A Simple Oscillometric Technique for Determining New Indices of Arterial Distensibility

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Recently, oscillometric devices have been developed that can measure blood pressure in the extremities and analyze pulse volume record. On the basis of the extremity pulse volume record, these devices can automatically determine three types of simply measured pulse wave velocity (PWV) (brachial PWV: heart to right upper arm; R-PWV: right upper arm–right ankle; and L-PWV: right upper arm–left ankle). The percent mean pulse volume record (%MPVR = the height that bisects the area of the pulse volume record/pulse pressure × 100), a quantitative index of right brachial pulse volume record, can also be determined. To evaluate the usefulness of these new indices, we studied 1,067 consecutive subjects undergoing health checkups (648 men, 419 women; mean age, 50 ± 9 years). In both sexes, age correlated positively with simply measured PWVs (men, brachial PWV: r = 0.46, p < 0.0001; R-PWV: r = 0.47, p < 0.0001; L-PWV: r = 0.47, p < 0.0001; women, brachial PWV: r = 0.37, p < 0.0001; R-PWV: r = 0.47, p < 0.0001; L-PWV: r = 0.48, p < 0.0001) and correlated negatively with %MPVR (men: r = -0.40, p < 0.0001; women: r = -0.45, p < 0.0001). Simply measured PWVs and %MPVR were significantly correlated with mean blood pressure. In a separate group of 60 patients, simply measured PWVs correlated positively with carotid PWV (heart to carotid) derived from an elastic vessel (brachial PWV: r = 0.76, p < 0.0001; R-PWV: r = 0.43, p < 0.01; L-PWV: r = 0.43, p < 0.01). %MPVR correlated negatively with carotid PWV (r = -0.35, p < 0.01). In conclusion, simply measured PWVs and %MPVR are easier to determine than conventional PWV and may be useful as new indices of age-related changes in arterial distensibility. (Hypertens Res 2002; 25: 351–358)

Key Words: pulse wave velocity, age, blood pressure, arterial distensibility

Introduction

Pathological changes in large arteries make an important contribution to the pathogenesis of cardiovascular disease. The etiology and progression of such changes involve both structural and functional components, yet remain poorly understood. Increased aortic stiffness is associated with aging (1), hypertension (2, 3), end-stage renal disease (4–6), and atherosclerosis (7). Physiological evaluation of arterial stiffness may assist in the early detection of atherosclerosis. Pulse wave velocity (PWV) has conventionally been used as an index of arterial stiffness (8, 9). PWV is usually calculated on the basis of pulse transit time and the distance traveled by a pulse between the carotid artery and femoral artery (10). Although conventional techniques for measuring PWV are noninvasive, a femoral artery transducer carefully adjusted to obtain an accurate pulse wave is required, increasing psychological stress. Such sophisticated and complex techniques are inconvenient, particularly in large clinical trials.

Recently, a device has been developed that can simply measure PWV by a modified technique based on the pulse volume record, derived by simultaneous oscillometric measurement of pulse waves in all four extremities. Increased ar-
Material stiffness is likely to be associated with an increase in these simply measured PWVs, similar to the conventional PWV. The waveform of aortic pressure is known to change with increased arterial stiffness (11), but to our knowledge no study has evaluated associated changes in pulse volume record.

In this study, we quantitatively analyzed right brachial pulse volume record and measured the percent mean pulse volume record (%MPVR) (Study 1), as well as with carotid PWV (Study 2). Our ultimate goal was to determine whether simply measured PWVs and %MPVR could be used as indices of arterial stiffness.

**Methods**

**Comparison of New Indices with Age and Blood Pressure (Study 1)**

The study group comprised 1,067 consecutive persons (648 men, 419 women) undergoing routine health checkups at Kagoshima Prefectural Comprehensive Health Center. On the basis of personal interviews, 99 subjects were receiving treatment for hypertension, 32 treatment for diabetes mellitus, and 18 treatment for hyperlipidemia. Nine subjects had a history of stroke, and 4 had a history of ischemic heart disease. Information on smoking was obtained by means of a self-administered questionnaire. Blood samples were taken after the subjects had fasted overnight. Serum concentrations of total cholesterol, triglyceride (TG), and high density lipoprotein (HDL)-cholesterol were measured by standard laboratory procedures. Low-density lipoprotein (LDL)-cholesterol was estimated by the Friedwald equation. Fourteen subjects with a serum TG concentration of 400 mg/dl or higher were excluded from calculation of LDL-cholesterol, because they were unsuitable for use of the Friedwald equation.

Cuffs were applied to the extremities, and electrocardiographic electrodes were attached to the upper arm. A microphone for phonocardiography was placed at the second intercostal space at the left margin of the sternum. The subjects rested in a supine position for 5 min, and the following variables were measured with the use of a Colin Waveform Analyzer (model BP-203RPE; Colin, Komaki, Japan). First, the extremity blood pressure was measured by oscillometry. Then, the pulse volume record (PVR) was measured at a cuff pressure of 60 mmHg. The brachial PWV (heart to brachial), right PWV (R-PWV: right upper arm–right ankle), and left PWV (L-PWV: right upper arm–left ankle) were automatically calculated according to the following equations (Fig.

![Image](image-url.com/example.png)

**Fig. 1.** Calculation of simply measured pulse wave velocities (PWVs) (A) and percent mean pulse volume record (%MPVR) (B). (A) Brachial PWV = D1/T1, R-PWV = (D2 - D1)/T2, L-PWV = (D2 - D1)/T3. D1, distance from the heart to the right upper arm; D2, distance from the heart to the ankle; T1, time from the second heart sound of the phonocardiogram to the notch of the pulse volume record (PVR) of the right upper arm; T2, time from onset of rise in PVR of the right upper arm to onset of rise in PVR of the right ankle; T3, time from onset of rise in PVR of the right upper arm to onset of rise in PVR of the left ankle. (B) %MPVR is defined as a/b x 100. a, height that bisects the area of the pulse volume record; b, pulse pressure.
Comparison of New Indices with Carotid PWV (Study 2)

To compare the simply measured PWVs and %MPVR with the carotid PWV (heart to carotid) derived from elastic vessels, 60 consecutive outpatients (38 men, 22 women; mean age, 59 ± 15 years) presenting at Kagoshima University Hospital were studied. Thirty-four patients had hypertension, 16 ischemic heart disease, 7 diabetes mellitus, and 3 hyperlipidemia. In addition to the procedures described in Study 1, a tonometry transducer was placed over the left carotid artery, and carotid PWV was measured. Carotid PWV was calculated by dividing the distance from the heart to the neck transducer by the time from the second heart sound of the phonocardiogram to the notch of the carotid pulse wave. The distance from the heart to the transducer was determined by measuring the distance from the second intercostal space at the left margin of the sternum to the transducer. Simply measured PWVs and %MPVR were determined simultaneously. Carotid PWV was also measured over a period of 10 s, and mean values were used. This variable was measured two times consecutively, and the second value was used to eliminate error caused by physical stress.

Reproducibility of Measurement of New Indices (Study 3)

To assess the reproducibility of simply measured PWVs and %MPVR, these variables were determined in 20 consecutive patients after a 5-min rest in the supine position. Fifteen minutes after the measurement, the variables were determined again. The reproducibility of these variables was examined by linear regression analysis of the calculated values obtained from each pair of measurements.

The protocol for this study was in compliance with the institutional review board of Kagoshima University. Informed consent was obtained from all volunteers and patients.

Statistical Analysis

Data are expressed as the means ± SD. Differences in frequency were tested by χ² tests. Differences between mean values of 2 groups were analyzed by unpaired t-tests. Relations between continuous variables were analyzed by linear regression analysis. The independence of association between variables was tested with multiple regression analysis. All statistical analyses were done with StatView-5 software on a Macintosh computer. P values less than 0.05 were considered to indicate statistical significance.

Results

Correlation of New Indices with Age and Blood Pressure (Study 1)

The clinical characteristics of the subjects are shown in

Table 1. Characteristics of Subjects

<table>
<thead>
<tr>
<th>Variables</th>
<th>Men (n = 648)</th>
<th>Women (n = 419)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years old)</td>
<td>50.9</td>
<td>50.8</td>
<td>NS</td>
</tr>
<tr>
<td>Body mass index (kg/m²)</td>
<td>24.0 ± 2.9</td>
<td>22.5 ± 3.1</td>
<td>0.017</td>
</tr>
<tr>
<td>HDL-cholesterol (mg/dl)</td>
<td>57 ± 15</td>
<td>69 ± 17</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>LDL-cholesterol (mg/dl)</td>
<td>120 ± 32</td>
<td>119 ± 32</td>
<td>NS</td>
</tr>
<tr>
<td>Smoking history (%)</td>
<td>69</td>
<td>6</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Systolic BP (mmHg)</td>
<td>128 ± 15</td>
<td>117 ± 16</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Diastolic BP (mmHg)</td>
<td>83 ± 11</td>
<td>72 ± 10</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mean BP (mmHg)</td>
<td>100 ± 13</td>
<td>89 ± 14</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Systolic BP of right ankle (mmHg)</td>
<td>149 ± 20</td>
<td>136 ± 23</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Systolic BP of left ankle (mmHg)</td>
<td>148 ± 21</td>
<td>135 ± 23</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

HDL, high density lipoprotein; LDL, low density lipoprotein; BP, blood pressure; NS, not significant.
Table 1. There was no significant difference in age between men and women. The proportion of subjects with a history of smoking was significantly higher in men than in women. Ankle blood pressure was bilaterally about 20 mmHg higher than brachial blood pressure. The mean ankle-brachial index (ABI) of blood pressure was about 1.14. In men, the average brachial PWV, R-PWV, L-PWV, and %MPVR were 471 ± 70 cm/s, 1,373 ± 291 cm/s, 1,381 ± 288 cm/s, and 51.1 ± 3.2, respectively. In women, the average brachial PWV, R-PWV, L-PWV, and %MPVR were 416 ± 61 cm/s, 1,194 ± 281 cm/s, 1,206 ± 281 cm/s, and 52.1 ± 3.0, respectively.

The relations of these variables to age, a known determi-

Fig. 2. Relations between new indices and age in 648 men. Simply measured PWVs correlated positively with age, and %MPVR correlated negatively with age. Abbreviations are the same as Fig.1.

Fig. 3. Relations between new indices and age in 419 women. Simply measured PWVs correlated positively with age, and %MPVR correlated negatively with age. Abbreviations are the same as Fig.1.
nant of arterial stiffness, were studied. Figure 2 shows the correlation of simply measured PWVs and %MPVR with age in men. Brachial PWV, R-PWV, and L-PWV correlated positively with age and %MPVR correlated negatively with age (brachial PWV: $r = 0.46$, $p < 0.0001$; R-PWV: $r = 0.46$, $p < 0.0001$; L-PWV: $r = 0.47$, $p < 0.0001$; %MPVR: $r = -0.40$, $p < 0.0001$). The correlation of simply measured PWVs and %MPVR with age in women is shown in Fig. 3. Similar to the findings for men, brachial PWV, R-PWV, and L-PWV in women correlated positively with age, and %MPVR correlated negatively with age (brachial PWV: $r = 0.37$, $p < 0.0001$; R-PWV: $r = 0.47$, $p < 0.0001$; L-PWV: $r = 0.48$, $p < 0.0001$; %MPVR: $r = -0.45$, $p < 0.0001$).

The relations of these variables to LDL-cholesterol or HDL-cholesterol were also studied. In men, there were no significant correlations between these values and LDL-cholesterol or HDL-cholesterol levels. In women, LDL-cholesterol levels correlated with R-PWV, L-PWV and %MPVR (R-PWV: $r = 0.23$, $p < 0.0001$; L-PWV: $r = 0.24$, $p < 0.0001$; %MPVR: $r = -0.12$, $p = 0.01$), and HDL-cholesterol levels correlated with R-PWV and L-PWV (R-PWV: $r = -0.13$, $p = 0.01$; L-PWV: $r = -0.12$, $p = 0.018$).

Since conventional PWV is dependent on blood pressure, the relations of simply measured PWVs and %MPVR to mean blood pressure were studied. Brachial PWV, R-PWV, and L-PWV correlated positively with mean blood pressure in men ($r = 0.59$, $p < 0.0001$; $r = 0.64$, $p < 0.0001$; $r = 0.67$, $p < 0.0001$, respectively) as well as in women ($r = 0.60$, $p < 0.0001$; $r = 0.75$, $p < 0.0001$; $r = 0.73$, $p < 0.0001$, respectively). There were weak negative correlations between %MPVR and mean blood pressure in both sexes (men: $r = -0.28$, $p < 0.0001$; women: $r = -0.21$, $p < 0.0001$).

To examine how simply measured PWVs and %MPVR are affected by age or by mean blood pressure, multiple regression analysis was performed. In both sexes, simply measured PWVs were independently correlated with age and mean blood pressure. %MPVR correlated with age and mean blood pressure in men and with only age in women (Table 2).

The major determinants of PWV were age and blood pressure, as shown in Table 2. The following regression equations were observed for the simply measured PWVs in this study.

Men:

\[
\text{brachial} \text{PWV} (\text{cm/s}) = 2.3 \times \text{age (years)} + 2.7 \times \text{mean BP (mmHg)} + 87.8
\]

Table 2. Multiple Regression Analysis of New Indices

<table>
<thead>
<tr>
<th></th>
<th>Regression coefficient</th>
<th>SE</th>
<th>$t$ value</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Men</strong></td>
<td><strong>Brachial PWV</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>2.345</td>
<td>0.253</td>
<td>9.3</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Mean BP</td>
<td>2.672</td>
<td>0.176</td>
<td>15.2</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>R-PWV</td>
<td>9.191</td>
<td>0.971</td>
<td>9.5</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Mean BP</td>
<td>12.653</td>
<td>0.688</td>
<td>18.4</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>L-PWV</td>
<td>9.361</td>
<td>0.924</td>
<td>10.1</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Mean BP</td>
<td>13.015</td>
<td>0.655</td>
<td>19.9</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>%MPVR</td>
<td>-0.130</td>
<td>0.013</td>
<td>-9.3</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Mean BP</td>
<td>-0.043</td>
<td>0.009</td>
<td>-4.3</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td><strong>Women</strong></td>
<td><strong>Brachial PWV</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>1.257</td>
<td>0.318</td>
<td>4.0</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Mean BP</td>
<td>2.464</td>
<td>0.199</td>
<td>12.4</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>R-PWV</td>
<td>7.281</td>
<td>1.158</td>
<td>6.3</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Mean BP</td>
<td>14.330</td>
<td>0.716</td>
<td>20.2</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>L-PWV</td>
<td>8.141</td>
<td>1.229</td>
<td>6.6</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Mean BP</td>
<td>14.063</td>
<td>0.760</td>
<td>18.5</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>%MPVR</td>
<td>-0.159</td>
<td>0.018</td>
<td>-9.0</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Mean BP</td>
<td>-0.010</td>
<td>0.011</td>
<td>-1.0</td>
<td>NS</td>
</tr>
</tbody>
</table>

PWV, pulse wave velocity; Brachial PWV, PWV from the heart to the right upper arm; R-PWV, PWV the right upper arm–the right ankle; L-PWV, PWV the right upper arm–the left ankle; BP, blood pressure; %MPVR, % mean pulse volume record; NS, not significant.
R-PWV (cm/s) = 9.2 \cdot \text{age (years)} + 12.7 \cdot \text{mean BP (mmHg)} - 346.5
L-PWV (cm/s) = 9.4 \cdot \text{age (years)} + 13.0 \cdot \text{mean BP (mmHg)} - 383.5

Women:
brachial PWV (cm/s) = 1.3 \cdot \text{age (years)} + 2.5 \cdot \text{mean BP (mmHg)} + 134.3
R-PWV (cm/s) = 7.3 \cdot \text{age (years)} + 14.3 \cdot \text{mean BP (mmHg)} - 448.7
L-PWV (cm/s) = 8.1 \cdot \text{age (years)} + 14.1 \cdot \text{mean BP (mmHg)} - 452.7

All individual data were recalculated according to these adjusted equations. In men, average brachial PWV, R-PWV and L-PWV were 472 \pm 46 cm/s, 1,380 \pm 204 cm/s and 1,383 \pm 209 cm/s, respectively. In women, average brachial PWV, R-PWV and L-PWV were 423 \pm 39 cm/s, 1,194 \pm 220 cm/s and 1,211 \pm 222 cm/s, respectively. All PWV values were significantly higher in men than in women (brachial PWV: \( p < 0.0001 \); R-PWV: \( p < 0.0001 \); L-PWV: \( p < 0.0001 \)).

Correlation of New Indices with Carotid PWV (Study 2)
The correlation of carotid PWV with simply measured PWVs and \%MPVR in 60 patients is shown in Fig. 4. Brachial PWV showed the strongest positive correlation with carotid PWV (\( r = 0.76, p < 0.0001 \)). R-PWV and L-PWV also correlated positively with carotid PWV (\( r = 0.43, p < 0.01 \); \( r = 0.43, p < 0.01 \), respectively). \%MPVR correlated negatively with carotid PWV (\( r = -0.35, p < 0.01 \)).

Reproducibility of Measurement of New Indices (Study 3)
The reproducibility of the study variables was analyzed in 20 subjects. Linear regression analysis showed a very strong correlation between the two measurements of brachial PWV (\( r = 0.99, p < 0.0001 \)), R-PWV (\( r = 0.99, p < 0.0001 \)), and L-PWV (\( r = 0.97, p < 0.0001 \)). Good reproducibility was also obtained for \%MPVR (\( r = 0.94, p < 0.0001 \)).

Discussion
Simply Measured PWV
Conventional PWV is calculated by simultaneous tonometric measurement of pulse waves in the carotid artery and femoral artery. The use of the femoral artery requires a transducer to be attached to the inguinal region, which has a strong psychological impact on the subject. This disadvantage makes the conventional technique for PWV measurement unsuitable for routine use. Our technique for estimating PWV is simpler and uses extremity arteries, minimizing psychological stress. It is therefore better suited for routine examinations and large clinical trials. Moreover, ABI can also be determined automatically because blood pressure is simultaneously measured in the extremities. Subjects can therefore be screened for arteriosclerosis obliterans.
Several studies have used peripheral arteries to estimate PWV (12, 13). However, the carotid artery and femoral artery are generally used because they are elastic vessels relatively unaffected by vasomotor reflex, and the elasticity of their walls is considered to reflect that of the aorta (10). We used extremity arteries, which are muscular vessels, to estimate PWV. When simply measured PWVs were compared with carotid PWV (heart to left carotid) derived from an elastic artery, we found that all three types of simply measured PWVs correlated positively with carotid PWV, demonstrating the validity of our technique. Carotid PWV correlated more strongly with brachial PWV than did R-PWV and L-PWV, which were measured at the ankles. The weaker correlation of ankle PWV with carotid PWV is attributed to the fact that peripheral arteries are more susceptible to the effects of wave reflection (11). Our results show that simply measured PWVs correlate with carotid PWV, suggesting that our simpler, more convenient technique for estimation of PWV can replace conventional methods.

Aging causes degeneration of elastic fibers and is associated with arterial wall stretching and remodeling. These alterations lead to increased numbers of collagen fibers and accumulation of smooth muscle cells. With aging, arteries progressively stiffen, dilate, and lengthen, and the arterial wall thickens (14, 15). Increased arterial stiffness has been reported to lead to the age-related rise in PWV (16, 17). Consistent with these previous findings, we showed that simply measured PWVs were significantly correlated with age, similar to conventional PWV.

Along with age, blood pressure is an important determinant of PWV (18). The dependence of PWV on blood pressure increases with increased stiffness of the vascular wall and elevation of internal pressure. In the present study, simply measured PWVs correlated significantly with mean blood pressure as well as with age. Therefore, for the comparison between individual patients, these PWVs should be adjusted to blood pressure in the same way as the conventional PWV.

%MPVR

Freis et al., noninvasively and qualitatively analyzed the carotid artery pulse wave and found that the effects of aging on the pulse wave were similar to those of hypertension (19). Nichols et al. invasively and qualitatively analyzed the pulse wave of the ascending aorta and reported that with aging late systolic pressure usually exceeded early systolic pressure (20). Kelly et al. used applanation tonometry to measure the arterial pulse wave and quantitatively analyzed waveform on the basis of an augmentation index, defined as the ratio of the height of the peak above the shoulder of the wave to the pulse pressure. The augmentation index was found to increase with age (21). We analyzed the waveform of the pulse volume record on the basis of %MPVR. With aging, the systolic peak and diastolic decay became steeper, the diastolic wave became less prominent, and %MPVR decreased. The %MPVR is also useful as an index of age-related arterial distensibility.

In conclusion, simply measured PWVs and %MPVR were significantly correlated with age as well as with conventional PWV of elastic vessels, suggesting that these indices reflect age-related changes in vascular stiffness. Simply measured PWVs and %MPVR can be oscillometrically determined noninvasively at the same time as the extremity pulse volume record. These variables have the promise of becoming new indices of arterial distensibility and are likely to be useful for routine examinations and large clinical trials.

References

13. Avolio AP, Deng FQ, Li WQ, et al.: Effects of aging on arterial distensibility in populations with high and low prevalence of hypertension: comparison between urban and rural


