A Vascular Characteristic Index of Blood Pressure Variation using the Pulse Wave Signal

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Pulse waves continuously change with respect to the characteristics and status of the cardiovascular system and in relation to the blood pressure (BP) and the pulse wave velocity (PWV). Monitoring the vascular condition by analyzing the variations in pulse waveforms has been used to diagnose vascular disorders and in drug treatment of arteriosclerosis and peripheral circulatory obstruction. In this paper, we investigated the vascular characteristic index with regard to the BP and classified by pulse wave signals. The pressure pulse wave and photoplethysmography (PPG) were measured simultaneously while subjects exercised, producing changes in the BP, to analyze the variation in the vascular characteristic index. We investigated the correlation between the BP and vascular characteristic index with regard to the classification methods of the pulse wave. The reflection index (RI) and vascular stiffness index were correlated with the diastolic BP, but no correlation was found between these parameters and the systolic BP. These results suggest the possibility of estimating BP through simple measurements of pulse waves.

Keywords : Pulse wave velocity (PWV), Photoplethysmography (PPG), Vascular characteristic index, Blood pressure(BP)

1. INTRODUCTION

The pressure, fluid, and volume waves produced during the cardiac cycle are transferred as pulse waves throughout blood vessels. These pulse wave signals are continuously influenced by the characteristics of the walls of the blood vessels and also change constantly according to the pulse transit time (PTT) and blood pressure (BP). The pulse wave velocity (PWV) increases in proportion to the wall thickness of the blood vessels and inversely to the radius of the blood vessels. The PWV can also increase due to age-related decreases in the compliance of blood vessels. The PWV in patients with hypertension appears to be high due to blood vessel compliance as well. Therefore, the PWV likely reflects the compliance of the human vascular system and depends on the stiffness of blood vessels. Furthermore, the PWV can gradually change over a lifetime or can be effectively changed in a short time due to vascular movement or medications such as vasodilator.

Studies have been performed on the clinical applications of monitoring vascular vessels through analyses of pulse waves. These studies have concentrated on tailoring medication therapy with regard to patient characteristics as well as vascular diseases such as arteriosclerosis and peripheral circulatory obstruction. Chowienczyk et al.[1] in 1999 and Gopaul et al.[2] in 2001 formulated the reflection index (RI) after recording photoplethysmography (PPG) and then evaluating the function of peripheral arterial blood vessels. In 2002, Millasseau et al.[3] and Oliver and Webb[4] proposed a stiffness index for blood vessels using the time difference between the arrival of the maximum point and peak of reflected waves in PPG and evaluated the stiffness of the aorta. Previous studies have investigated the indices of vascular characteristics, such as the RI and vascular stiffness index, using the conveniently measured PPG signal; however, an analysis of the shape of the pulse wave with regard to the method of measurement has not been attempted. Even though research has recently been performed using pulse waves measured in the peripheral artery, no study has analyzed the variation according to the BP, which reflects the characteristics of arterial blood vessels.

Accordingly, variation in the vascular characteristic index according to the BP was observed using pressure pulse wave and PPG signals measured at the same body site. The correlation between the BP and vascular characteristic index was evaluated with regard to the method of measuring pulse waves.

2. TRANSFER CHARACTERISTICS OF PULSE WAVES AND THE VASCULAR CHARACTERISTIC INDEX

2.1 Transfer characteristics of pulse waves

To understand the arterial pulsation, which is dependent on ventricular contraction and the properties of the arterial system, we must consider the arterial hemodynamics and the concept of progressive and reflective waves, which determine the relationship between systolic and diastolic BPs in the aorta and peripheral arteries. The pressure wave that is generated by cardiac output in the left ventricle and progresses to the peripheral arteries along the circulatory pathway is called the progressive wave. The reflective wave is generated in the opposite direction of the progressive wave due to the interaction between the progressive wave and a part of the blood vessel. The phase of the reflected wave lags behind that of the progressive wave, so the measured pressure waves at any position of the vascular system represent a superposition of the progressive wave from the heart to the peripheral circulatory system and the reflective wave progressing from the peripheral circulatory system to the heart[5]. The progressive wave is dependent on the left ventricular ejection and arterial stiffness, whereas the reflective wave is dependent on arterial stiffness and the position of reflection. Figure 1 represents progressive and reflective waves. A solid line indicates a pressure wave recorded by a pressure gauge. A dashed line denotes a progressive wave, and a dotted line represents a reflective wave.

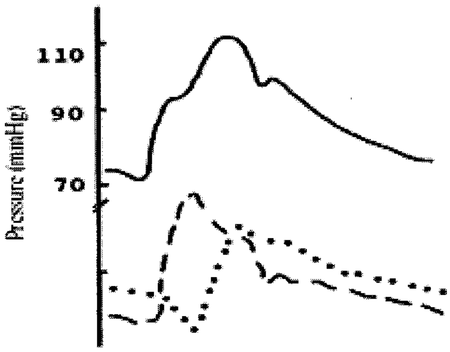

Fig. 1. Separation of progressive and reflective waves from the measured pressure pulse wave. (-) denotes the measured pressure pulse wave, (--) represents a forward incident wave, and (···) indicates a backward reflected wave.

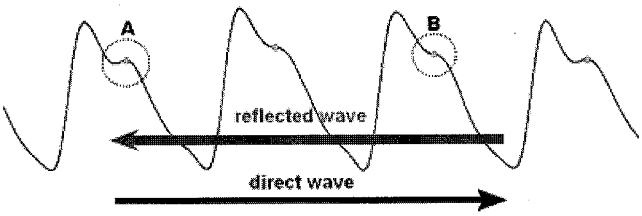

Fig. 2. Variation aspect of the pulse wave shape according to the arrival time of the reflective.

The pressure pulse wave changes in both amplitude and shape as it travels from the aorta to the peripheral arteries due to various factors, as follows. First, the magnitude of the pulse wave decreases due to the viscoelasticity of blood vessel walls and the viscosity of blood. Second, distortion of the signal occurs due to differences in the PWV with regard to the frequencies component. Third, the shape is changed and magnitude is amplified due to the reflected wave from the peripheral arteries. Fourth, the shape of the pulse wave is distorted due to the intrinsic vibration of living tissue. Fifth, the magnitude of the pulse wave at the peripheral artery is amplified due to a high stiffness of the blood vessel[7]. To observe the variation in the pulse wave shape according to the arrival time of the reflective wave, PPG was recorded in a finger as shown in Fig. 2. For healthy adults in their twenties or thirties, the shape of the inflection point is represented as a local maximum point as shown in (A) in Fig. 2, whereas the inflection point shown in(B) with the second differential value of 0 appears because the velocity of the reflected wave increases when the pulse wave becomes faster. These phenomena arise from the factors that influence the shape of the pulse wave such as the constantly changing characteristics of blood vessel walls in the arterial system[8].

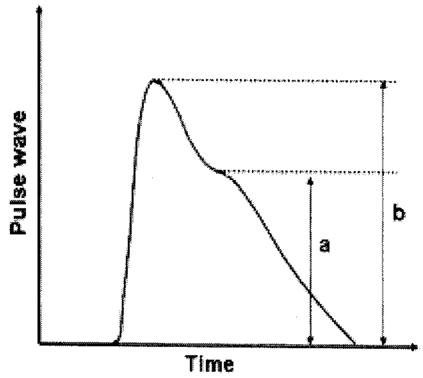

Fig. 3. Calculation method of the reflection index(RI) in the pulse wave signal.

2.2 Characteristic index of blood vessels

The RI represents the stiffness of the peripheral arteries. Even though for convenience, the RI is defined as the ratio of the magnitude of progressive and reflective waves separated from the pulse wave, it is determined as a percentage of the magnitude of the maximum point to the magnitude of the inflection point from the base point as shown in Fig. 3. The RI can be represented in numerical form as follows:

$$RI = \frac{a}{b} \times 100(\%) \quad (1)$$

where a is the magnitude of the inflection point in the pulse wave and b is the magnitude of the maximum point in the pulse wave.

The magnitude of the reflective wave in the pulse wave is related to the vascular tone. Accordingly, the variation aspect of the pulse wave signal is greatly influenced by the vasoconstriction and vasodilatation of blood vessels. The traveling velocity of the reflected wave increases as the PWV increases according to the increase in the stiffness of the peripheral arteries. Consequently, the time difference between the peaks of progressive and reflective waves decreases, and then the RI increases because the relative amplitude of the inflection point increases. The RI decreases as the stiffness of the peripheral arteries decreases. The RI is mainly used in clinical settings to evaluate the function of the endothelium of blood vessels after the prescription of a vasodilator[9].

The PWV varies according to the vascular state through variables such as the stiffness, elasticity, and compliance of blood vessels and appears different at different body sites. Variation in the velocity of the PWV is generated rapidly. The time in which the progressive and reflective waves in the pulse wave signal arrive is different according the pulse PTT. Accordingly, the reflection time index decreases as the stiffness of the blood vessel increases and the reflection time index increases as the stiffness of the blood vessel decreases. Therefore, the reflection time index is inversely proportional to the stiffness of the blood vessel.

The vascular stiffness index is recognized as being a vital index of the cardiovascular system, reflecting the stiffness of the aorta[3]. Reflective waves arrive faster as the rigidity of blood vessels increases. PTT acts as the major factor in aortic stiffness because the time delay changes according to the transit time and velocity of the pulse wave. The length of a blood vessel should be taken into account when calculating the vascular stiffness because the distance traveled by the pulse wave significantly influences the time delay of the reflective wave.

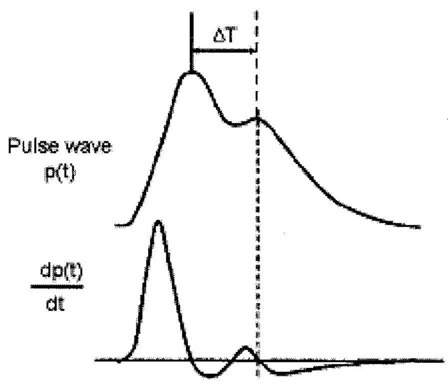

Fig. 4. Calculation method of the vascular stiffness index in the pulse wave signal.

The vascular stiffness index can be calculated from the time difference between when the progressive wave is transmitted and the reflective wave arrives divided by the height as shown in Fig. 4. The inflection point to calculate the arrival time of the reflective wave was detected using the derivative signal of the pulse wave. The equation to calculate the vascular stiffness index can be given as follows:

$$SI = \frac{H}{\Delta T} \quad (ms) \tag{2}$$

where T is the time difference between the progressive and reflective waves and H is the height. The PWV increases as aortic stiffness increases. Therefore, the vascular stiffness index increases as the arrival time difference between the progressive and reflective waves is shortened.

3. DETECTION METHOD OF THE VASCULAR CHARACTERISTIC INDEX

The characteristic points, namely, the maximum point in the systolic period and minimum point in the diastolic period, and the magnitude and time information of the inflection point according to the reflective wave were detected to calculate the vascular characteristic index such as the RI and vascular stiffness index in the pressure pulse wave and PPG signal. Although the inflection point in the pulse wave is the peak of the reflective wave, inferring the shape of the real pulse wave, according to nomenclature of other studies, this point is used in this work as the inflection point of the pulse wave signal. Detecting the inflection point generated by the reflective wave, which is dependent on the shape of the pulse wave, is not easy. The position of the inflection point can appear as a local maximum point even for a normal person and can be represented by the 2nd differential of 0 because the progressive velocity becomes faster as the velocity of the pulse wave increases.

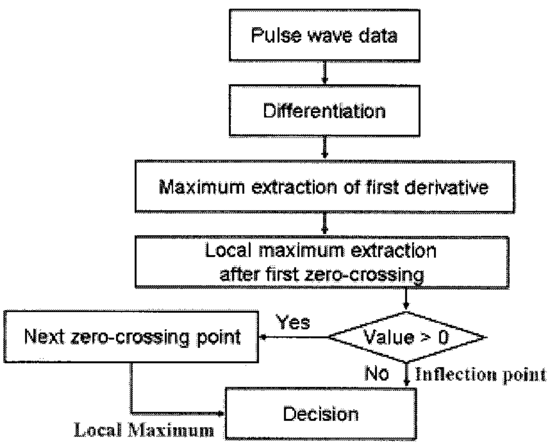

Fig. 5. Flowchart showing the signal processing of extracting various inflection points in the pulse wave signal.

The proposed flowchart of signal processing to extract the various inflection points in the pulse wave signal is shown in Fig. 5. The inflection point in the pulse wave is detected as a local maximum point after connecting the intersection point of 0 after detecting the maximum point. The inflection point corresponding to B in Fig. 2 is detected when the value of the local maximum detected in the pulse wave is negative, whereas the inflection point corresponding to A in Fig. 2 is detected when the value of the local maximum detected in the pulse wave is positive. The maximum point in the systolic period, minimum point in the diastolic period, and inflection points from the reflective wave could be extracted from the pulse wave signal. The extracted characteristic points for calculating the vascular characteristic index in the pressure pulse wave and PPG signals are shown in Fig. 6. The detection method of the inflection point can induce detection error when noise occurs in the pulse wave; however, the detection error can be significantly reduced by applying a low-pass filter with a cutoff frequency of 20 Hz to the pulse wave signal.

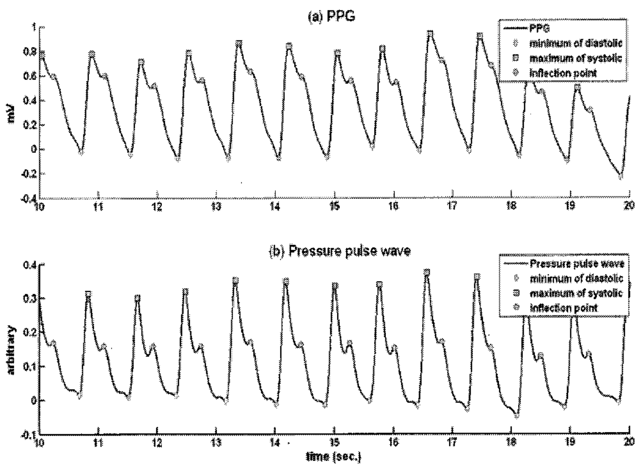

Fig. 6. Characteristic points extracted for calculating the vascular characteristic index in the pulse wave signal.

The RI and the vascular stiffness index were extracted using equations (1) and (2), after the characteristic points in the pulse wave signal were extracted to calculate the vascular characteristic index. The magnitude and shape of the pressure pulse wave and PPG signal exhibited the most difference at the inflection point, as shown in Fig. 6. As a result, we can see that more information on the reflective wave would be obtainable if the transfer functions of the pressure pulse wave and PPG were extracted.

4. EXPERIMENTAL RESULTS AND CONSIDERATIONS

The velocity of the reflective wave in the pulse wave signal increased as the PWV increased due to the increase in BP. The magnitude of the peak of the reflective wave increased as the difference in the arrival time between the progressive wave and reflective wave lessened. Due to these phenomena, we can predict that the more the BP increases, the more the RI and the vascular stiffness index increase.

We observed the variation in the vascular characteristic index according to the variation in BP, and examined the correlation between the BP and the vascular characteristic index using the pulse wave signal and the PPG, which were measured at the same body site. The variation aspect of the vascular characteristic index according to the BP was investigated 20 times in a healthy male subject without vascular disease. The BP of the subject was controlled through exercise, such as climbing stairs, and the pressure pulse wave, PPG, and BP were simultaneously measured. A combined sensor that could detect the pressure pulse wave and PPG at the same site in the body was fixed on the middle finger of the left hand, and the cuff was attached on the right upper arm to measure the BP. A PPG-Amp (PhysioLab, Korea) was used to measure the PPG signal and the bridge-Amp (PhysioLab) for monitoring the pressure pulse wave was used as the signal amplifier of the pulse wave signal. Measured data were recorded with a 12-bit A/D converter at a sampling rate of 1 kHz using an iDAQ400 (PhysioLab). The reference sphygmomanometer in the measurement system was a BP-1 (Casio, Japan).

The information on the real BP measured from the subject and simple statistics of the vascular characteristic index, which is variable according to the BP, are shown in Table 1. The BP measured with the reference sphygmomanometer showed a systolic BP of 110-137 mmHg and a diastolic BP of 65-80 mmHg.

systolic BP, indicating a low dispersion. According to Table 2, the variation in the RI according to the diastolic BP indicated that the correlation was below 0.05 and the correction coefficient was above 0.7.

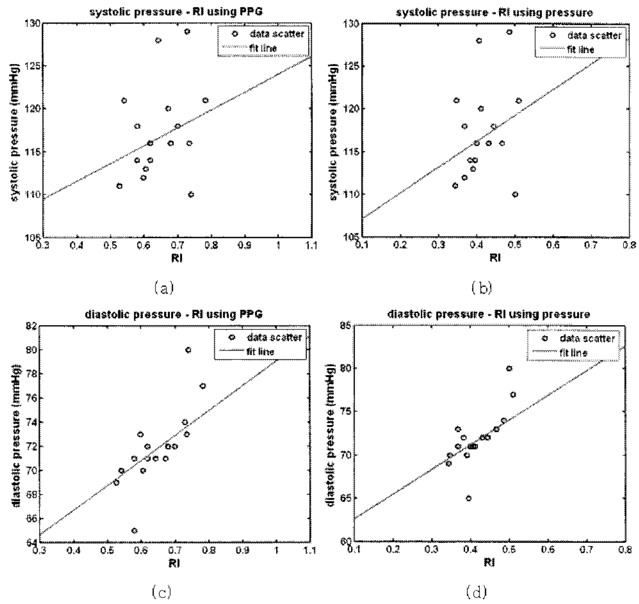

Fig. 7. The variation aspect of the reflection index according to variation inthe systolic and diastolic BPs (a) between the systolic BP and the reflection index calculated from the PPG, (b) between the systolic BP and the reflection index calculated from the pressure pulse wave, (c) between the diastolic BP and the reflection index calculated from the PPG, and (d) between the diastolic BP and the reflection index calculated from the pressure pulse wave.

Table 1. The mean and standard deviation in SMA and SVM according to walking speed changes.

		Number	Mean ± S.D.	Min.	Max.
Blood Pressure	Systolic	20	118.1 ± 5.888	100	137
	Diastolic	20	72.38 ± 3.517	65	80
RI	PPG	20	0.6470 ± 0.089	0.437	0.947
	Pressure	20	0.4164 ± 0.060	0.271	0.646
SI	PPG	20	8.109 ± 1.538	6.560	31.260
	Pressure	20	6.817 ± 0.721	6.024	15.110

Table 2. Correlation between the BP and the vascular characteristic indices.

	Index	Method	Correlation Coefficient	RMSE	p-value
Systolic Pressure	RI	PPG	0.287	4.290	0.282
		Pressure	0.254	4.093	0.342
	SI	PPG	0.094	5.807	0.729
		Pressure	0.341	4.095	0.196
Diastolic Pressure	RI	PPG	0.748	1.261	0.001
		Pressure	0.733	0.850	0.001
	SI	PPG	0.697	2.550	0.003
		Pressure	0.562	1.435	0.023

The variation in the RI according to variations in the systolic and diastolic BPs is shown in Fig. 7, and the correlation between the BP and RI is given in Table 2.

As shown in Fig. 7, the RI exhibited a positive correlation with the systolic and diastolic BPs, but the diastolic BP represented a higher correlation than the

In contrast, the RI was not correlated with the systolic BP. The method using the PPG signal showed a correlation coefficient of 0.748 for the diastolic BP and exhibited a somewhat higher correlation than that using the pressure pulse wave, which had a correlation coefficient of 0.733. However, the method using the pressure pulse wave with a RMSE of 0.850 exhibited less errors than that using the PPG signal with a RMSE of 1.261.

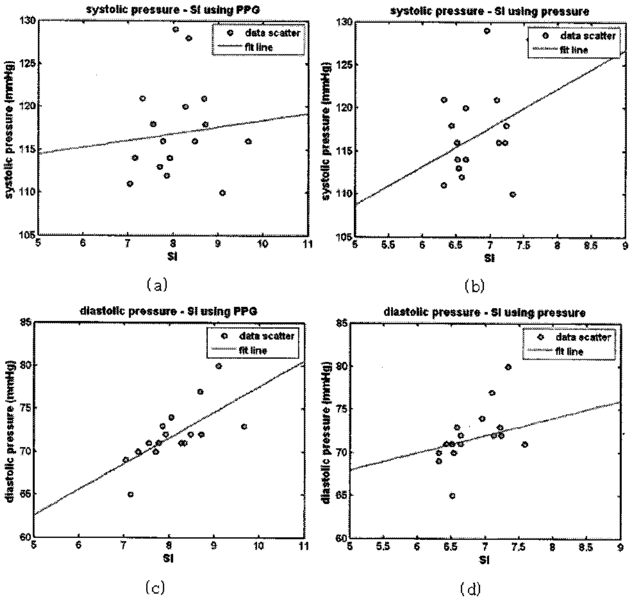

Fig. 8. The variation in the stiffness index according to the transition between systolic and diastolic BP (a) between the systolic BP and RI calculated from the PPG, (b) between the systolic BP and RI calculated from the pressure pulse wave, (c) between the diastolic BPand RI calculated from the PPG, and (d) between the diastolic BP and RI calculated from the pressure pulse wave.

The variation in the vascular characteristic indices, such as the RI and vascular stiffness index, according to the variation in BP can be summarized as follows. First, the variation in vascular characteristic indices proposed in this study exhibited a very high correlation with the variation in the diastolic BP, but was observed to be unrelated to the variation inthe systolic BP. Second, the vascular characteristic index extracted from the PPG signal had a higher RMSE and correlation than that from the pulse pressure wave in RMSE based on the variation in the diastolic BP.

The possibility of accessing the diastolic BP was shown by using the pulse wave obtained from a finger, even though some limitations, for example, few data points to analyze the data as well as a narrow range of the BP did exist. The low correlation between the vascular characteristic index and the systolic BP arises from the motion noise caused by the tachypnea after exercise. Accordingly, we can assess the BP conveniently if we extract an equation to evaluate the BP related to the correlation between the BP and the vascular characteristic index. Hereafter, this work can be applicable to developing real-time monitoring equipment of the cardiovascular system and the long-time monitoring of BP.

5. CONCLUSION

We examined the variation aspect of the vascular characteristic index according to BP using the pulse wave signal and the PPG measured at the finger. The correlation between BP and the vascular characteristic index according to method of measurement was also investigated. The variation in the RI and vascular stiffness index from the pressure pulse wave and PPG signal according to BP indicated a high correlation, with statistical significance below 0.05 and a correction coefficient above 0.5, to the diastolic BP; however, no correlation with the systolic BP was detected. These results suggest the possibility of partially assessing the BP only from measuring the pulse wave. Thus, a new technique of measuring BP that is applicable to home health care can be realized through supplementary research.

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