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Influence of aging and increased blood pressure on oscillometric cuff pressure waveform characteristics

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Abstract

Objective: The oscillometric blood pressure (BP) measurement technique estimates BPs from analyzing the envelop of oscillometric cuff pressure waveform. The oscillometric waveform envelope shape is associated with physiological changes and influences BP measurement accuracy. The aim of this study was to comprehensively quantify BP- and age-related changes of oscillometric waveform envelope characteristics.

Methods: Manual systolic and diastolic BPs were measured from 472 subjects (219 female, 253 male), and the cuff pressure were digitally recorded during linear cuff deflation that was used to derive oscillometric waveform envelopes. All subjects were divided into different categories according to their BP level and age. The envelope width in high-pressure region (above mean arterial pressure, MAP) and low-pressure region (below MAP) were compared between different BP and age categories to qualify their changes with increased BP and aging.

Results: The envelop widths increased significantly with increased BPs ($P < 0.001$ between optimal, normotensive and hypertensive groups) and aging ($P < 0.001$ for 50+ years old group in comparison with younger groups). The envelope widths in high-pressure region were significantly larger than in low-pressure region in normal and hypertensive categories (all $P < 0.05$) and elderly subjects aged over 60 years (all $P < 0.001$), and the envelope width ratios between them increased with increased BP and aging.

Conclusion: This study has concluded an asymmetrical oscillometric waveform envelope in normotensive and hypertensive categories, as well as in elderly group (aged over 60 years), and their asymmetrical features were significantly more obvious with increased BP and aging.

Introduction

High blood pressure (BP) is the primary risk factor of cardiovascular disease, contributing to the greatest global burden of disease.[1, 2] BP measurement helps to identify the presence of high BP, which contributes to better BP management and reducing the risk of future cardiovascular events.[3, 4] The oscillometric BP measurement method is the most common non-invasive technique for automatic BP measurement, which has been widely used for clinical practice and home monitoring.

During oscillometric BP measurement, an inflatable cuff is wrapped around the upper arm. The operator inflates the cuff to block blood flow and then releases the cuff pressure linearly and slowly (2-3 mmHg/s). During cuff deflation, the amplitude of the oscillometric pulse waveform increases to a maximum, and then decreases with further deflation of cuff pressure, resulting in a bell-shaped oscillometric waveform envelope. The oscillometric method determines mean arterial blood pressures (MAP) from the cuff pressure when the amplitude of oscillometric waveform envelope is maximal, and then mathematically computes systolic and diastolic blood pressures (SBP and DBP) using empirical ratios derived from the oscillometric waveform envelope.[5, 6] The shape of the oscillometric waveform envelope could significantly influences the BP measurement accuracy, which has been confirmed that the differences between oscillometric and the reference manual auscultatory methods are partially caused by more complex shapes and broader plateau of oscillometric waveform envelope.[7, 8] Therefore, it is physiologically and clinically important to investigate how oscillometric waveform envelope changes with associated factors, which would provide valuable physiological information or fundamental basis to improve BP measurement accuracy.

Gui *et al*. has investigated the effect of respiration on oscillometric waveform envelope and quantified its effect in BP measurement.[9] Ng *et al*. found that the cuff size could also affect the oscillometric waveform envelope and hence BP measurement result.[10] Our pilot study with twenty healthy normotensive and hypertensive found the asymmetrical feature of the oscillometric waveform envelope in both groups, which preliminarily indicated BP is an important factor influencing the shape of oscillometric waveform envelope.[11] Aging has been reported as a potential factor for arterial pulse shape changes, and hence the oscillometric pulse.[12-16] As the oscillometric waveform envelope is extracted and constructed from the oscillometric pulses, aging may affect the oscillometric waveform envelope shape. However, to the best of our knowledge, there is no study that comprehensively investigates the effect of BP and aging on the oscillometric waveform envelope. This is the aim of this study.

Methods

Subjects and manual blood pressure measurement

Manual BP measurements were performed on 472 subjects (46.4% female, age of 55 ± 17 years, body mass index of 27.2 ± 5.1 kg/m^2 and 47.9% hypertensive) following the guideline from British Hypertension Society and American Heart Association.[17, 18] Prior to the measurement, each subject had been asked to rest on a chair for 5 minutes and breathe gently during the whole measurement. For each subject, there were two repeated manual auscultatory BP measurements with a one-minute interval between them. Manual auscultatory SBP and DBP were determined from the appearance and disappearance of the Korotkoff sound, respectively. All BP measurements were measured in a quiet and temperature-controlled clinical measurement room by two trained observers simultaneously with a clinically validated manual electronic sphygmomanometer (Accoson Greenlight 300; AC Cossor & Son (Surgical) Ltd, Harlow, UK). Each pair of manual BP measurements from two trained operators was reviewed. If the observers' BP reading disagreed with > 4 mmHg in SBP or DBP, another BP measurement was taken. According to the statistical analysis, there was no significant manual BP difference (for both SBP and DBP) between the readings from the two observers. The mean BP values obtained from the two observers were then used as the reference BP for that measurement of each individual, which was used for the following group classification process.

All subjects were classified into three BP categories: optimal (SBP < 120 and DBP < 80 mmHg), normal (SBP 120 -139 and/or DBP 80 - 89 mmHg) and hypertension (SBP ≥ 140 and/or DBP ≥ 90 mmHg) categories and five age groups (≥ 70, 60 – 69, 50 – 59, 40 -49 and < 40 years).[19] The detailed subject demographic information including age, gender, height, weight, arm circumference, BP, body mass index, BP distribution and age distribution are summarized in Table 1. All subjects gave their written informed consent to participate. The study received ethical permission from the Newcastle & North Tyneside Research Ethics Committee. The investigation conformed with the principles in the Declaration of Helsinki. All the analysis involved were performed on anonymized data.

Table 1. Baseline characteristics of the study subjects.

Characteristics	
Total No. of subject	472
Female	219 (46.4)
Male	253 (53.6)
Age (years)	55 ± 17
Biomarkers	
Height (cm)	168.6 ± 10.4
Weight (kg)	77.4 ± 16.7
Arm circ (cm)	28.8 ± 3.3
SBP (mmHg)	136.7 ± 24.3
DBP (mmHg)	80.2 ± 13.9
Body mass index (kg/m^2)	27.2 ± 5.1
BP distribution	
Optimal	108 (22.9)
Normal	138 (29.2)
Hypertension	226 (47.9)
Age distribution	
≥ 70 years	117 (24.8)
60 – 69 years	96 (20.3)
50 – 59 years	92 (19.5)
40 – 49 years	75 (15.9)
< 40 years	92 (19.5)

Values are n (%) or mean ± SD

Cuff pressure recording

During each manual auscultatory BP measurement, an automatic and programmable air pump was used to firstly inflate the cuff, and then deflate linearly at the recommended rate of 2-3 mmHg/s. The cuff pressure was recorded by a pressure sensor connected to the cuff via a tube, and then converted to digital signals with a sampling rate of 2000 Hz and a resolution of 16 bits. The final digital cuff pressure signals were stored in a computer for off-line processing and analysis. Totally, there were 944 cuff pressure recordings (from 472 subjects * 2 repeated measurement) in this study.

Oscillometric waveform analysis

Oscillometric waveform envelope extraction

A custom software was developed using MATLAB (MathWorks Inc, Natick, MA, USA) to extract the oscillometric pulses from the recorded cuff pressure after segmenting each pulse and removing the baseline cuff pressure. The oscillometric waveform envelope was obtained by fitting a sixth-order polynomial model to the extracted oscillometric pulse peak amplitude, which was plotted against the baseline cuff pressure. The oscillometric waveform envelope was then normalized to the maximum amplitude of the waveform envelope. Figure 1 demonstrates three typical examples of the oscillometric waveforms and their envelops from hypertensive, normal and optimal subjects.

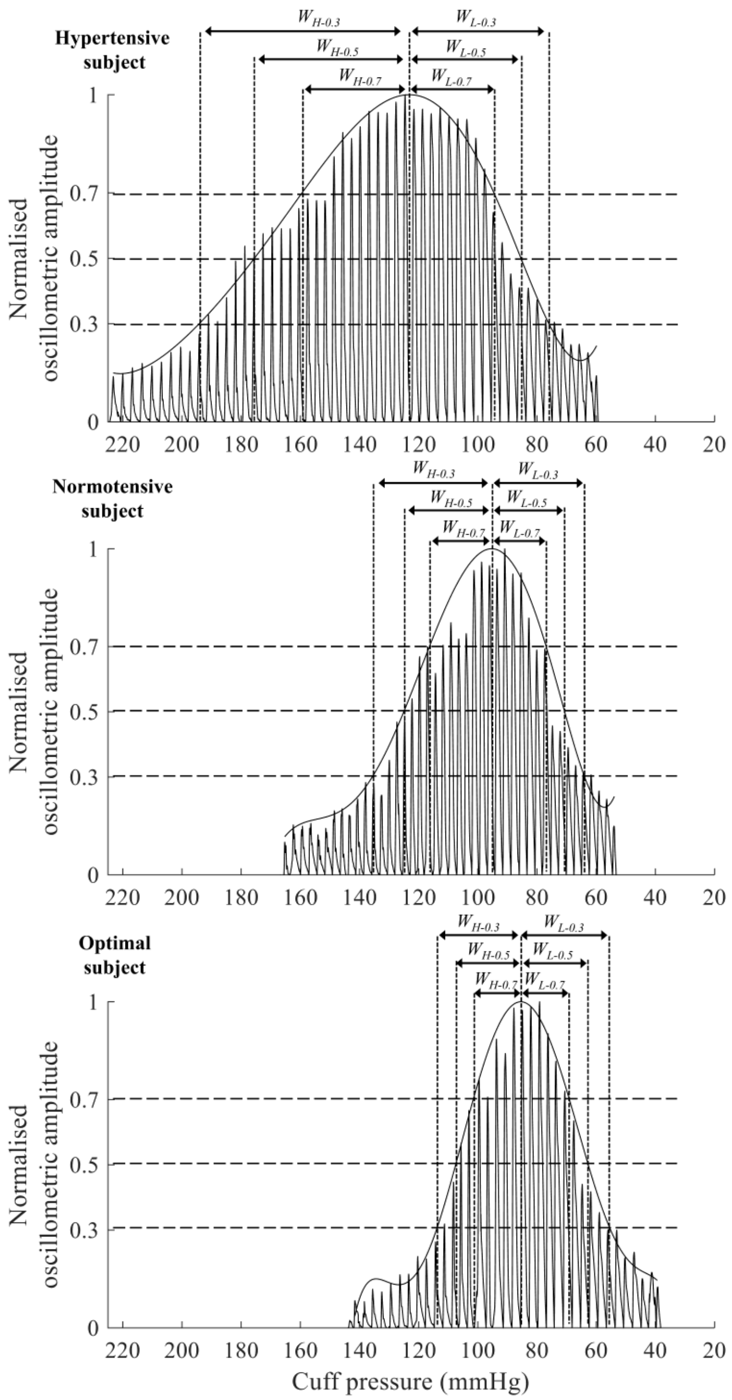

Figure 1. Typical oscillometric waveforms and their envelopes from hypertensive, normal and optimal subjects. The calculation method for the envelope widths in the high and low pressure regions (W_{H} and W_{L}) with the threshold of 0.3, 0.5 and 0.7 are also given respectively.

Envelope widths calculation

The cuff pressure corresponding to the maximum oscillometric envelope amplitude was taken as the MAP. The envelope widths were defined as the cuff pressures corresponding to three thresholds (0.3, 0.5 and 0.7) of the normalized oscillometric envelope amplitude, which were measured for both the high-pressure region (region of pressure > MAP) and low-pressure region (region of pressure < MAP). At each of the three thresholds, the envelope widths (absolute pressure difference referenced to the MAP) were named as W_{H} and W_{L} for the high-pressure region and low-pressure regions, respectively. The calculation method of the envelope widths is illustrated in Figure 1.

Data and statistical analysis

There are two repeat measurements for each subject and therefore in total there was 944 SBP, 944 DBP values and 944 cuff pressure recordings (from 472 subjects * 2 repeats). The SPSS Statics 19 software package (SPSS Inc, Chicago, IL, USA) was used to perform the repeated measures analysis of variance to study the measurement repeatability and a value of $P < 0.05$ was considered to be significantly different. Statistical analysis showed that there was no significant envelope width difference between the two repeat measurements. The average envelope widths from the two repeat measurements in each subject were used for the following data and statistical analysis.

The means and SDs of envelope widths (W_H and W_L) in the high and low pressure regions and their ratios (W_H / W_L) between the two regions were calculated, respectively for the three thresholds (0.3, 0.5 and 0.7), three BP categories (optimal, normal and hypertensive) and five age categories (≥ 70, 60 – 69, 50 – 59, 40 -49 and < 40 years). Analysis of variance (ANOVA) with post-hoc multiple comparisons was applied to investigate the effect of BP categories on the envelope widths at each of the three thresholds (0.3, 0.5 and 0.7) and compare the difference among different BP categories. Similar analysis was performed to investigate the aging effect.

Results

Comparison of envelope widths among different BP categories

It can be observed from Figure 2 that, at both high and low pressure regions, the envelope widths corresponding to the three thresholds (0.3, 0.5 and 0.7) from normal and hypertensive BP category groups were significantly larger than those from the optimal category (all $P < 0.001$), and those from hypertensive BP category were significantly larger than those from the normal category (all $P < 0.001$). This suggested that the width of oscillometric waveform envelope increased significantly with increased BPs.

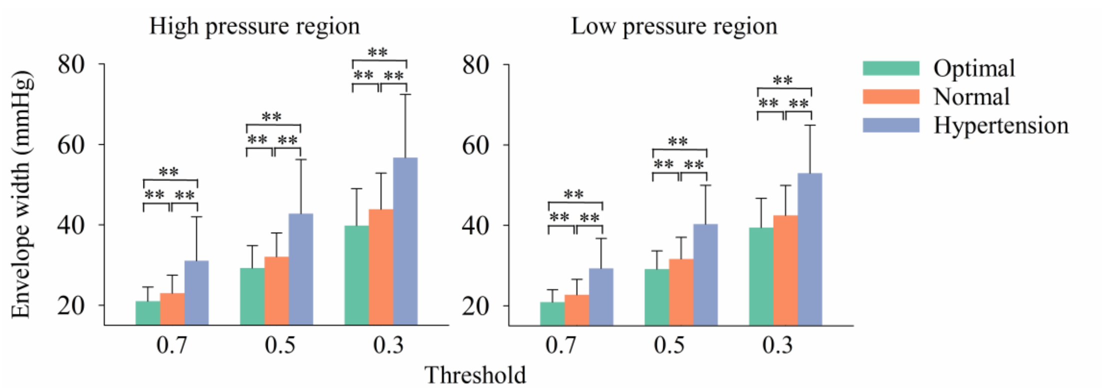

Figure 2. Overall mean ± SD of the envelope width at the three thresholds (0.3, 0.5

and 0.7) for both high and low pressure regions. **Significant difference between comparisons, $P < 0.001$.

Comparison of envelope widths between high and low pressure regions among different BP categories

As shown in Figure 3 and Table 2, for the optimal BP category, there were no significant differences of envelope width between the high and low pressure regions (all $P > 0.05$) at all the three thresholds levels (characteristic ratios of 0.7, 0.5 and 0.3), suggesting the symmetry of oscillometric waveform envelope in this category.

Whereas, for the normal and hypertension categories, the envelope widths in the high-pressure region were significantly larger than in the low-pressure region (the ratios between high and low pressure region were statistically significantly larger than 1, all $P < 0.05$) at all the three thresholds, indicating an asymmetrical feature of the oscillometric waveform envelope in the two BP categories. Moreover, from the hypertension category, because the envelope width in the high-pressure region increased more with increased BPs than in the low-pressure region, the width ratios were significantly larger than those of normal and optimal categories (all $P < 0.001$), suggesting the asymmetrical feature of the oscillometric waveform envelop was significantly more obvious with increased BPs.

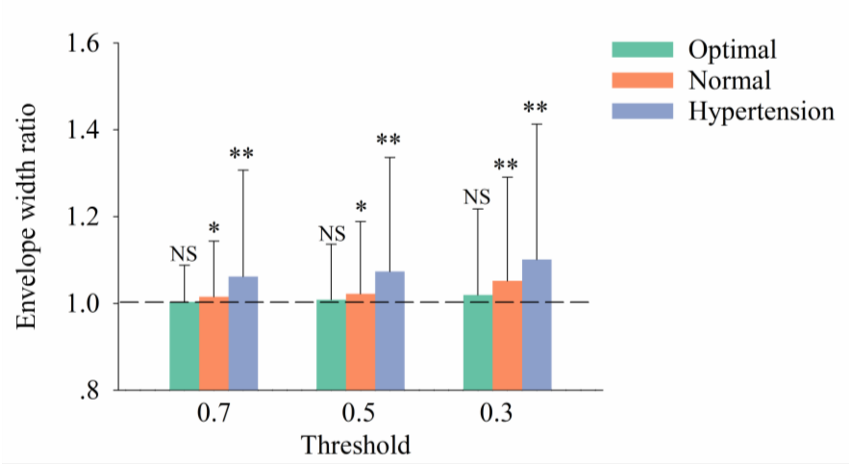

Figure 3. Overall mean ± SD of the ratios of envelope width between the high and low pressure region at the three thresholds and different BP categories. *Significant difference between high and low pressure regions, $P < 0.05$. ** $P < 0.001$.

Table 2. Comparison of envelope width ratios (the ratio between high and low pressure regions, W_H / W_L) among different BP categories at the three thresholds. *Significant difference between comparisons, $P < 0.05$. ** $P < 0.001$. NS: No significant difference.

Threshold	**0.7**			**0.5**			**0.3**		
BP categories	O	N	H	O	N	H	O	N	H
O	-	NS	**	-	NS	**	-	*	**
N	NS	-	**	NS	-	**	*	-	**
H	**	**	-	**	**	-	**	**	-

O for Optimal, N for Normal, H for Hypertension

Comparison of envelope widths among different age categories

It can be observed from Figure 4 that, at both high and low pressure regions, there were no significant differences of envelope width between the two categories aged less than 50 years corresponding to the three thresholds (0.3, 0.5 and 0.7). The envelope widths of the categories aged over 50 years (50 - 59 years, 60 – 69 years and ≥ 70 years) were significantly larger than those of the categories aged less than 50 years (all P <

0.001). This suggested that the width of oscillometric waveform envelope increased significantly with aging.

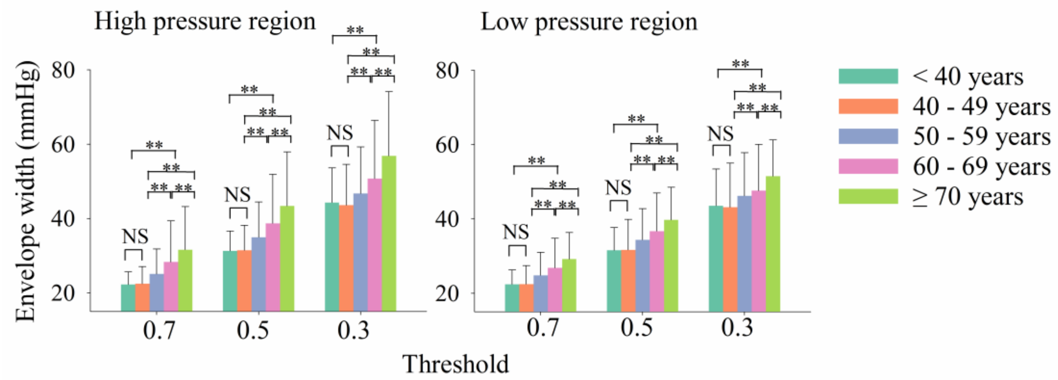

Figure 4. Overall mean ± SD of the envelope width at three thresholds for both high pressure region and low pressure region. **Significant difference between comparisons, $P < 0.001$.

Comparison of envelope widths between high and low pressure regions among different age categories

As presented in Figure 5 and Table 3, for all the three thresholds, the envelope width between high and low pressure regions were not significantly different for subjects aged less than 60 years (all $P > 0.05$, except the two categories aged less than 50 years at threshold of 0.3), indicating the symmetry of oscillometric waveform envelope in these categories (<40, 40-49 and 50-59 years old).

Whereas, for subjects aged over 60 years the envelop widths in the high-pressure region were significantly larger than in the low-pressure region (the envelope width ratio > 1, all $P < 0.001$) at all three thresholds. For the two categories aged over 60 years, the envelope width ratios were significantly larger than those of three categories aged less than 60 years, suggesting the asymmetry of the oscillometric waveform envelop was significantly obvious with aging.

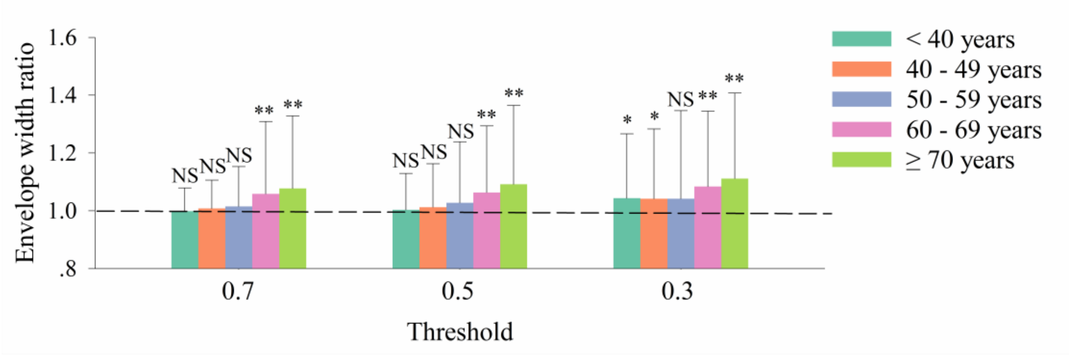

Figure 5. Overall mean + SD of the ratios of envelope width between the high and low pressure region at three thresholds and five different age categories. *Significant difference between comparisons, $P < 0.05$. ** $P < 0.001$.

Table 3. Comparison of envelope width ratios (the ratio between high and low pressure regions, W_H / W_L) among different age categories, respectively for the three thresholds. *Significant difference between comparisons, $P < 0.05$. ** $P < 0.001$.

Threshold			**0.7**		
Age categories	< 40	40 - 49	50 - 59	60 - 69	≥ 70
< 40	-	NS	NS	**	**
40 - 49	NS	-	NS	**	**
50 - 59	NS	NS	-	**	**
60 - 69	**	**	**	-	NS
≥ 70	**	**	**	NS	-
Threshold			**0.5**		
Age categories	< 40	40 - 49	50 - 59	60 - 69	≥ 70
< 40	-	NS	NS	**	**
40 - 49	NS	-	NS	*	**
50 - 59	NS	NS	-	*	**
60 - 69	**	*	*	-	NS
≥ 70	**	**	**	NS	-
Threshold			**0.3**		
Age categories	< 40	40 - 49	50 - 59	60 - 69	≥ 70
< 40	-	NS	NS	*	**

40 - 49	NS	-	NS	*	**
50 - 59	NS	NS	-	*	**
60 - 69	*	*	*	-	NS
≥ 70	**	**	**	NS	-

Discussion

This study has quantified that the oscillometric waveform envelope widths increased significantly with increased BP and aging. This could be explained by that the envelope widths are positively related to the pulse pressure (PP, PP = SBP - DBP).[20] It is expected that wider envelope width is associated with higher PP. Since PP is always larger in people with high BP especially isolated systolic hypertension,[21] they are more likely to have wider envelope width. In term of the influence of aging, our results agreed with published studies where they concluded that PP increased with aging[22], resulting in wider oscillometric waveform envelope width as demonstrated in this study. One observational finding from this study is that the significant widening of envelope widths occurred over aged 50 years. This finding agreed with Skurnick's study where the PP swings upward more rapidly from age 40 years.[23]

Another finding in this study is that, the asymmetry of oscillometric waveform envelope was observed in higher BP categories (normal and hypertension) and in elderly subjects (>60 years old). It is known that the oscillometric waveform envelope maximum occurs when the transmural pressure (internal arterial pressure - external cuff pressure) is zero.[24, 25] Therefore, there is a negative transmural pressure region (internal arterial pressure < external cuff pressure) at the high-pressure region as defined in our study, while at the low-pressure region, there is positive transmural pressure across the arterial wall. One possible explanation of the asymmetry in high BP (normal and hypertension) and elderly subjects is that the artery compliance behaves with changing pressure is different between negative and positive transmural pressure region. Anand *et al*. has proposed a parametric model to study the relationship between transmural pressure and artery compliance (P - C) and the artery compliance curve was plotted as an asymmetric bell-shaped curve, where the arterial compliance changed rapidly during negative transmural pressure region, whereas changed slowly during positive transmural pressure region.[26] Our results supported their further study where they derived a model of oscillogram (amplitude of the oscillometric pulse), and the oscillogram was a left-skewed curve associated with external pressure, which is consistent with our result of asymmetry.

More interestingly, our results provide clinical evidence of that the asymmetric features of oscillometric waveform envelop increased with increased BP and aging. The oscillometric waveform envelope of subjects under the age of 60 is close to symmetry, while those of elderly subject (> age of 60) are significantly asymmetry. This could be associated with how artery compliance behaves with increased BP and aging, suggesting that there is physiological relationship between oscillometric waveform envelope shape and artery compliance behavious difference (between negative and positive transmural pressure region) with increased BP and aging. Some future theoretical and experimental studies is required to confirm whether the oscillometric waveform envelope shape information (envelope width and its asymmetry information) can serve as markers to evaluate arterial compliance and future vascular injury or cardiovascular events.

In conclusion, the effects of increased BP and aging on oscillometric waveform envelope shape have been quantified in this study. It demonstrated for the first time that the asymmetry of oscillometric waveform envelop increased with higher BP and aging. These changes could be theoretically linked with how artery compliance changes with BP and aging, providing a potential method to evaluate arterial compliance based on the analysis of oscillometric waveform envelope shape.

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Disclosures

All authors declare that we have no conflicts of interest, and this study has no relationships with industry.

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