Biomechanical properties of the ascending aorta in patients with primary hypertension by velocity vector imaging

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Research Article

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Abstract

Objective: To evaluate the biomechanical properties of the ascending aorta (AA) in patients with primary hypertension (PH) by velocity vector imaging (VVI).

Methods: Fifty patients with PH and 53 normal healthy control participants were prospectively enrolled. AA biomechanical properties, i.e., ascending aortic global longitudinal strain (ALS), ascending aortic global circumferential strain (ACS), and fractional area change (FAC), were evaluated by VVI. Pulse pressure (PP) was calculated. Distensibility (D) and stiffness index (SI) of AA were also obtained.

Results: The ALS, ACS and FAC in the PH group were significantly lower than those in the control group (31.8%±10.3% vs. 38.6%±14.7%, 10.5%±3.5% vs. 13.8%±4.2%, 20.7%±5.5% vs. 28.5%±6.2%, respectively, all p<0.05). There were significant associations between biomechanical properties and D, SI and PP (ALS and D: r 0.621, ALS and SI: r -0.556, ALS and PP: r -0.526, ACS and D: r 0.653, ACS and SI: r -0.634, ACS and PP: r -0.513, FAC and D: r 0.622, FAC and SI: r -0.600, FAC and PP: r -0.459, respectively, p<0.05).

Conclusions: The biomechanical properties of AA were impaired in patients with PH and correlated with pulse pressure and stiffness.

Introduction

Aortic stiffness is a common clinical feature in patients with hypertension and plays a key role in the occurrence and development of hypertension (1). It is also an important risk factor for cardiovascular events and morbidity (2). The total hypertensive population is predicted to reach 1.56 billion by 2025 in the world (3). Increased aortic stiffness, which may complicate the control of blood pressure, is direct evidence of target organ damage and hinders optimal ventricular–vascular coupling and left ventricular function (4). Monitoring of aortic stiffness may prevent the misclassification of asymptomatic hypertensive patients as low risk (5). Clinical guidelines classify increased aortic stiffness as a negative factor to be considered in the management of patients with hypertension (6).

Although there was a comprehensive study that evaluated aortic elasticity in hypertensive patients, few studies have reflected aortic elasticity from the perspective of biomechanics. Pulse wave velocity (PWV) is the recommended gold standard measurement of arterial stiffness, but it is not widely used because of the limitation of available equipment. Using the biomechanical properties of the aorta to evaluate the function of the vascular wall has become one of the most valuable diagnostic methods (7–9). Velocity vector imaging (VVI) is a noninvasive and simple imaging method that can be used to automatically track aortic wall border detection and quantify instantaneous deformation in both the longitudinal and circumferential directions without angle dependence (10). Since 2009, VVI studies have successfully been used to evaluate vascular properties in patients with aortic valvular disease and Turner syndrome (11–12). However, until now, there have been few data about the biomechanical properties of the ascending aorta in patients with hypertension. Therefore, we aimed to evaluate the biomechanical characteristics of AA in
Materials And Methods

Study population

This prospective study was conducted with the permission of the Institutional Ethics Committee of Second Xiangya Hospital of Central South University. Patients with PH who visited our cardiovascular clinic from January 2021 to December 2021 were included in this study. The inclusion criteria were an SBP of at least 140 mmHg and/or a DBP of at least 90 mmHg on three consecutive occasions or an assumption based on use of antihypertensive medications \(^{13}\) with a course of less than 5 years. The exclusion criteria were as follows: poor image quality, secondary hypertension, congenital heart disease, hyperlipidemia, hypercholesterolemia, diabetes, cirrhosis, long-term smoking, chronic bronchus or lung diseases, biliary duct system diseases, immune-related diseases, severe arrhythmia, any valvulopathy more severe than mild, aortic valve malformation, and clinical characteristics suggesting aortic disease such as Marfan syndrome, Loeys–Dietz syndrome or Turner syndrome, long term medication, too high or short or narrow (posterior to the anterior diameter) of the body building. We enrolled healthy subjects matched for age, sex and body surface area from the Health Management Center as the control group. Informed consent was obtained from all subjects.

A detailed medical history inquiry and comprehensive examination were conducted for all subjects and included height and weight measurement, ECG examination, fasting blood sample collection, fasting blood glucose (FPG), glycosylated hemoglobin (HbA1c), total cholesterol (TCH), triglyceride (TG), high-density lipoprotein cholesterol (HDL-C) and low-density lipoprotein cholesterol (LDL-C). All blood pressure measurements were performed in a quiet environment according to the European Society of Hypertension/European Society of Cardiology (ESH/ESC) recommendations \(^{13}\). In the morning between 8 AM and 12 PM, prior to echocardiographic examination, systolic blood pressure (SBP) and diastolic blood pressure (DBP) were measured twice and averaged after the subject was allowed to lie in the supine position for 10 minutes at rest. The interval between the two measurements was > 5 minutes. Pulse pressure (PP) was calculated from the SBP and DBP.

Echocardiographic Study

All subjects were placed in a supine left lateral position and underwent ECG recording simultaneously. Standard transthoracic echocardiography was obtained on a Siemens S2000 ultrasound system (Axius, Siemens Medical Solutions, Malvern, PA, USA) by an experienced sonographer (XGQ) with a 4Px probe (2.75–4.25 MHz). All images and clips were stored in the echo machine for analysis. The left atrial diameter (LAD), LV end-diastolic diameter (LVEDD), interventricular septal thickness in diastolic (IVSD) and heart rate (HR) were all detected by M-mode tracing. The ejection fraction (EF) was estimated using
Simpson’s biplane method. Early (E) and late (A) diastolic transmitral velocities between the tips of the mitral leaflets were measured by pulsed Doppler. Early diastolic mitral annular velocity (e’) was obtained by tissue Doppler. The ratios of E/A and E/e’ were calculated. In the parasternal long-axis view, the M-mode tracings of the ascending aorta were obtained from 3 cm above the aortic annulus. The aortic diastolic diameter (AoD) and aortic systolic diameter (AoS) were measured. The stiffness and elastic parameters of the ascending aorta were calculated with the following formulas (14):

Aortic distensibility (D): \(2(AoS - AoD)/AoD(SBP - DBP)\)

Aortic stiffness index (SI): \(\ln (SBP/DBP)/(AoS - AoD)/AoD\)

### VVI Analysis

VVI images were obtained by an experienced sonographer (YL) who was blinded to the group status. The long axis and short axis of the ascending aorta were clearly displayed on the parasternal long-axis view of the left ventricle and the short-axis view of the great artery. The image was adjusted to ensure that the frame rate was between 60–90 frames. Two-dimensional images were continuously collected for three cardiac cycles, and VVI analysis software (Axius, Siemens Medical, Solutions) was started. The imaging was stopped in the early or middle stage of systole. On long-axis views, four sampling points were placed in the inner face of the ascending aorta (AA) walls. The first point was placed at the level of the sinotubular junction (STJ), and the others were placed at the same distance from each other to include approximately 4 cm of the AA. On short-axis views, we focused on the region of the AA approximately 2–3 cm above the aortic valve, with a line manually drawn along the inner aspect of the aortic wall in the short axis. The software tracks the intima of blood vessels in real time according to the marked points. The system automatically divides the region of interest, deletes two segments in the long-axis section, and divides the ascending aorta into the anterior wall and posterior wall. On the short-axis section, the ascending aorta was divided into the anterior wall, left lateral wall, posterior wall and right lateral wall (Supplementary Fig. 1). Strain curves corresponding to all segments of the ascending aorta were generated. The systolic strain of each wall of the ascending aorta was recorded. The ALS was the average of the maximum systolic strain peaks of the anterior and posterior walls of the ascending aorta; the ACS was the average of the maximum circumferential strain peaks of the four segments of the ascending aorta during systole. FAC referred to the change fraction of the cross-sectional area of the ascending aorta in a cardiac cycle. VVI analysis can automatically obtain the overall FAC of the aorta in the short-axis section.

### Statistical Analysis

All statistical analyses were performed using SPSS software version 20.0 (SPSS, Chicago, IL, USA). The Kolmogorov–Smirnov test was used to assess the normality of the continuous variables, and the results are presented as the mean ± SD if normally distributed or as the median and interquartile range if not. Categorical data are represented as percentages. Differences between the PH group and the control group
were compared with an independent t test and the chi-square test. A Pearson correlation analysis was performed to determine the relationships of AA biomechanical properties with conventional echo parameters and PP. Reproducibility of the measurements of the ALS, ACS and FAC by the VVI method was examined in 10 randomly selected cases. The Bland–Altman method was performed to test interobserver and intraobserver variability from the stored images of 40 randomly selected observations. Interobserver measurement was performed by YL and another fetal echocardiographer (YZR, who is not a coauthor), and intraobserver measurement was repeated by YL the next day. $P<0.05$ was considered indicative of statistical significance.

**Results**

**Population features**

We included a total of 124 subjects. Twenty-one people were excluded because the quality of the echocardiography images was too poor for further analysis by VVI. We ultimately included 103 participants: 53 controls and 50 patients with PH. The mean age of the subjects was 52.82 ± 7.68 years. The mean SBP, DBP, and PP were 126 ± 13, 78 ± 8 and 47 ± 9 mmHg, respectively. The course of hypertension ranged from 1 to 5 years. There was no significant difference between the two groups with regard to age, sex, smoking habits, BMI or heart rate (HR) ($P>0.05$). SBP and DBP were higher in PH patients than in controls (Table 1).
<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Control (n = 53)</th>
<th>PH (n = 50)</th>
<th>P value</th>
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</thead>
<tbody>
<tr>
<td><strong>Clinical characteristics</strong></td>
<td></td>
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<tr>
<td>Age (years)</td>
<td>51.23 ± 7.49</td>
<td>53.16 ± 8.27</td>
<td>0.328</td>
</tr>
<tr>
<td>Women, n (%)</td>
<td>27(50.9%)</td>
<td>24(48.0%)</td>
<td>0.653</td>
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<tr>
<td>BMI (kg/m2)</td>
<td>21.16 ± 0.78</td>
<td>20.49 ± 0.85</td>
<td>0.593</td>
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<tr>
<td>Smoking, n (%)</td>
<td>8(15.1%)</td>
<td>9(18.0%)</td>
<td>0.746</td>
</tr>
<tr>
<td>SBP (mmHg)</td>
<td>116 ± 10</td>
<td>135 ± 17</td>
<td>&lt;0.01</td>
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<tr>
<td>DBP (mmHg)</td>
<td>74 ± 7</td>
<td>81 ± 10</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>PP (mmHg)</td>
<td>42 ± 6</td>
<td>54 ± 13</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>HR (bpm)</td>
<td>68 ± 7</td>
<td>70 ± 9</td>
<td>0.593</td>
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<tr>
<td><strong>2D measurements</strong></td>
<td></td>
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<tr>
<td>LAD (mm)</td>
<td>27.81 ± 3.23</td>
<td>28.92 ± 4.14</td>
<td>0.189</td>
</tr>
<tr>
<td>LVEDD (mm)</td>
<td>45.64 ± 3.87</td>
<td>46.72 ± 4.04</td>
<td>0.654</td>
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<tr>
<td>IVSD (mm)</td>
<td>8.96 ± 0.98</td>
<td>9.54 ± 1.06</td>
<td>0.669</td>
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<tr>
<td>EF (%)</td>
<td>63.81 ± 3.40</td>
<td>64.92 ± 3.71</td>
<td>0.658</td>
</tr>
<tr>
<td>E/A</td>
<td>1.22 ± 0.15</td>
<td>1.15 ± 0.14</td>
<td>0.842</td>
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<tr>
<td>E/e'</td>
<td>7.16 ± 1.52</td>
<td>8.02 ± 1.64</td>
<td>0.035</td>
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<tr>
<td><strong>M-mode</strong></td>
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<tr>
<td>AoD (mm)</td>
<td>31.14 ± 1.57</td>
<td>31.66 ± 1.68</td>
<td>0.294</td>
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<tr>
<td>AoS (mm)</td>
<td>33.56 ± 1.69</td>
<td>33.62 ± 2.01</td>
<td>0.506</td>
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<tr>
<td>D (10^{-7} Pa^{-1})</td>
<td>182.71 ± 25.92</td>
<td>92.84 ± 24.33</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>SI (-)</td>
<td>4.56 ± 0.64</td>
<td>6.68 ± 1.29</td>
<td>0.035</td>
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<td><strong>VVI</strong></td>
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<td>ALS (%)</td>
<td>38.6 ± 9.7</td>
<td>31.8 ± 6.3</td>
<td>0.038</td>
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BMI, body mass index; SBP, systolic blood pressure; DBP, diastolic blood pressure; PP, pulse pressure; HR, heart rate; LAD, left atrial diameter; LVEDD, LV end-diastolic diameter; IVSD, interventricular septal thickness in diastolic; EF, ejection fraction; E/A, mitral early diastolic filling ratio; E/e', early diastolic mitral annular velocity; AoD, aortic diastolic diameter; AoS, aortic systolic diameter; D, distensibility; SI, stiffness index; ALS, ascending aortic global longitudinal strain; ACS, ascending aortic global circumferential strain; FAC, fractional area change.
### Characteristics

<table>
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<th>Control (n = 53)</th>
<th>PH (n = 50)</th>
<th>P value</th>
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</thead>
<tbody>
<tr>
<td>ACS (%)</td>
<td>13.8 ± 3.8</td>
<td>10.5 ± 3.1</td>
<td>0.030</td>
</tr>
<tr>
<td>FAC (%)</td>
<td>28.5 ± 4.5</td>
<td>20.7 ± 4.2</td>
<td>0.035</td>
</tr>
</tbody>
</table>

BMI, body mass index; SBP, systolic blood pressure; DBP, diastolic blood pressure; PP, pulse pressure; HR, heart rate; LAD, left atrial diameter; LVEDD, LV end-diastolic diameter; IVSD, interventricular septal thickness in diastolic; EF, ejection fraction; E/A, mitral early diastolic filling ratio; E/e’, early diastolic mitral annular velocity; AoD, aortic diastolic diameter; AoS, aortic systolic diameter; D, distensibility; SI, stiffness index; ALS, ascending aortic global longitudinal strain; ACS, ascending aortic global circumferential strain; FAC, fractional area change.

### Conventional Echocardiographic Evaluation And M-mode Measurements Of Aorta Elasticity

There was no significant difference in LAD, LVEDD, IVSD, EF, or E/A between the two groups (all P > 0.05). The E/e’ was higher in the PH group than in the control group. There was no difference in the AA inner diameter between the two groups. The distensibility of the AA was lower, whereas the stiffness index was higher, in the PH group than in the control group (Table 1).

### Measurements Of The Vvi Parameters

The ALS, ACS and FAC of the AA in the PH group were significantly lower than those in the control group (P < 0.05). (Table 1) (Fig. 1) (Fig. 2)

ALS showed a significant positive correlation with aortic D (r = 0.621, P < 0.05) and a negative correlation with SI (r=-0.556, P < 0.05) and PP (r=-0.526, P < 0.05). ACS showed a significant positive correlation with aortic D (r = 0.653, P < 0.05) and a negative correlation with SI (r=-0.634, P < 0.05) and PP (r=-0.513, P < 0.05). FAC showed a significant positive correlation with aortic D (r = 0.622, P < 0.05) and a negative correlation with SI (r=-0.600, P < 0.05) and PP (r=-0.459, P < 0.05). There were no significant associations of ALS, ACS and FAC with E/e’ or EF. (Fig. 3)

### Reproducibility

The interobserver differences for ALS, ACS and FAC were 1.2% (95% limit – 6.1–8.5%), 0.2% (95% limit – 4.0–4.4%) and – 0.4% (95% limit – 6.9–6.1%), respectively. The intraobserver differences for ALS, ACS and FAC were 0.4% (95% limit – 5.3–6.1%), 0.4% (95% limit – 4.5–3.8%) and – 0.2% (95% limit – 4.4–3.9%), respectively. (Fig. 4)

### Discussion
To our knowledge, this study firstly demonstrated decreased AA biomechanical properties in patients with PH by VVI. This study also revealed that the impaired AA biomechanical parameters correlated positively with aortic distensibility and negatively with the aortic stiffness index and pulse pressure.

This work showed decreased ALS, ACS and FAC in patients with PH, suggesting that the biomechanical properties of AA were impaired both in longitudinal and circumferential directions. The specific mechanism that contributes to aortic stiffness is complex and has been incompletely elucidated. Poorly controlled blood pressure accelerates damage to the aorta. As blood pressure rises, the increased mechanical and shear stress of blood ow induces biomechanical pathological vascular remodeling. Focal accumulations of collagen and disorganization of smooth muscle are visible along the medial aorta. The ascending aortic media exhibits focal breakdown or discontinuous segments of elastic bers (15).

Moreover, in the arterial wall, elastic bers are replaced with collagen bers, which is characterized by a decreased compliance of the tube wall (16–17), leading to reduced longitudinal and circumferential strain of the aorta. FAC is also related to the structure and elasticity of the aortic wall (9). If there are fewer elastic bers and more collagen bers in the aortic wall, the aortic wall will be stiffer, and the aortic dilation ability and elastic retraction ability will be reduced.

Previously, Lei Wang et al (18) found that the movement amplitude of the anterior wall of the AA in hypertension patients was lower than that in healthy subjects. Additionally, the velocity of the systolic S wave and diastolic E wave was slower in hypertension patients. However, the authors analyzed the movement of the anterior wall of the AA only in the long-axis view. Recently, other strain imaging technologies, such as two-dimensional speckle tracking imaging (2D-STI), have been used to assess aortic biomechanics in hypertensive patients. Ahmed et al (19) found that the longitudinal strain (LS) of the aortic root in hypertensive patients was signicantly decreased compared to that in controls. Juan Wu et al (20) also demonstrated that the LS of the ascending aorta in hypertensive patients was signicantly decreased. In a study by Teixeira et al (21), the aortic arch circumferential strain (CS) and strain rate were lower in the hypertensive patient group than in the healthy patient group. The authors found a negative correlation between the CS and pulse wave velocity. In addition, some investigators assessed aortic elasticity via M-mode echocardiography or tissue Doppler imaging (TDI) in hypertensive patients, demonstrating that hypertensive patients have reduced aortic elasticity (22–24).

Traditional methods can be used for the global assessment of arterial elasticity, which usually begins with regional changes, and only one-dimensional analysis of vascular dilatation has some limitations (25). However, VVI can quantify the instantaneous deformation of the aorta from different directions without angle dependence. Compared with the 2D-STI, VVI technology adopts the speed to synchronously superimpose on the two-dimensional ultrasound image in the form of vector graph. The length of the vector represents the change amplitude of the tissue velocity, and the direction of the vector represents the direction of the tissue movement. It can more intuitively observe the shape and functional state of the vascular wall. Biomechanical parameters of AA estimated by VVI correlate strongly with strain measured by sonomicrometry (26). In an in vivo experimental study, Kim et al (25) assessed the aortic elasticity of
dogs of different ages via VVI and found that the CS was significantly correlated with the collagen content of the corresponding segment of the aortic wall. In our study, there was a significant correlation between VVI parameters and the aortic elastic parameters D and SI. D and SI have been proven to reflect changes in aortic elasticity in many studies \(^{(22, 23, 27)}\). These findings indicate that VVI could sensitively and directly reflect the elasticity of the vascular wall in evaluating early aortic biomechanical dysfunction.

In this study, we also found that there were no correlations between VVI parameters and left ventricular function. This is probably because hypertensive diastolic dysfunction is more complex with several etiologies that are not simply explainable by arterial stiffness \(^{(23, 28)}\). The EF values of these study subjects were normal, and the fluctuation range was limited, so the correlation research was limited.

This study has some limitations. First, like other ultrasound technologies, VVI is highly dependent on images. When the original image quality is poor, it affects the vector tracking and strain results. For elderly individuals, obese individuals and other patients with unclear two-dimensional images, the accuracy of measurement is limited. Second, VVI is a semiautomatic technology that requires the operator to manually mark the region of interest along the inner wall of the aortic wall. Therefore, it is relatively time-consuming, taking about 15 minutes (range, 8–20 minutes) per person.

**Conclusions**

In summary, the biomechanical properties of AA were impaired in patients with PH, even patients with grade I hypertension and correlated with pulse pressure and stiffness. VVI seems to be a reliable speckle tracking technique to assess aortic biomechanical properties. In clinical applications, VVI would provide better evaluation of the aortic elasticity and could be useful to detect early vascular regional changes. This technique could be used to evaluate arterial stiffness in patients with PH and provide valuable information regarding future cardiovascular or cerebrovascular events.

**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>AA</td>
<td>ascending aorta</td>
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<td>PH</td>
<td>primary hypertension</td>
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<td>VVI</td>
<td>velocity vector imaging</td>
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<td>ALS</td>
<td>ascending aortic global longitudinal strain</td>
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<tr>
<td>ACS</td>
<td>ascending aortic global circumferential strain</td>
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<tr>
<td>FAC</td>
<td>fractional area change</td>
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</table>
PP
Pulse pressure

E
Pulsed Doppler early transmitral peak flow velocity

e'
early diastolic mitral annular velocity

D
distensibility

SI
stiffness index

SBP
systolic blood pressure

DBP
diastolic blood pressure

LAD
left atrial diameter

LVEDD
LV end-diastolic diameter

IVSD
interventricular septal thickness in diastolic

HR
heart rate

EF
ejection fraction

AoD
aortic diastolic diameter

AoS
aortic systolic diameter.

Declarations

Ethics approval and consent to participate

All participants had given informed consent, and the study design was approved by the Medical Ethics Committee of the Second Xiangya Hospital of Central South University.

Consent for publication

Not applicable.

Availability of data and materials
The data and material in the current study are available from the corresponding author on reasonable request.

**Competing interests**

The authors declare that they have no competing interests.

**Funding**

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**Authors’ contributions**

SZ conceived and designed the study. LY analyzed and interpreted data. LY performed the statistical analysis. LY drafted the manuscript. SZ, LY, GQX, QCZ, MZOY, LG participated in revision of manuscript. All authors read and approved the final manuscript.

**Acknowledgements**

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**Authors’ information**

Not applicable.

**References**


Figures
Figure 1

The longitudinal and circumferential strain curves are displayed in the segmental model with a specific color. Fractional area change was automatically calculated. A: the control group; B: the primary hypertension group.
Figure 2

Box scatter plots of ascending aortic biomechanical parameters in the control group and primary hypertension (PH) group. ALS, ascending aortic global longitudinal strain; ACS, ascending aortic global circumferential strain; FAC, fractional area change.
Figure 3

Correlation of VVI parameters with D, SI and PP in the primary hypertension group. ALS, ascending aortic global longitudinal strain; ACS, ascending aortic global circumferential strain; FAC, fractional area change. D, distensibility; SI, stiffness index; PP, pulse pressure.
Figure 4

Bland–Altman plots of interobserver and intraobserver differences at the ALS, ACS and FAC. Solid lines represent the means, and dashed lines indicate limits of agreement. ALS, ascending aortic global longitudinal strain; ACS, ascending aortic global circumferential strain; FAC, fractional area change.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- FigureS1.png