the peak amplitudes of the first and third Gaussians had negative correlation with age whereas the peak amplitude of the second Gaussian had positive correlation (all significant, $P<0.01$), leading to higher peak amplitudes of the first and third Gaussians and lower peak amplitude of the second Gaussian in the younger group (all $P<0.05$). The effect of age on the peak time interval between the first and third Gaussian curves was also negative ($P<0.01$), resulting in longer peak time interval in the younger group($P<0.05$).For the effect of MAP, the group with lower MAP had significantly higher peak amplitude of the first Gaussian, significant shorter peak time interval between the first and second Gaussian curves(all $P<0.05$). The current study extended the clinical application of Gaussian modelling for the arterial pulse analysis and provided better understanding of the underlying physiological mechanisms of the finger PPG.

Keywords: Arterial function, Blood pressure, Finger photoplethysmography, Gaussian fitting, Pulse waveform;

1. Introduction

It has been widely accepted that arterial pulse waveform characteristics could provide information of cardiacfunction and arterial properties. Different mathematic models have been used to analyze arterial pulse wave contour [1-3], including the derivative methods or wave intensity analysis [4-6], and physiological model methods, such as Windkessel model[7]or Transmission line model[1, 8].

Recently, the waveform fitting technique has been reported as a useful tool for the analysis of pulse waveform contour due to its high fitting accuracy and low sensitivity to noise. Arterial pressure that is initially induced by cardiac output has been shown to contain Gaussian features [9]. Logarithmic normal function and Gaussian function [9] have been used to decompose arterial pulse waveforms[10]. It has been shown that using three positive Gaussian functions could achieve a relatively accurate fitting[11, 12].

When using Gaussian modeling method, the potentially useful physiological information of the heart and peripheral arteries could be represented by the modelling characteristics, including the peak amplitude, peak time and half-width of the modelled Gaussian function. Rubins's study reported that peak time of Gaussian curve are highly related to the traditional augmentation index (AI) and reflection index (RI), but in their study the physiological relevance of other characteristic features, including the half-width and the peak amplitude of the modeled Gaussian curves has not been analyzed. The application of using the Gaussian modelling methods to understand the arterial pulse waveform changes with diseases has been attempted. Significantly different modelling characteristics between normal subjects and heart failure patients have been reported by Liu *et al* with the modeling application on the carotid and radial artery pressure waveforms [10].

However, to the best of our knowledge, the effects of age and blood pressure on Gaussian modeling characteristics have not been reported. This study aimed to provide this information. In this study, the finger photoplethysmographic (PPG) pulse, an accurate and reliable non-invasive arterial pulse waveform [13], would be used for the Gaussian modelling.

2. Methods

2.1. *Subjects*

300 subjects aged 18 to 80 were enrolled. None of the subjects had known cardiovascular disease. The study was fully approved by the Clinical Ethics Committee of Beijing Anzhen Hospital of Capital Medical University. Information consent was obtained from each subject prior to the measurement. Their overall basic clinical information, including the age, height and weight, is shown in Table1.

The subjects were then divided into to two groups based on age and blood pressure respectively (for age: <50 vs ≥50 years old; for mean arterial pressure, MAP: <93 vs ≥93 mmHg, 93 mmHg was the overall MAP from all the subjects). The subjects in both age and blood pressure groups were matched by gender. Table1 also gives the basic clinical information for the two sub-groups, respectively for age and MAP

Table1 Basic clinical information of the subjects studied

Show in Appendix

2.2. *Signal acquisition and analysis*

Measurements were performed in a temperature controlled room (20℃-30℃). Before the PPG measurements, subjects were asked to lie supine on a measurement bed quietly for more than 5 minutes to allow cardiovascular stabilization. .The brachial systolic and diastolic blood pressures (SBP and DBP) were then measured by a clinically trained observer, with the MAP calculated using an empirical equation. These blood pressure values are also given in Table 1.

Finger PPG pulses were recorded non-invasively from the left middle finger for each subject to obtain at least 1 min stable signal. Signals were digitally recorded at a sampling rate of 100Hz and then filtered by a high-pass filter with 0.05Hz cut-off frequency.

For each subject, finger PPG pulses were normalized beat-by-beat in both width (1000 sampling points) and amplitude (0-1) from the foot of each pulse, and then averaged to obtain a single reference pulse, which was used for subsequent analysis. .

2.3. *Gaussian modellingmethod*

For the averaged single normalized pulse waveform (f^*), three Gaussian functions from Liu *et al*'s study were used to fit f^*. The Gaussian functions are defined as follows[10]:

$$f_i(n) = H_i \times \exp(-\frac{2(n-n_i)^2}{W_i^2}), i = 1, 2, 3 \qquad (1)$$

And f^* is expressed by sum of three modelled Gaussian functions

$$f^* = \sum_{i=1}^{3} f_i(n) + \varepsilon \qquad (2)$$

For each Gaussian function, *H* means the peak amplitude, *n* means the peak time position and *W* means the half-width of the curve, and 'ε' is the fitting error. Figure 1 gives the demonstration of Gaussian modelling characteristics for one example finger PPG waveform.

Figure.1 Demonstration of Gaussian fitting for one example finger PPG waveform.
Show in Appendix

The mean absolute error (MAE) was used to evaluate the accuracy of the Gaussian fitting. It is calculated as [10]:

$$MAE = \frac{\sum_{n=1}^{1000} \left| f^* - \sum_{i=1}^{3} f_i(n) \right|}{1000} \times 100\% \qquad (3)$$

To solve the optimization problem, the parameter determination method suggested in Liu *et al*. was used [10]. A *MAE* of 2% was used to stop the optimization procedure, which was accurate enough for the arterial waveform fitting.

2.4. *Data and statistical analysis*

Mean and standard deviation (SD) of the nine Gaussian parameters (the peak amplitude, peak time and half-width from each of the three Gaussian functions) were calculated across all the subjects, as well as for the age and MAP groups respectively. Next, regression analysis was performed to determine the effect of age and MAP on the nine Gaussian parameters, with the correlation equations, correlation coefficient R values and P values obtained. Finally, the differences between two age groups and between two MAP groups were calculated and compared. All the statistical tests were performed using the SPSS 19.0 software package (SPSS). A value of $P<0.05$ was considered statistically significant.

3. Result

3.1. *Effect of age*

Figure 2 gives a comparison between Gaussian fitting on a young and old subject. As shown in Table 2 and Figure 3, the peak amplitude of the first and third Gaussians had negative correlation with age whereas the peak amplitude of the second Gaussian had positive correlation (all significant, $P<0.01$). In addition, the peak time between the first and third Gaussians had significant negative correlation with age($P<0.01$), which is shown in Figure 4. Consequently, younger group in comparison with older group had higher peak amplitude of the first and third Gaussians, lower peak amplitude of the second Gaussian, and longer peak time interval between the first and third Gaussian curve(all significant, $P<0.05$).

Figure.2 Comparison between Gaussian fitting on 35 years subject with MAP 87mmHg (left) and a 55 year subject with MAP 97mmHg (right).
Show in Appendix

Table 2 Correlation results between Gaussian characteristics and age and comparison between the two age groups
Show in Appendix

Figure.3. (A1-A3) Relationship between peak amplitudes (H_1, H_2 and H_3) of the three Gaussians functions and age.(B1-B3) Comparison of peak amplitudes of the three Gaussians functions between the two age groups. Their mean±SD are given.
Show in Appendix

Figure.4. (A1-A2) Relationship between peak time intervals of Gaussian functions and age.(B1-B2)Comparison of peak time intervals of three Gaussians functions between the two age groups. Their mean±SD are given. n2-n1 is the time peak time interval between first and second Gaussian curves, and n3-n1 is the time peak time interval between first and third Gaussian curves.
Show in Appendix

3.2. *Effect of MAP*

As shown in Table 3 and Figure 5 and 6, the peak amplitude of the first Gaussian had significant negative correlation with MAP($P<0.01$). The peak time interval between the first and second Gaussians had significant positive correlation with MAP ($P<0.05$). When compared with higher MAP group, lower MAP group had significantly higher peak amplitude of the first Gaussian, significantly shorter peak time interval between the first and second Gaussian curve (all $P<0.05$).

Table 3 Correlation results between Gaussian characteristics and MAP, and comparison between the two MAP groups.
Show in Appendix

Figure.5. (A1-A3) Relationship between peak amplitudes (H_1, H_2 and H_3) of three Gaussians functions and MAP. (B1-B3) Comparison of peak amplitudes of three Gaussians functions between the two MAP groups. Their mean±SDs are given.
Show in Appendix

Figure.6. (A1-A2) Relationship between peak time intervals (n_2-n_1, n_3-n_1) of Gaussian functions and MAP.(B1-B2) Comparison of peak time intervals of three Gaussians functions between the two MAP groups. Their mean±SD are given. n_2-n_1 is the time peak time interval between first and second Gaussian curves, and n_3-n_1 is the time peak time interval between first and third Gaussian curves.
Show in Appendix

4. Discussion and conclusion

In this study, Gaussian modeling method was used to model the finger PPG pulse signals. Nine modelling characteristics from three Gaussian functions has been extracted with their relationships with age and blood pressure determined. Our study confirmed that Gaussian modeling could be a useful tool to analyze the PPG pulse waveform.

As traditionally accepted, the first Gaussian curve is more likely to be linked with the ejection wave of left ventricle [10]. The second Gaussian curve is possibly associated with reflection waveform and the third Gaussian curve associated with the second rise in early diastole after the incisura, which signifies aortic valve closure [17].

In this study, significantly lower peak amplitudes of the first Gaussian have been found in older and higher MAP groups, which agreed with the physiological study reported by Allen [18]. In older and higher blood pressure groups, the decrease of H_1 may reflect left ventricle function declines. Higher peak amplitude of the second Gaussian (H_2) in older group may indicate the amplitude of reflection wave increase as aging. Our results were also similar with the work from Millasseau [19], where increasing vascular tone was founded as ratio of H_1 and H_3 has negative correlation with aging. In addition, we also found significantly shorter peak time of the third Gaussian curve in both older and higher MAP groups, which was consistent with the study from Padilla [13]. With the process of ageing and hypertension, a forward shift of the backward wave is caused by arterial stiffening.

It is noted that the effects of age and MAP on Gaussian modelling of the finger PPG waveform were not exactly the same. Both factors have similar effect on H_1, which as a reflection of left ventricle function. However, the second Gaussian curve associated with backward waveform has different effect from aging and blood pressure. The amplitude of reflection wave increased with age while the position and duration of reflection wave change with blood pressure. A further investigation needs to be followed to understand the potential different effect of aging and blood pressure on arterial pulse waveform change.

Some further investigation could be performed in the future. Previous work from Liu *et al.* employed advanced particle swarm optimizer to achieve more accurate and waveform fast fitting [20].This would help the implementation of its clinical application. In addition, linking PPG pulse signals used in this study with brachial artery blood pressure pulses using Gaussian modelling methods would help understand the physiological relationship between the two pulse waveforms.

In conclusion, the effects of age and blood pressure on Gaussian modelling characteristics of the finger PPG pulse waveform has been determined with their physiological explanations provided. The current study extended the clinical application of Gaussian modelling for the arterial pulse analysis and provided better understanding of the underlying physiological mechanisms of the finger PPG pulse.

Acknowledgements

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6. Appendix

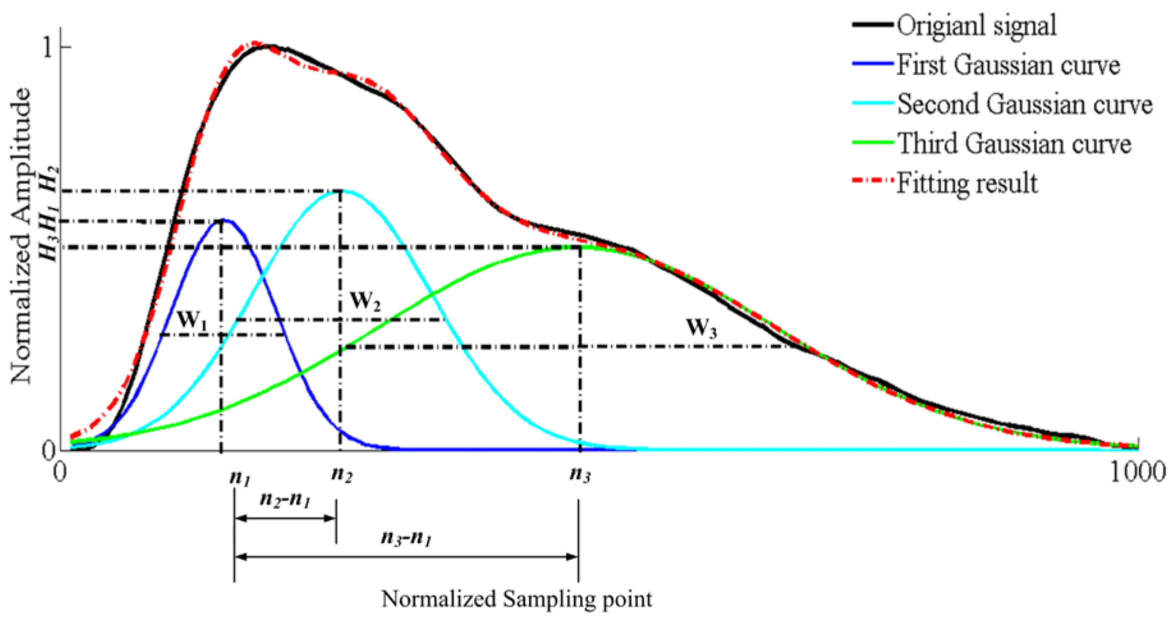
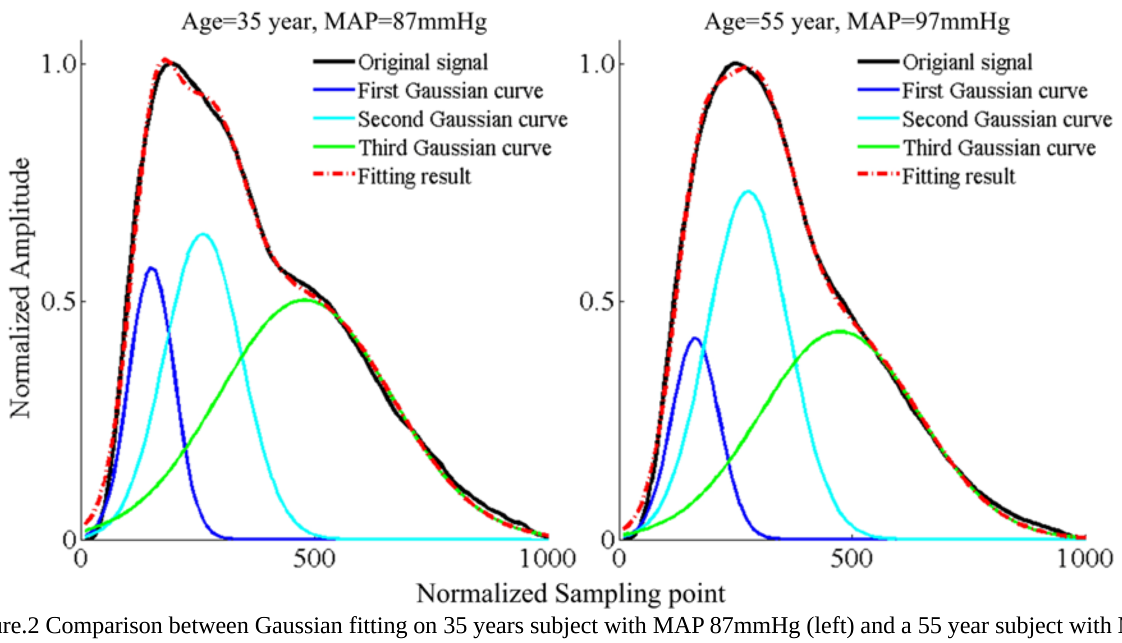


Figure.1 Demonstration of Gaussian fitting for one example finger PPG waveform.



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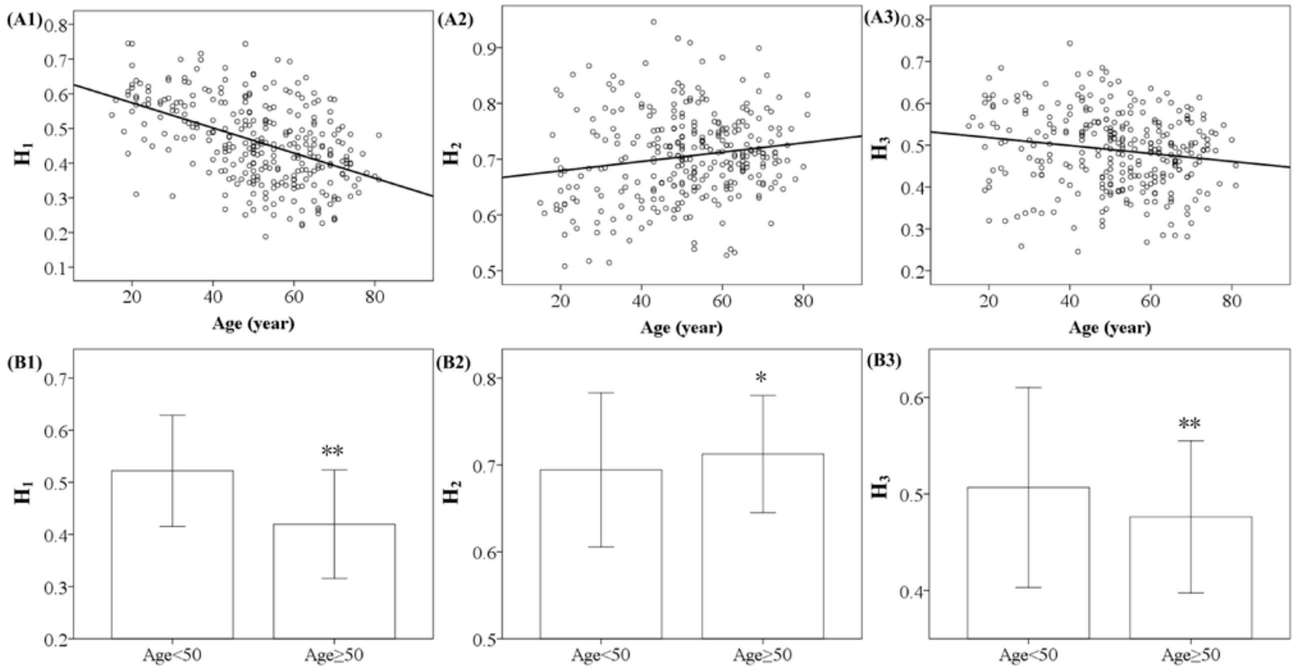

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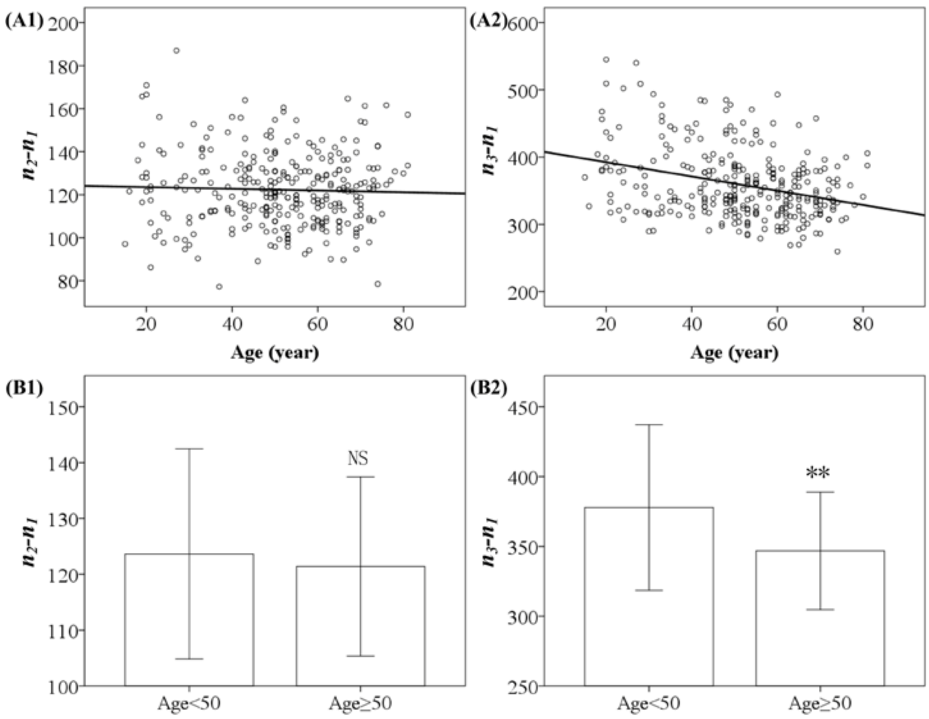

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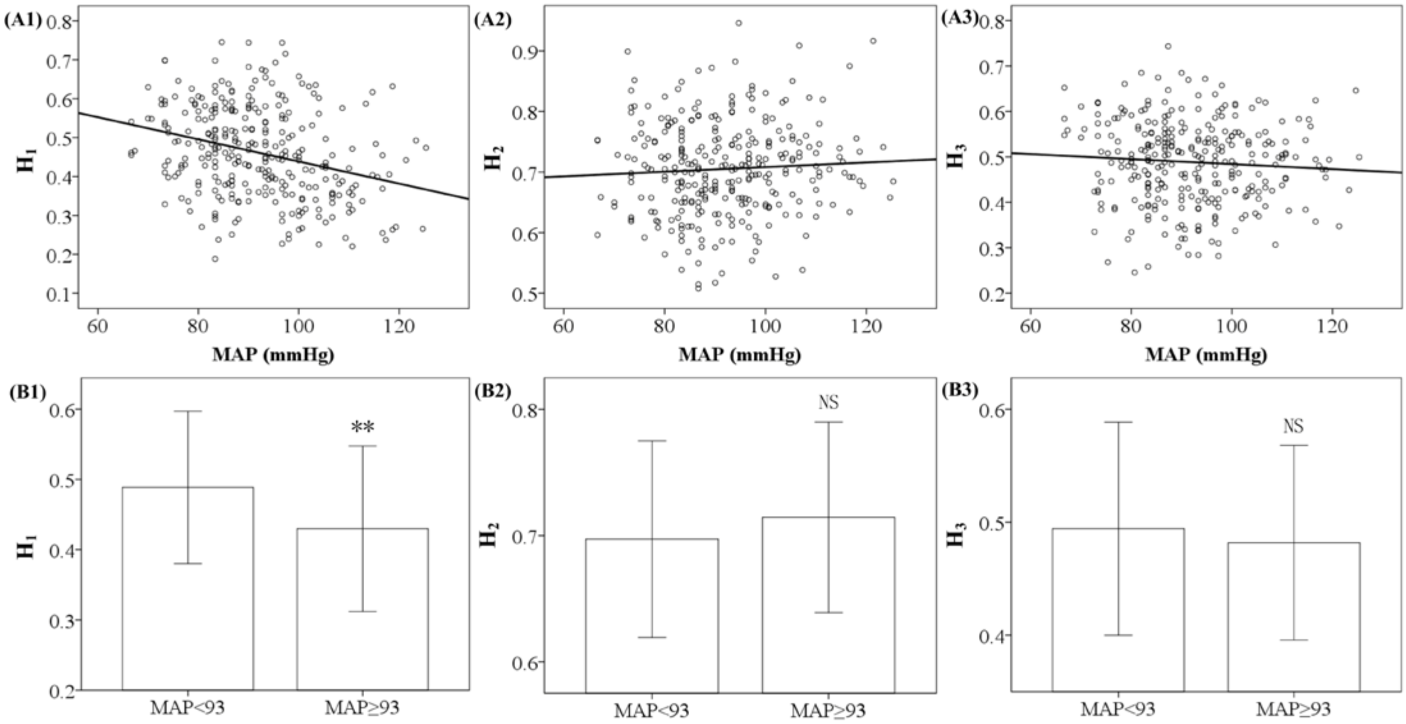

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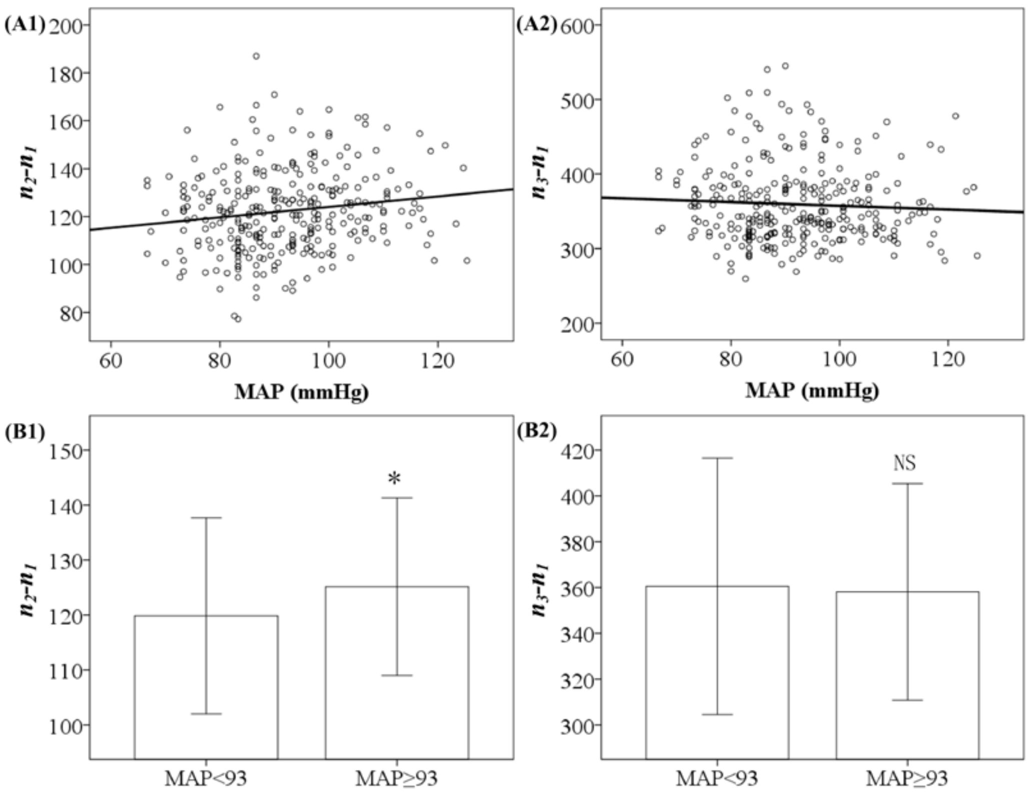

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Table1 Basic clinical information of the subjects studied

Variables	Overall	Age group			Blood pressure group		
		age<50 year	age≥50 year	*P*	MAP<93 mmHg	MAP≥93 mmHg	*P*
No.	300	122	178	-	161	139	-
Male/Female	156/144	59/63	97/81	-	78/83	78/61	-
Age (year)	51±15	36±10	61±8	<0.01	46±16	56±12	<0.01
Height (cm)	165±8	167±8	164±8	<0.05	164±9	166±8	0.2
Weight (kg)	68±13	67±15	68±12	0.4	66±13	70±13	<0.01
SBP (mmHg)	126±19	117± 14	132±19	<0.01	113±11	140±14	<0.01
DBP (mmHg)	75±11	75±11	75±11	0.2	68±7	84±8	<0.01
MAP (mmHg)	92±12	89±11	94±12	<0.01	83±6	103±8	<0.01
HR (beat/min)	71±12	73±12	70±11	0.2	70±12	72±12	0.1

Table 2 Correlation results between Gaussian characteristics and age and comparison between the two age groups

Characteristics		Correlation with age			Comparison between age groups		
		Equations	r	*P*	Age<50 year	Age≥50 year	*P*
Peak amplitude	H_1	H_1=-0.004×age+0.65	-0.48	<0.01**	0.52±0.10	0.42±0.11	<0.01**
	H_2	H_2=0.001×age +0.66	0.17	<0.01**	0.69±0.09	0.71±0.07	<0.05*
	H_3	H_3=-0.001×age +0.54	-0.16	<0.01**	0.51±0.10	0.48±0.08	<0.01**
Peak time	n_1	-	-	0.1	141±19	140±21	0.5
	n_2	-	-	0.2	265±34	261±32	0.3
	n_3	n_3=-1.176×age +559.81	-0.28	<0.01**	519±74	486±57	<0.01**
Half-width	W_1	-	-	0.1	149±23	147±25	0.5
	W_2	-	-	0.9	263±40	263±33	0.9
	W_3	-	-	0.6	525±48	526±39	0.7

Table 3 Correlation results between Gaussian characteristics and MAP, and comparison between the two MAP groups.

Characteristics		Correlation with MAP			Blood pressure group		
		Equations	r	*P*	MAP<93 mmHg	MAP≥93 mmHg	*P*
Peak amplitude	H_1	H_1=-0.003×MAP+0.72	-0.30	<0.01**	0.49±0.11	0.43±0.12	<0.01**
	H_2	-	-	0.3	0.70±0.08	0.71±0.07	0.1
	H_3	-	-	0.2	0.49±0.09	0.48±0.09	0.2
Peak time	n_1	-	-	0.3	139±21	141±19	0.3
	n_2	n_2=0.329×MAP +232.41	0.12	<0.05*	259±35	267±29	<0.05*
	n_3	-	-	0.6	500±71	500±59	0.9
Half-width	W_1	-	-	0.1	146±25	150±23	0.1
	W_2	W_2=0.425×MAP +223.61	0.15	<0.05*	259±37	267±33	<0.05*
	W_3	-	-	0.3	524±47	529±37	0.3