CARDIO-ANKLE VASCULAR INDEX, AORTIC COMPLIANCE, AND PRESSURE WAVE VELOCITY AS MEASURES OF ARTERIAL STIFFNESS

FIŠER B., SIEGELOVÁ J., DOBŠÁK P., DUŠEK J.

Department of Physiology, Department of Physiotherapy and Rehabilitation, Department of Functional Diagnostics and Rehabilitation, Faculty of Medicine, Masaryk University, St. Anne’s Faculty Hospital, Brno, Czech Republic

Received after revision June 2008

Abstract

Stiffness of large arteries has been related to cardiovascular mortality. It can be expressed by pressure wave velocity (PWV), aortic compliance (C), and by the cardio-ankle vascular index (CAVI). C was measured non-invasively in normotensive and hypertensive human subjects and in human cadavers’ aortas, PWV and CAVI were calculated. Despite completely different experimental situation the results of both analyses were similar. Also, regression coefficients between C and blood pressure were similar in both experimental conditions.

INTRODUCTION

Stiffness of large arteries has been related to cardiovascular mortality (1). Methods used to estimate this stiffness include cardiac ultrasound and pulse wave velocity (PWV) (2). Arterial stiffness can be expressed by various indexes. Except PWV it is aortic compliance and the cardio-ankle vascular index (CAVI) (3). The relationship between these indexes is determined by mathematical equations.

The aim of the present paper was to calculate PWV and CAVI in a group of normotensive and hypertensive subjects where the aortic compliance was non-invasively measured and to compare the results with published data obtained from isolated aortas of human cadavers.

METHODS

The stiffness parameter beta is reported to be independent of blood pressure and is calculated as:

$$\text{BETA} = \ln\left(\frac{P_s}{P_d}\right) \cdot \frac{D}{dD}$$

where $P_s$ and $P_d$ are respectively the systolic and diastolic blood pressures in mmHg, $D$ is the diameter of the blood vessel and $dD$ is the change of $D$. $D/dD$ can be replaced by $2*V/dV$, where $V$ is the volume of the tube, in our case the volume of the aorta.

$$\text{BETA} = \ln\left(\frac{P_s}{P_d}\right) \cdot 2\frac{V}{dV}$$

The relationship between the volume elastic modulus $V*dP/dV$ (index of the stiffness) and PWV is expressed by the formula.
\[ \text{PWV}^2 = \frac{(V \cdot dP/dV)}{\rho} \] ...............................................................(3)

where \( \rho \) is blood density. Aortic compliance is \( dV/dP \). Thus
\[ \frac{V}{dV} = \rho \cdot \text{PWV}^2/dP \] ........................................................................................................(4)

If we substitute equation (4) for equation (2), we obtain the stiffness parameter
\[ \text{BETA} = \text{CAVI} = \ln(Ps/Pd) \cdot 2 \cdot (\rho/dP) \cdot \text{PWV}^2 \] ...............................................................(5)

and volume measurement by ultrasound is superfluous. The last equation expresses the relationship between CAVI and PWV. On the other hand, direct comparison of these parameters with compliance (\( dV/dP \)) is not possible because the value \( V \) (aortic volume) is missing. The estimates of \( V \) from cadaver studies were used in our comparison.

The cadaver study includes 27 aortas from subjects 20 to 83 years old. The results after (4) are published in the Kenner-Wetterer monograph (5).

The compliance data were obtained by non-invasive measurement from 8 healthy men 27±9 years old (from 21 to 49 years) with 24-hour blood pressure 121±10 / 75±8 mmHg, from 10 non-treated hypertensive men 48±8 years old (from 38 to 58 years) with 24-hour blood pressure values 147±12 / 88±9 mmHg, and from 6 hypertensive patients treated with verapamil (slow release formula) 240 mg/24 h for 3 months. The mean age was 43±9 years (from 32 to 53). Twenty-four-hour blood pressure values were 143±7 / 88±4 mmHg before the treatment and 131±4 / 80±4 mmHg at the time of compliance investigation. The method and the results of the compliance measurement are described elsewhere (5).

**RESULTS**

The results of the cadaver study are seen in Fig.1. From Fig. 1 it is clear that the slopes of the curves (which correspond to the compliance \( dV/dP \)) are pressure-dependent. The parameters of the best fitted polynomial curves are seen in Table 1, together with compliance values at 80 mmHg (value of diastolic pressure), the parameters of linear relationship between compliance and pressure, and the calculated PWV at 90 mmHg (value of mean arterial pressure) and CAVI (which is not pressure-dependent). PWV was calculated according to equation (3). Because PWV is the aortic pulse-wave velocity, which is different from the cardio-ankle pulse wave velocity, we calculated at first aortic beta according to equation (5), and then we calculated CAVI using the regression equation CAVI = 7.5 + 0.15*aortic BETA (3). For CAVI we assume Ps/Pd = 120/80 mmHg.

![Aorta, pressure-volume diagram](image)

**Fig. 1**
Pressure-volume diagram of cadavers’ aortas

176
Table 1  
Study of cadavers’ aortas

<table>
<thead>
<tr>
<th>Ages (n)</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>A</th>
<th>B</th>
<th>dV/dp (80 mmHg)</th>
<th>PWV</th>
<th>BETA aortic</th>
<th>CAVI</th>
</tr>
</thead>
<tbody>
<tr>
<td>years</td>
<td>ml/mmHg</td>
<td>m/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20–39 (8)</td>
<td>40.54</td>
<td>1.897</td>
<td>-0.0051</td>
<td>1.897</td>
<td>-0.0102</td>
<td>1.081</td>
<td>11.71</td>
<td>21.08</td>
<td>10.66</td>
</tr>
<tr>
<td>40–59 (9)</td>
<td>76.77</td>
<td>1.778</td>
<td>-0.0050</td>
<td>1.778</td>
<td>-0.0100</td>
<td>0.978</td>
<td>13.20</td>
<td>26.78</td>
<td>11.51</td>
</tr>
<tr>
<td>60–69 (5)</td>
<td>105.10</td>
<td>1.849</td>
<td>-0.0054</td>
<td>1.849</td>
<td>-0.0108</td>
<td>0.985</td>
<td>14.20</td>
<td>31.00</td>
<td>12.15</td>
</tr>
<tr>
<td>70–83 (6)</td>
<td>144.40</td>
<td>1.510</td>
<td>-0.0045</td>
<td>1.510</td>
<td>-0.0090</td>
<td>0.790</td>
<td>15.95</td>
<td>39.11</td>
<td>13.36</td>
</tr>
</tbody>
</table>

Legend: parameters a, b, c correspond to equation; volume = a + b* pressure +c* pressure^2; parameters A, B: compliance = A + B* pressure; dV/dP (80 mmHg): compliance at pressure 80 mmHg; PWV: pulse wave velocity; BETA: aortic stiffness; CAVI cardio-ankle vascular index.

The results of the analysis of our compliance data are seen in Table 2. The compliance values were non-invasively measured as well as coefficients A and B, which we used for calculation of compliance at 80 mmHg. The volume V was not measured in our study and thus we used the values of V from the studies of cadavers’ aortas for the calculation of PWV estimates again for mean pressure of 90 mmHg. The calculation of CAVI was performed identically as in the analysis of cadavers’ aortas.

Table 2  
Human non-invasive study

<table>
<thead>
<tr>
<th>Group (n)</th>
<th>dV/dp</th>
<th>A</th>
<th>B</th>
<th>dV/dp (80 mmHg)</th>
<th>PWV</th>
<th>BETA aortic</th>
<th>CAVI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ML/mmHg</td>
<td>ml/mmHg</td>
<td>m/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normotensives (6)</td>
<td>1.18 ± 0.25</td>
<td>2.328</td>
<td>0.0154</td>
<td>0.969</td>
<td>11.77</td>
<td>21.29</td>
<td>10.69</td>
</tr>
<tr>
<td>Hypertensives (10)</td>
<td>0.96 ± 0.21</td>
<td>2.219</td>
<td>0.0144</td>
<td>0.923</td>
<td>13.37</td>
<td>27.48</td>
<td>11.62</td>
</tr>
<tr>
<td>Treated hypertensives (6)</td>
<td>0.90 ± 0.11</td>
<td>1.843</td>
<td>0.0122</td>
<td>0.745</td>
<td>13.86</td>
<td>29.50</td>
<td>11.92</td>
</tr>
</tbody>
</table>

Legend: dV/dp (±SD): measured compliance. Other parameters as in Table 1.

Despite a completely different experimental situation the results of both analyses are similar. The most interesting finding is a similar regression coefficient B despite the fact that the smooth muscle cells in cadavers’ aortas are dead.

DISCUSSION

Several studies determined the aortic compliance invasively, and the values correspond to our non-invasive methods. Also, the regression coefficient between
diastolic pressure and compliance B (0.0157 ml*mmHg⁻²) is similar in our study and in the study of Liu et al. (14, 15). They found a value B = 0.0131 ml*mmHg⁻². In all compliance studies a big variation of compliance among various subjects was observed.

From this point of view, the accord between the data of cadavers’ aortas and those of living subjects is surprising.

A comparison of PWV calculated from our data and PWV measured in healthy subjects revealed that our data correspond to the high 2.5 centile of PWV variation in cadavers’ aortas and in our healthy subjects in all age categories. On the other hand, our data from hypertensive and treated hypertensive patients exceed the results of measurement in normotensives. It is interesting that the stiffness is higher in treated hypertensive patients than in non-treated ones. This finding can explain the fact that blood pressure in treated patients was initially higher and blood pressure was relatively quickly normalised by the treatment, while remodelling of the arterial wall needed much more time.

Our analysis indicates that all parameters, aortic compliance, PWV, and CAVI can be used for estimation of arterial stiffness. It seems that the stiffness data are more reliable for determination of patient prognosis without treatment than blood pressure measurement. For screening, the method must be simple to perform. Here is the advantage of the CAVI measurement. CAVI is only age-dependent. PWV is both pressure- and age-dependent. However, CAVI and aortic compliance measurement are not equal. CAVI takes into account the atherosclerosis of arteries of the lower extremities. Thus aortic compliance and CAVI measurement are complementary. Aortic compliance is both pressure- and age-dependent but can be relatively simply normalised for the distinct value of diastolic pressure. The complicated methodical approach causes a limitation of the aortic compliance method for screening purposes.

Acknowledgement

Supported by MSM0021622402.

REFERENCES


