A Novel Compliance Measurement in Radial Arteries Using

Strain-Gauge Plethysmography

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Abstract

We propose a novel method for assessing the compliance of the radial artery by using a two-axis mechanism and a standard positioning procedure for detecting the optimal site. A modified sensor was designed to simultaneously measure the arterial diameter change waveform (ADCW) and pressure pulse waveform with a strain gauge and piezoresistor. In the X-axis scanning, the sensor could close to the middle of the radial artery when the ADCW arrived to maximum amplitude. In the Z-axis scanning, the contact pressure was continuously increased for data measurement. Upon the deformation of the strain gauge following the change in the vascular cross-section, the ADCW was transferred to the change of the vascular radius. The loaded strain compliance of the radial artery ($C_{strain}$) can be determined by dividing the dynamic changed radius by the pulse pressure. Twenty-three untreated, mild or moderate hypertensive patients aged 29-85 were compared with 14 normotensive patients aged 25-62. The maximum strain compliance between groups was significantly different ($p<0.005$). Of the hypertensive patients, 14 were at risk of developing hyperlipidemia. There was a significant difference between this and the normotension group ($p<0.005$).

Keywords: Two-axis Mechanism, Strain Gauge, Loaded Strain Compliance.

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1. Introduction

Noninvasive and quantitative measurement of the mechanical properties of the vascular system is required for the evaluation of hemodynamic conditions in various cardiovascular diseases (Glasser 1997, Franklin 1997). These mechanical properties are related to arterial stiffness, such as the relative change in arterial diameter, absolute diameter change, the velocity of pulse propagation, and the relationship between pressure change and volume change. Important indices related to arterial stiffness include distensibility, compliance, pulse wave velocity, and vascular impedance (Mackenzie 2002, Oliver 2003). However, interpreting these indices is complicated and is rarely done by simultaneously taking the blood pressure and diameter measurements. Diameter measurements are made using an echo-based method or magnetic resonance imaging (MRI) (Murai 2005, Levenson 1981, Khder 1997). The vascular compliance, C, which is used to describe the degree of atherosclerosis, can be measured by simultaneously observing the absolute diameter change, $\Delta D$, and the corresponding change in blood pressure, $\Delta P$, in a segment of vessel. Compliance can thus be calculated as: $C = \frac{\Delta D}{\Delta P}$ (Mackenzie 2002, Oliver 2003).

Some studies focused on the arterial compliance measurement without using an echo-based or MRI method. These studies defined the capacitative compliance or oscillatory compliance as the ratio of the arterial volume change to the arterial pressure change. Shanker and Webster proposed a maximal compliance which used electrical plethysmography to record the arterial pulse volume at different transmural pressures by applying a pressurized cuff wrapped around a lower leg (Shanker 1997). Lopez-Beltran et al. offered a peripheral vascular compliance indicator by applying an infrared photoplethysmography to represent the pulsatile change in arterial volume (Lopez-Beltran 1998). Drzewiecki and Pilla calculated the pressure-lumen area
measurements by determining the cuff compliance (Drzewiecki 1998). Liu et al. used an airflow meter and a pressure transducer to characterize a cuff model which embedded the change in the arterial volume (Liu 2008).

The arterial stiffness index (ASI) was obtained simultaneously with the measurement of brachial arterial blood pressure by calculating the oscillometric waveform at the arm (Sharma 2002, Kaibe 2002). ASI has been reported to show a good correlation with pulse wave velocity between the carotid and femoral arteries. Hence, it is considered valuable for evaluating arterial stiffness in hypertensive patients (Kaibe 2002). Sato et al. reported that the ASI correspondingly rose when other risk factors were present, including hypertension, hyperlipidemia, and diabetes (Sato 2005).

In our study, a two-axis mechanism and a standard positioning procedure have been designed to detect the optimal measurement site for accurately measuring the pulse pressure waveform (Tyan 2008). A modified sensor was designed to detect the arterial diameter change waveform (ADCW) and pulse pressure waveform with the strain gauge and the piezoresistor, simultaneously. Because the designed two-axis mechanism can place the sensor very close to the middle of the radial artery, the change in the arterial radius for the different contact pressure can be measured according to the vascular geometry. Thus, a nonlinear relationship between the change in the arterial radius and the pulse pressure in a radial artery can be obtained. Many studies have proven that hypertension can accelerate the increase in vascular wall thickness and decrease vascular elastic and systemic compliance (Kannel 1985, Safar 1984). This study comprised of 23 patients with untreated, mild or moderate hypertension and 14 normotensive patients to investigate the designed compliance method. Of the 23 patients, there were 14 who also had the risk of hyperlipidemia. The ASI of these patients was also measured.
The purpose of this research was to develop a novel noninvasive measuring method that had a two-axis mechanism and employed a standard positioning procedure for measuring the loaded compliance with strain-gauge plethysmography. This paper is organized as follows: Section 2 describes the two-axis mechanism apparatus, our method for analyzing the vascular geometry, and data collection, Section 3 presents statistical analysis of the data and a comparison of the measured compliance. Discussion of the results and conclusions are in Section 4.

2. Method

In this section, we describe the noninvasive measurement system used to measure the ADCW. This was done with strain-gauge plethysmography at different contact pressures. According to the deformation of the strain gauge following the change in the vascular cross-sections, the ADCW would be transferred to the change of the vascular radius.

2.1 Two-axis Mechanism and Sensor

In order to obtain an accurate ADCW, the sensor must be placed directly above the middle of the radial artery. We have designed a two-axis mechanism and employed a standard positioning procedure to detect the optimal measurement position on the X-axis. The designed two-axis mechanism is shown in Figure 1. The arm is positioned between the platform and the sensor and held in place with the Velcro strap. The hand grasps the handgrip to let the radial artery easily appear. Each axis contained a screw and sleeve for producing movement, with two auxiliary sliding rods on each side helping to maintain stability. Each screw and sleeve was separated by 1mm. The stepping motor turned the screw at 1.8 deg/sec and moved the sensor (Tamagawa Seiki, Japan) with a precision of 1/200 mm. A modified sensor
combined a piezoresistor (diameter: 12 mm, range: 15 psi; NPI-12, Lucas, USA) with a strain gauge (size: 5×2 mm, resistance: 119.8±0.2% Ω, mean ± SD, gage factor: 2.12; KFG-5-120-C1, Kyowa, Japan). Its active surface was semispherical and constructed from soft silicone rubber as shown in Figure 2. We have shown that the sensor is very close to the middle of the radial artery when the amplitude of the ADCW is maximal in the X-axis (Tyan 2008). The waveform signals were recorded using a digital-to-analog acquisition card (PCI 6014, National Instruments), with LabView software used for data retrieval and manipulation. The analog bandwidth, pressure-sensor gain, strain-gauge gain and sampling frequency were 0.1-40 Hz, 100, 5000 and 500 Hz, respectively. The pressure sensor was calibrated using a mercury-column pressure gauge.

2.2 Changes in Vascular Radius

The circuit of the strain gauge is shown in Figure 3. In the full bridge circuit, the R3 was used to adjust the output offset voltage to zero. R4 is the strain gauge. When the offset voltage is zero, the output voltage, \( V_{ADCW} \), is:

\[
V_{ADCW} = 5000 \times I \times \Delta R ,
\]

where \( I \) is current source, \( \Delta R \) is the changed resistor of the strain gauge. According to the piezoresistive effect, the ratio of the changed resistor and basic resistor of the strain gauge is:

\[
\frac{\Delta R}{R} = G \frac{\Delta L}{L},
\]

where \( G \) is the gauge factor, \( \Delta L \) is the total changed length of the strain gauge, \( L \) is the basic total length of the strain gauge (5×10 mm), and \( R \) is the basic resistor (119.8 Ω). Figure 4 shows the change in the cross-section of the radial artery when the blood
pressure is at diastolic blood pressure (DBP) and systolic blood pressure (SBP).

The change in the vascular radius, $\Delta x$, is calculated as:

$$\Delta x = \frac{1}{2} \sqrt{(l + \Delta l)^2 - l^2},$$

(3)

where $l$ is the basic length of the strain gauge, $\Delta l$ is the change in length of the strain gauge. Thus, we define the strain compliance, $C_{\text{strain}}$, as:

$$C_{\text{strain}} = \frac{\Delta x}{\Delta P},$$

(4)

where $\Delta P$ is the pulse pressure, which is the difference between the SBP and DBP.

In several previous investigations (Baker 1997, Raamat 1999), the arterial pressure-volume relation could be described as an exponential model following the transmural pressure. In the Z-axis scanning, the contact pressure would be continuously increased for data measurement. The strain compliance could be considered as a transmural pressure function:

$$C_{\text{strain}}(P_t) = \frac{\Delta x(P_t)}{\Delta P},$$

(5)

where $P_t$ is the transmural pressure (i.e., the difference between mean arterial pressure $P_a$ and contact pressure $P_c$). During this measuring period, it is acceptable to assume that the mean arterial pressure is constant. Under this assumption, the linear relation is present between $P_t$ and $P_c$. Thus, the strain compliance under the different contact pressures is defined by the following equation;

$$C_{\text{strain}}(P_c) = \frac{\Delta x(P_c)}{\Delta P}.$$

(6)

According to this formula, $C_{\text{strain}}(P_c)$ could be considered to be a function of the contact pressure, and be used to elucidate the properties of the arterial compliance.

2.3 Data Collection
The experimental protocol was applied to 37 patients (24 men and 13 women) aged 51 ± 13.8 years (mean ± SD; range: 25 to 85 years) who were selected by the doctor according to their anamneses. All patients underwent blood pressure and cholesterol tests. The 14 patients without hyperlipidemia and hypertension were assigned to the control group (11 men and 3 women). The hypertensive group had 23 patients (14 men and 9 women) whose blood pressures were always in the mild or moderate range. In this group, there were 14 patients who also had hyperlipidemia. The patients’ characteristics are shown in Table 1. This experiment was approved by the institutional review board of Chinese Medical University Hospital, and written informed consent was obtained from each patient. All patients were asked to stop smoking and alcohol intake, and avoid consuming stimulants (e.g., coffee and tea) and medications for at least 24 hours before participating in the experiments. They rested in a temperature-controlled room (at 22±1°C) for 30 minutes before the waveform examination was performed. During the waveform measurement, each patient was asked to sit on an adjustable-height chair. The patient’s left hand was placed on a table at the same horizontal height as the heart with the palm pointing upwards and the wrist resting on a soft pillow.

The sensor used the radial styloid process as the reference point to search for the middle position of the radial artery. Measurements began from the X-axis. One step of the stepping motor corresponded to a movement of 0.25 mm, and the recording time was 4 seconds. In the Z-axis, one step of stepping motor was only 0.125 mm, and the recording time was 4 seconds. The entire measurement protocol, including putting the sensor above the middle of the artery and Z-axis scanning, took 3 – 5 minutes in each patient. Figure 5 shows the measured contact pressure and ADCW of a patient (sex: man, age: 30 years, SBP: 182 mm Hg, DBP: 122 mm Hg, mean arterial pressure: 142 mm Hg, heart rate: 82 BPM) in the X-axis. According to
our proposed geometric analysis, the amplitude of the ADCW was maximal when the sensor was placed at 2.5 mm. In this position, the sensor will be above the middle of the artery. Figure 6 shows the measured contact pressure waveform and ADCW in the Z-axis from the same patient in Fig. 5. In one step there were two to three complete cycles for the beat pulses. The ADCW of each beat pulse was detected separately. According to Eq. (1), (2), and (3), the ADCW would be transferred to the change of the vascular radius. Figure 7 shows the whole change of the vascular radius from the same patient in Fig. 5 under the different contact pressure. In one step, the change in vascular radius was described by the mean (solid circle) and standard deviation (bar).

The blood pressure measurement was performed before and after the ADCW measurement. The blood pressure was measured with an electric sphygmomanometer (DINAMAP PROCARE 100, GE Medical Systems) in the left arm of each patient. Hypertension was defined as SBP exceeding 140 mm Hg and/or DBP exceeding 90 mm Hg. Hyperlipidemia was defined as total serum cholesterol (TC) > 220 mg/dl, and/or low-density lipoprotein cholesterol (LCD-C) > 140 mg/dl, and/or triglyceride (TG) > 150 mg/dl. An ASI was measured in all subjects using CardioVision (MS-2000; IMDP, Las Vegas, NV, USA). Abnormal ASI was defined as the ASI exceeding 70 mm Hg.

3. Results

Student’s t-test analysis revealed that the age, body mass index (BMI), and TG did not differ significantly (p>0.05) between the control group and the hypertensive groups nor between the hypertensive and the hyperlipidemia groups (Table 1). However, there were significant differences (p<0.005) in the SBP, DBP, and PP between the control group and the hypertensive groups and between the hypertensive
and hyperlipidemia groups. In addition, the T-Cho and LDL-C were significantly different \( (p<0.05) \) between the control group and the hypertensive group with hyperlipidemia.

In this study, the ASI was significantly different between the control and the hypertensive groups \( (p<0.005) \) as well as between the hypertensive with the hyperlipidemia groups \( (p<0.05) \). Therefore, to validate the proposed method, the maximal strain compliance, \( C_{\text{strain_max}} \), was compared between the control and the hypertensive groups and between the control group and the hypertensive with hyperlipidemia group. In Table 1, Student’s \( t \) test analysis revealed that the \( C_{\text{strain_max}} \) differ significantly \( (p<0.005) \) between the control and the hypertensive groups and between the control group and the hypertensive group with hyperlipidemia.

4. Discussion and Conclusions

Many noninvasive methods have been used to indirectly estimate the local arterial stiffness or the systematic compliance. These methods include pulse wave velocity (Bramwell 1992), echocardiography (Levenson 1981, Khder 1997), MRI (Murai 2005), impedance plethysmography (Shanker 1991), photoplethysmography (Lopez-Beltran 1998), oscilometry (Drzewiecki 1998, Liu 2008), and model-based approaches (Brinton 1997). Imaging methods like echocardiography and MRI can measure an absolute vascular diameter change to determine the arterial stiffness. These methods only measure the relative arterial volume change (Shanker 1991, Lopez-Beltran 1998, Drzewiecki 1998, Liu 2008) or related physical parameters (Sharma 2002, Sato 2005). In these indirect measurement methods, our method was first proposed with the strain gauge to measure the change in the vascular radius. The major consideration is that the sensor must be placed at the middle of the artery. We have succeeded in designing a two-axis mechanism that can place the sensor close
to middle of the radial artery in the X-axis, and increase the contact pressure step by step in the Z-axis (Tyan 2008).

Yamakoshi et al. showed that increases in loading cause the volume of a blood vessel to change from small to large and then back to small again (Yamakoshi 1983, Shimazu 1985). The largest volume change was termed the unloading condition, which occurred when the contact pressure was equal to the mean arterial pressure. In Fig.6, the measured ADCW also had the same change from small to large, and then back to small again. In Fig. 7, the maximum change in the vascular radius happened when the contact pressure was at 150 mmHg. This pressure is greater than the mean arterial pressure (142 mm Hg). This was due to the contact area between the sensor and skin being very small and was also probably attributable to the radial artery being loaded unilaterally by the sensor until the vessel moved downwards sufficiently for it to be supported by the radius. This explains why the contact pressure became larger than the mean arterial pressure.

Ultrasound and MRI are the general methods used in detecting the absolute vascular diameter. In the two-axis mechanism, the sensor can only detect the partial change in vascular radius, since the radial artery is an elastic material. When the sensor and the radius all push the radial artery together, the cross-section of the blood vessel may become an ellipse. Therefore, we used the equation, $\frac{\Delta x^2}{\Delta P}$, to compare between the control group (10.17 ± 4.17 um^2 x mm Hg^-1), the hypertensive group (7.97 ± 3.09 um^2 x mm Hg^-1) and the hypertensive group with hyperlipidemia (7.07 ± 2.66 um^2 x mm Hg^-1). In all cases the results were not significantly different ($p>0.05$).

Hypertension is known to decrease arterial elasticity and systemic compliance (Kannel 1985, Safar 1984). Although the arterial tree is not a homogenous system, the
radial artery belongs to a distal medium-sized artery. Previous studies have shown a significant difference in isobaric compliance and distensibility between normotensive and untreated hypertensive patients (Khder 1997, Laurent 1993). In our study, the maximum strain compliance, \( C_{\text{strain,max}} \), was significantly different between the control group (0.457 ± 0.101 um x mm Hg\(^{-1}\)), and the hypertensive group (0.353 ± 0.087 um x mm Hg\(^{-1}\)) and between the control group and the hypertensive group with hyperlipidemia (0.351 ± 0.079 um x mm Hg\(^{-1}\)).

Although the majority of the stiffness measurements were made for experimental and physiological studies rather than in clinical practice, there is significant evidence to indicate that a strong correlation exists between arterial stiffness and certain cardiovascular disease (Glasser 1997, Mackenzie 2002, Oliver 2003). Therefore, these stiffness measurements could have prognostic value or could be used as predictors of risk. In our studies, the strain compliance was determined in the loaded condition, and the maximum strain compliance was applied to evaluate the compliance of the radial artery. According to the unloading condition this was optimum. Finally, since our designed measurement method is simpler and easier than echo-based methods or MRI, the \( C_{\text{strain,max}} \) would be a useful predictor of cardiovascular events in hypertensive subjects. But, the repeatability of the measurements over time scales of minutes, hours and days remains to be assessed.

Reference


Khder Y, Bray-Desboscs L, Aliot E and Zannad Faiez 1997 Effects of blood pressure control on radial artery diameter and compliance in hypertensive patients Am. J. Hypertens 11 269-274.


Table 1. Characteristics of subjects

<table>
<thead>
<tr>
<th></th>
<th>Control Group (n=14)</th>
<th>Hypertension Group (n=23)</th>
<th>Hypertension with Hyperlipidemia Group (n=14)</th>
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<tbody>
<tr>
<td>Sex (men/women)</td>
<td>11/3</td>
<td>14/9</td>
<td>9/5</td>
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<tr>
<td>Age (years)</td>
<td>47 ± 11</td>
<td>53 ± 11</td>
<td>50 ± 11</td>
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<tr>
<td>BMI (kg/m²)</td>
<td>26 ± 2</td>
<td>27 ± 3</td>
<td>28 ± 2</td>
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<tr>
<td>SBP (mm Hg)</td>
<td>124 ± 11</td>
<td>151 ± 15**</td>
<td>155 ± 16**</td>
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<tr>
<td>DBP (mm Hg)</td>
<td>76 ± 11</td>
<td>87 ± 16</td>
<td>93 ± 16</td>
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<tr>
<td>PP (mm Hg)</td>
<td>48 ± 6</td>
<td>64 ± 14</td>
<td>62 ± 9</td>
</tr>
<tr>
<td>ASI (mm Hg)</td>
<td>34 ± 26</td>
<td>131 ± 81**</td>
<td>106 ± 87</td>
</tr>
<tr>
<td>T-Chol (mg/dl)</td>
<td>198 ± 32</td>
<td>208 ± 36</td>
<td>226 ± 39</td>
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<td>LDL-C (mg/dl)</td>
<td>107 ± 17</td>
<td>124 ± 19</td>
<td>136 ± 19</td>
</tr>
<tr>
<td>TG (mg/dl)</td>
<td>175 ± 32</td>
<td>162 ± 30</td>
<td>198 ± 30</td>
</tr>
<tr>
<td>C_strain_max (µm/mm Hg)</td>
<td>0.457 ± 0.101</td>
<td>0.353 ± 0.087</td>
<td>0.351 ± 0.079*</td>
</tr>
</tbody>
</table>

BMI, body mass index; SBP, systolic blood pressure; DBP, diastolic blood pressure; PP, pulse pressure; ASI, arterial stiffness index; T-Chol, total cholesterol; LDL-C, low-density lipoprotein; TG, triglyceride; *P < 0.05; **P < 0.005.
Figure 1. Schematic of the two-axis mechanism.

Figure 2. Structure of the sensor.
Figure 3. The full bridge circuit of the strain gauge.

Figure 4. The change of the cross-section of the radial artery follows the change of the blood pressure. The dot circle represents the diastolic blood pressure condition, the real circle represents the systolic blood pressure condition.
Figure 5. In X-axis scanning, each movement was 0.25 mm, and each capture comprised 2000 points. (a) The contact pressure, (b) The arterial diameter changed waveform.
Figure 6. In Z-axis scanning, each movement was 0.125 mm, and each capture comprised 2000 points. (a) The contact pressure, (b) The arterial diameter changed waveform.
Figure 7. Relationship between the contact pressure and the change of the vascular radius according Fig. 6 data.