Validity of the Water Hammer Formula for Determining Regional Aortic Pulse Wave Velocity: Comparison of One-Point and Two-Point (Foot-to-Foot) Measurements Using a Multisensor Catheter in Human

Shizuo Hanya

Background: Lack of high-fidelity simultaneous measurements of pressure and flow velocity in the aorta has impeded the direct validation of the water-hammer formula for estimating regional aortic pulse wave velocity (AO-PWV) and has restricted the study of the change of beat-to-beat AO-PWV under varying physiological conditions in man.

Methods: Aortic pulse wave velocity was derived using two methods in 15 normotensive subjects: 1) the conventional two-point (foot-to-foot) method (AO-PWV2) and 2) a one-point method (AO-PWV1) in which the pressure velocity-loop (PV-loop) was analyzed based on the water hammer formula using simultaneous measurements of flow velocity (VM) and pressure (PM) at the same site in the proximal aorta using a multisensor catheter. AO-PWV1 was calculated from the slope of the linear regression line between PM and VM where wave reflection (PB) was at a minimum in early systole in the PV-loop using the water hammer formula, PWV1 = (PM/VM)/ρ, where ρ is the blood density.

AO-PWV2 was calculated using the conventional two-point measurement method as the distance/traveling time of the wave between 2 sites for measuring P in the proximal aorta. Beat-to-beat alterations of AO-PWV in relationship to aortic pressure and linearity of the initial part of the PV-loop during a Valsalva maneuver were also assessed in one subject.

Results: The initial part of the loop became steeper in association with the beat-to-beat increase in diastolic pressure in phase 4 during the Valsalva maneuver. The linearity of the initial part of the PV-loop was maintained consistently during the maneuver. Flow velocity vs. pressure in the proximal aorta was highly linear during early systole, with Pearson’s coefficients ranging from 0.9954 to 0.9998. The average values of AO-PWV1 and AO-PWV2 were 6.3 ± 1.2 and 6.7 ± 1.3 m/s, respectively. The regression line of AO-PWV1 on AO-PWV2 was y = 0.95x + 0.68 (r = 0.93, p <0.001).

Conclusion: This study concluded that the water-hammer formula (one-point method) provides a reliable and conventional estimate of beat-to-beat aortic regional pulse wave velocity consistently regardless of the changes in physiological states in human clinically. (*English Translation of J Jpn Coll Angiol 2011; 51: 215-221)

Keywords: multisensor catheter, water-hammer formula, regional pulse wave velocity of the proximal aorta, aortic elasticity, aortic wave reflection

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**IntroductIon**

Regional pulse wave velocity (PWV1) is a conventional surrogate of regional elasticity of the aorta, and is known to increase with distance away from the heart owing to decreased elastin and increased collagen content. Atherosclerosis is known to alter these properties, principally through the reduction of arterial elastin. The distribution of elastin and collagen differs strikingly between the proximal and the distal aorta. An important feature of elasticity is that it varies from site to site in the aorta and may be influenced to different extents in different sites by a disease such as atherosclerosis. It is therefore desirable to be able to measure the regional pulse wave velocity over as short a region of the aorta as possible in order to provide a reliable estimate of the natural consequence of atherosclerosis. Accordingly, noninvasive methods based on the water-hammer formula (abbreviated to W-H method hereinafter) have been increasingly attempted to estimate aortic regional pulse wave velocity (abbreviated to AO-PWV1 hereinafter) from velocity (Vm) and pressure (Pm), or the change in the cross sectional area measured at a single site in the aorta using magnetic resonance imaging (MRI) etc. However, for its clinical application, it is necessary to verify that the W-H method satisfy the basic principle of a W-H formula; there should be linear relationship between Pm and Vm during early systole where the effect of arterial wave reflection (Pb) is minimum in man. Although there has been several reports on the validity of this method, none have reported a direct validation of the linearity between Pm and Vm during early systole in relation to Pb during varying physiologic conditions in conscious humans, using a high-fidelity measuring system.

The aim of this study are: (1) confirm the linearity between Pm and Vm during early systole in relation to Pb in steady and analyze the constancy of these relationships under unsteady-states such as Valsalva maneuver, (2) compare the results of the W-H method with those of the conventional two-point (foot-to-foot) measurement method and (3) use the W-H method to analyze beat-to-beat changes in AO-PWV1 with the changes in aortic pressure during Valsalva maneuver in conscious human using a multisensory catheter.

**Subjects and Methods**

The study population comprised 15 normotensive subjects undergoing diagnostic cardiac catheterization, who did not have abnormality in the aorta and the aortic valve. The cardiac rhythm was normal sinus for all subjects (Table 1). This study was carried out with sufficient informed consent obtained from all subjects prior to the study and approval by the Institutional Review Board of the medical organization that was the venue of the study.

During routine cardiac catheterization, a high-fidelity custom-designed multisensor catheter (VPC-684A, Millar Instrument Inc., Houston, Texas, USA), which has Mikro-tip pressure and electromagnetic-velocity sensors mounted in the same location and permits the simultaneous measurement of pressure and flow velocity at the same site, was inserted into the ascending aorta, and the Pm and Vm were measured simultaneously at the same site first, then the catheter was withdrawn to the proximal thoracic descending aorta, and the Pm at this site was measured to calculate the PWV2 by conventional two-point measurement method.

The flow meter used was Narcomatic–RT500 (Narco Biosystems Inc., Houston, Texas, USA), and all data were recorded at a sampling rate of 500 Hz and stored digitally and analyzed with an analytical system MP-100WS (BIOPACK Systems Inc., Santa Barbara, California, USA).

Firstly, the AO-PWV2 was calculated from the time delay between the two aortic pressure waveforms and the distance between the two measuring sites, which was measured physically during pullback of the multisensor catheter at the end of catheterization. The time delay was calculated by subtraction of the respective times of the onset of systolic upstroke of the pressure waveforms, which was defined as the first peak of the second-order differential pressure waveforms. Pressure waveforms at the 2 measurement points with nearly identical R-R intervals of electrocardiogram (ECG) were selected, and the mean of 5 heart beats was regarded as the final value.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Clinical characteristics of the study subjects</th>
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<tbody>
<tr>
<td>Patient (n)</td>
<td>15</td>
</tr>
<tr>
<td>Age (years)</td>
<td>54 ± 19</td>
</tr>
<tr>
<td>Male</td>
<td>8</td>
</tr>
<tr>
<td>Female</td>
<td>7</td>
</tr>
<tr>
<td>Aortic pressure (mmHg)</td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>123 ± 9</td>
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<tr>
<td>Minimum</td>
<td>59 ± 11</td>
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<tr>
<td>Mean</td>
<td>85 ± 7</td>
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<tr>
<td>Patient diagnoses</td>
<td></td>
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<tr>
<td>Chest pain syndrome</td>
<td>9</td>
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<tr>
<td>Pulmonary disease</td>
<td>3</td>
</tr>
<tr>
<td>Arrhythmia</td>
<td>3</td>
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The measured value of AO-PWV2 was used as the value of PWV in Formula (3), and all Pb(t) values calculated are presented in mmHg.

Then, linear regression equation between Pm and Vm during early systole where Pb exhibited minimal value and its Pearson’s coefficient were calculated. AO-PWV1 was derived from the slope of the linear regression equation. The above–mentioned procedure was repeated on five successive cardiac pulses, and the average was adopted as the final AO-PWV1 value. Moreover, in 1 subject, the Valsalva maneuver was performed during the examination, and changes in various waveforms before, during, and after the maneuver were recorded. Calculation of Pb and waveform analysis on each of the above-mentioned waveforms were carried out by an analytical system MP100WS (BIOPACK Systems Inc., USA).

Statistical analysis
Data obtained were expressed with mean ± 1SD. The relation between Pm and Vm was evaluated by linear regression analysis by calculation of Pearson’s correlation coefficients. The correlation of AO-PWV1 and AO-PWV2 was analyzed using Student’s t-test. A p-value of <0.01 was considered statistically significant.
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Results

Figure 1 shows representative ECG and pressure waveforms of pulses with nearly identical R-R intervals recorded in the proximal and descending aorta (lower panel) and second-order differential waveforms of the pressure (middle panel). The PWV2 value calculated from the time lag of the pulse wave (\(T_2 - T_1\)) and distance of catheter withdrawal (30 cm) was 6.8 m/s. Figure 2 shows ECG, Pm, Vm, and calculated pressure reflection (Pb) waveforms of 3 consecutive pulses recorded in the proximal aorta of this subject. The Pb was nearly minimum (↓) near the initial rise of the aortic ejection pressure waveform. It gradually elevated but remained low in early systole, indicated by dashed lines, then gradually increased almost to a maximum near the peak of the aortic pressure, and decreased gradually thereafter and returned to a minimum (↓) in early systole. In all subjects, the Pb waveform was nearly the same as the one shown in Fig. 2. Figure 3 shows the pressure-flow velocity curve (PV-loops) of the 3 consecutive pulses shown in Fig. 2. The lower left end of a loop is the beginning of cardiac contraction, and the loop progresses counterclockwise (the direction shown by →) with the cardiac cycle. The part in an early period of ejection is nearly linear in all loops (Fig. 3: parts indicated with →). The linear regression equation of the Pm and Vm showed a highly significant linearity of \(r = 0.9982\) during the 20 ms in an early period of ejection of the 3rd pulse (the above period between the dashed lines with a low Pb) in Fig. 3, and the PWV1 calculated from this slope was 6.5 m/s.

Figure 4 shows waveforms of the Vm, Pb, and Pm of 8 consecutive pulses during Phase 4 of the Valsalva maneuver recorded in the ascending aorta of the representative subject. All waves increased gradually after the end of breath-holding, and the Pb nearly reached a minimum (↓) near the initial rise of the aortic ejection pressure waveforms in early systole without exception. Figure 5 shows the PV-loops of these 8 consecutive pulses. All
loops are nearly linear in an early period of ejection, and the slope of the linear segment in this period is steeper as the diastolic pressure increases (the lower left end of the P-V loop is higher). The PWV1 values calculated from the maximum (●) and minimum (→) slopes of the P-V loop were 7.6 and 6.1 m/s, respectively.

The mean AO-PWV1 and AO-PWV2 values in the 15 subjects were 6.2 ± 1.2 and 6.7 ± 1.3 m/s, respectively.
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Pearson’s coefficient of the linear regression equation of the Pm and Vm during early systole was 0.99 or higher without exception, and a highly significant linear correlation was confirmed between the Pm and Vm in an early period of ejection in all subjects.

Figure 6 shows a regression line obtained by plotting the PWV1 and PWV2 values of the 15 subjects. A highly significant positive correlation with $y = 0.95x + 0.68$, $r = 0.93$ ($p < 0.001$) was observed between them.

**DISCUSSION**

A major role of the aorta as an elastic artery is serving as a buffer to maintain the blood flow during diastole and to prevent an excessive increase in the pulse pressure by the Windkessel effect. Since both of these functions depend on the elasticity of the aorta, they are reduced by arteriosclerosis, which causes a decrease in elastin of the media of the elastic artery. Here, some discussion about the concept of arteriosclerosis is necessary. In evaluating lesions of arteriosclerosis, the “stiffness of the artery” (loss of elasticity, arteriosclerosis) and “atheromatous change” (atherosclerosis) are often confused.
First, it is necessary to perceive them as different pathologic conditions. The “atherosclerotic lesion” is an atheromatous change and is a major risk factor for cerebral and myocardial infarctions, and can be diagnosed relatively easily by echosonography or computed tomography (CT) and MRI methods in clinical setting. On the other hand, the “stiffness of the artery”, if it progresses, induces an increase in left ventricular afterload and, consequently, heart failure, etc., but it is clinically difficult to diagnose accurately. Among several indices to evaluate the “stiffness of the aorta”, the PWV is widely used as a simple and conventional clinical index. The PWV is usually measured by the 2-point (foot-to-foot) method, but it is difficult to accurately measure the AO-PWV2 in the proximal aorta with a non invasive method, particularly if the aorta is tortuous. Clinically, therefore, PWV2 values measured between 2 peripheral muscular arteries, which can be palpated from the body surface between which the aorta is included, such as the carotid and femoral arteries (cfPWV) and brachial and ankle arteries (baPWV), are used as substitutes for the AO-PWV because of its simplicity. However, the amount of elastin varies among sites of the artery, and the PWV has a diagnostic value only in elastic arteries such as the aorta. Since the content of elastic fiber is low in the peripheral muscular arteries and PWV measured there is mainly affected not by the elasticity, but by the wall thickness and luminal cross sectional area as evident from the Moens-Korteweg equation, the clinical significance of cfPWV and baPWV as the index of the aortic elasticity are limited. Therefore, to get accurate estimates of aortic elasticity clinically, AO-PWV must be derived from direct measurements in the proximal aorta. Although there are various indices of the aortic elasticity including the distensibility, stiffness index (β), and compliance other than the PWV, they require a complicated procedures for derivation and clinicians are more familiar with the value of PWV compared with these indices as a surrogate of the aortic stiffness. Therefore, if the AO-PWV1 can be measured noninvasively, its clinical value is extremely high.

It should be again emphasized that following prerequisites must be satisfied for the W-H method permitted to be hold for measuring AO-PWV1 in clinical practice: (1) minimum impact of Pb and (2) good linear relationship between Pm and Vm in early systole. Although the W-H method has been validated in vitro and in vivo, clinical data using a high-fidelity measuring system in humans are limited owing to methodological limitations.

Therefore, our previous study firstly examined the validity of this method in the human pulmonary artery because of its physical characteristics of negligible development of Pb compared with aorta, and confirmed its reliability. Then, this study confirmed that these two major prerequisites were well satisfied not only under steady-condition but also in unsteady-conditions regardless of the abrupt changes of blood pressure in aorta. Furthermore, the correlation between the AO-PWV1 and AO-PWV2 was so high that the validity of the W-H method is proved for evaluating the aortic elasticity in clinical practice by this study. In this study, the AO-PWV1 was slightly higher than the AO-PWV2, but this probably reflected the difference in the site of measurement between the two methods. While the AO-PWV1 is the regional PWV of the ascending aorta, the AO-PWV2 reflects the mean PWV of 2 points between the ascending and thoracic aorta, so their values are naturally expected to differ. According to previous studies, the normal AO-PWV2 in middle-aged people is about 5–8 m/s, being close to the mean AO-PWV1 and AO-PWV2 values observed in this study.

Comparison of the regional PWV values in the human aorta showed that the values increase at more peripheral sites. The AO-PWV2 values determined by Latham, et al. at 10-cm intervals from the ascending to abdominal aorta simultaneously using a catheter-tip manometer with 6 pressure sensors showed progressive increases toward the most distal point, being in close agreement with the results of our study (AO-PWV1 < AO-PWV2). Also, PWV values are known to increase with elevation of the blood pressure. Indeed, the slope of the loop in the early period of ejection was steeper, i.e., the AO-PWV1 was greater, in a PV-loop with a higher diastolic blood pressure. In addition, as indicated by the finding that the linearity of the P-V relationship in early systole was maintained even during the Valsalva maneuver, during which the hemodynamics showed marked changes, beat-to-beat changes in the aortic elasticity including arrhythmia could be readily evaluated by the W-H method, and this is considered to be an additional advantage of the W-H method not obtained by the conventional 2-point measurement method.

It is clinically possible to calculate AO-PWV1 by measuring flow velocity and pressure or the change in a cross sectional area of the same site of the aorta simultaneously by the W-H method. Presently, MRI is the only clinically available noninvasive measuring system that fulfills this condition, and the first attempt at noninvasive
measurement of the AO-PWV1 in 2002 was made using MRI. However, measurement of the AO-PWV1 using MRI is impractical due to its high cost in routine clinical use. Therefore, as a surrogate of measuring AO-PWV1, clinical attempts at measuring the PWV1 in the carotid artery with a combination of ultrasound vascular echo-tracking and the Doppler technique are presently continued. However, to get accurate estimates of aortic elasticity clinically, AO-PWV1 must be derived from direct measurements in the proximal aorta using two different ultrasound beams which are independently steerable noninvasively. Technically, adjusting a wavelength of Doppler beam longer, the accuracy of the measurement of changes in the cross-sectional area of the ascending aorta by ultrasound echo-tracking has already reached a clinically applicable level. By combining this with the Doppler velocimetric technique, the accurate noninvasive measurement of the AO-PWV1 is considered to have sufficient clinical feasibility, and its realization is eagerly anticipated in routine clinical practice.

CONCLUSIONS

A close linear relationship unaffected by changes in the hemodynamics was observed between the Pm and Vm of the ascending aorta in an early period of ejection, and the W-H method was confirmed to have potential as a method for accurate clinical evaluation of the regional aortic elasticity.

DISCLOSURE STATEMENT

I (author) have no conflict of interest to disclose this paper.

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