Development paper:

**Simple and Noninvasive Estimate of Systemic Arterial Compliance by Using Peripheral Arterial Blood Pressure Waveform in Elderly People**

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[Received January 17, 2003; accepted February 2, 2003]

Systemic arterial compliance (SAC) defining the hemodynamics for the aged can be calculated from the blood pressure waveform of the carotid artery recorded by applanation tonometry (AT). However, the recording of the waveform by AT is not easy. This study was intended to investigate the validity of evaluation method of SAC using volume clamp method (VC) at peripheral artery (finger artery). Continuous blood pressure waveform was measured using VC and AT for 47 elderly patients. Blood pressure waveform of finger artery was transformed by transfer function into waveform of brachial artery. Significant correlation (r=0.73) between the measured values of the ratio of the area under arterial blood pressure waveform at one heart beat cycle and at left ventricular diastole by VC and AT was observed, and its agreement was good. As a consequence, validity of the method using waveform of brachial artery transformed from the blood pressure waveform recorded at peripheral artery by VC was verified as a noninvasive estimate of systemic arterial compliance for elderly people.

**Keywords:** volume clamp method, applanation tonometry, area method

[International Journal of Sport and Health Science Vol.1 (1) 136–141]

1. Introduction

Arterial distensibility is an important blood vessel factor defining the hemodynamics. Especially, it is considered to be very influential in circulatory function for elderly people as it is well known that arterial distensibility is reduced due to aging [Avolio et al. (1983); Avolio et al. (1985); Kanda et al. (2000)]. This means that the reduction of arterial distensibility leads to the increase of systolic blood pressure and to the increase of left ventricular after load, and the blood pressure reduction at diastole following the reduction of arterial distensibility results in the reduction of coronary blood flow [Belz (1995)]. Therefore, arterial distensibility can be considered to be an important risk factor of cardiovascular disorder. Recent study showed that for 710 elderly patients, significant correlations between arterial distensibility and cardiovascular disorders were observed (r= 0.44~0.50) and its influence on risk was stronger than that of blood pressure and that of smoking habit [Blacher et al. (1999)]. Also, follow-up of epidemiological study of 1980 middle aged male and female for average of 9.3 years suggests that arterial distensibility can be an independent risk factor of death caused from cardiovascular disorders [Laurent et al. (2001)]. Consequently, maintenance and increase of arterial distensibility is an important issue for maintaining the health of the elderly and it is necessary to develop the relevant study on this issue.

SAC (Systemic Arterial Compliance) is one of the evaluation indices of arterial distensibility. SAC is defined as the change in blood volume relative to a given change in distending pressure and can be calculated from the blood pressure waveform of central artery according to Windkessel Model [Liu et al. (1986)]. Although it is not possible to record the blood pressure waveform of central artery noninvasively, especially, aorta, it can be replaced by the record of blood pressure waveform at carotid artery by noninvasive way, such as AT (Applanation Tonometry) [Cameron and Dart (1994)].

The record of carotid arterial blood pressure wave-
form by AT can be made by percutaneous contact of the sensor on the subject’s artery. However, the subject is obliged to be in supine position. In case, when the subcutaneous fat of the subject is thick or the blood pressure is low, it is not easy to record the blood pressure waveform by positioning the sensor precisely at the carotid artery. Therefore, it is highly appreciated to have a simple and easy recording method of the blood pressure waveform. One of the simple and noninvasive recording method of blood pressure waveform is VC (Volume Clamp method) using Portapres (TNO-TPD Biomedical Instrumentation) [Langewouters et al. (1998); Staessen et al. (1995)]. This method can record the blood pressure waveform of peripheral artery (finger artery). By using the attached analysis software, the blood pressure waveform recorded at finger artery can be transformed into the blood pressure waveform of brachial artery by a transfer function. Although the transformed blood pressure waveform of brachial artery is in good agreement with the real waveform [Bos et al. (1996); Gizdulich et al. (1996); Gizdulich et al. (1997)], it is not yet verified that the waveform can be used for calculation of SAC.

The purpose of this study was to investigate the validity of the blood pressure waveform of finger artery recorded by VC as a simple and noninvasive estimate of systemic arterial compliance. In this study, both the blood pressure waveform of finger artery by VC and blood pressure waveform of carotid artery by AT were recorded at the same time. Then after the blood pressure waveform of finger artery by VC was transformed into the blood pressure waveform of brachial artery, SAC calculated from each waveform and the values of each component included in the calculation formula were compared.

2. Materials and Methods

2.1. Subjects

Subjects were 16 elderly males (59-79 years old) and 31 elderly females (50-76 years old). Table 1 shows physical characteristics and hemodynamics including SBP (Systolic Blood Pressure), DBP (Diastolic Blood Pressure), MBP (Mean Blood Pressure) and HR (Heart Rate) of the subjects. All the subjects were informed of the purpose and contents of the study and consent of the subjects was obtained.

2.2. Measurements

After maintaining rest for more than 15 minutes at supine position, the subjects were measured and recorded for blood pressure waveform at finger artery by VC using Portapres. At the same time, the blood pressure waveform at carotid artery was recorded by using recording instrument according to AT (form PWV/ABI, Colin). SBP, DBP and MBP were measured at brachial artery just before recording of the blood pressure waveform by using oscillometry stored in the recording instrument in order to transform the recorded blood pressure waveform by AT into the absolute value.

2.3. Data Analysis

Continuous record for 15 seconds was used for analysis of the blood pressure waveform. Finger arterial blood pressure waveform by VC was numerically transformed at 100 Hz and was taken into the computer. Then, by using analysis software (Beat scope, TNO-TPD Biomedical Instrumentation) to correct the waveform distortion and the blood pressure difference between central and peripheral vessel, the finger arterial blood pressure waveform was transformed by using transfer function into brachial arterial blood pressure waveform. Carotid arterial blood pressure waveform by AT was numerically transformed at 1200 Hz and was taken into the computer (BTFC 1.1, Colin). Transformation of carotid arterial blood pressure waveform into the absolute value was made by using MBP measured at brachial artery following the previous study [Cameron and Dart (1994)].

SAC can be calculated from the following formula using blood pressure waveform and SV (Stroke Volume) according to the area method [Liu et al. (1986)].

\[
\text{SAC} = \frac{\text{SV}}{K \times dP}
\]

where: \( K = \) area under the arterial blood pressure
Fig. 1. Relationships between systemic arterial compliances measured by using volume clamp method (SACc) and applanation tonometry (SACa). CI, Confidence interval.

Fig. 2. Relationships between ratios of area under the arterial blood pressure waveform measured by using volume clamp method (Kc) and applanation tonometry (Ka). CI, Confidence interval.

Fig. 3. Relationships between blood pressure differences (end systolic phase-end diastolic phase) measured by using volume clamp method (dpv) and applanation tonometry (dp). CI, Confidence interval.

waveform at left ventricular systole and at left ventricular diastole / area under the arterial blood pressure waveform at left ventricular diastole

\[ dp = \text{left ventricular end systolic blood pressure - left ventricular end diastolic blood pressure} \]

K and dp were calculated at each heart beat by using blood pressure waveform according to VC and AT for 15 seconds, and mean value for 15 seconds was obtained. The area under the arterial blood pressure waveform was obtained by integration of numerical blood pressure waveform. SV was calculated at each heart beat according to Modelflow Method [Wesseling et al. (1993)] from the finger arterial waveform recorded by VC using analysis software (Beat scope, TNO-TPD Biomedical Instrumentation). Mean value for 15 seconds was obtained. The validity of blood flow volume measured in this method has been verified in comparison with that of thermodilution method [Harms et al. (1999); Wesseling, et al. (1993)].

2.4 Statistics

Measured value are shown in mean ± standard deviation. The degree of the correlationship and agreement of SAC (each SACc and SACa) calculated from the blood pressure waveform recorded by VC and AT, K (each Kc and Ka) and dp (each dpv and dp) were analyzed by using Pearson’s simple correlation coefficient and Bland and Altman (1986) method. In the latter case, 95% confidence interval of the difference [mean of the difference ± (1.96 × standard deviation of the difference)] and 95% confidence interval of the bias [mean of the difference ± (standard error of the difference × t): t is a t distribution of freedom (number of specimen -1)] were calculated. Stat View 5.0 J (SAS Institute Inc.) was used for every statistical analysis in this study.

3. Results

A high significant correlationship (r=0.75, Fig.1) was observed between SACVC (1.18±0.36 ml/mmHg) and SACAT (1.11±0.36 ml/mmHg). But the analysis according to Bland and Altman (1986) showed the difference of 0.07±0.25 (95% confidence interval of the difference: -0.43 ~ -0.56, 95% confidence interval of the bias: 0.00 ~ -0.14) (Fig.1), and thus, the agreement of both values was not satisfactory. On the other hand, a high significant correlationship was observed (r=0.73, Fig.2) between KVC (1.64±0.13) and KAT (1.71±0.13) and the difference of both values was -0.07±0.09 (95% confidence interval of the difference: -0.26 ~ -0.11, 95% confidence interval of the bias: -0.10 ~ -0.04) (Fig.2), and thus, there was a good agreement. Significant and medium positive corelationship was observed (r= 0.67, Fig.3) between dpVC (27.1±6.9 mmHg) and dpAT (27.3±5.3 mmHg). And the difference of both values was -0.19±5.2 (95% confidence interval of the difference: -10.4 ~ 10.0, 95% confidence interval of the bias: -1.7 ~ 1.3) (Fig.3).
4. Discussion

The blood pressure waveform of central artery is used to calculate SAC, and the ratio of the area under the arterial blood pressure waveform at one heart beat cycle against the area under the arterial blood pressure waveform at left ventricular diastole (K) is used to calculate SAC in order to reduce the influence of distortion of blood pressure waveform caused by reflection wave from the peripheral artery in the area method proposed by Liu et al (1986). In this study, the validity to calculate SAC by transforming the blood pressure waveform recorded noninvasively at finger artery via transfer function into the waveform at brachial artery [Bos et al. (1996); Gizdulich et al. (1996); Gizdulich et al. (1997)] has been investigated. The blood pressure waveform used for comparison was a blood pressure waveform recorded noninvasively by AT at carotid artery. This blood pressure waveform is used to calculate SAC in a number of previous studies [Cameron and Dart (1994); Cameron et al. (1999); Kingwell et al. (1995); Kingwell et al. (1997); Kingwell et al. (2002); Rajkumar et al. (1997a); Rajkumar et al. (1997b); Waddell et al. (2001)]. There was a good correlation between $K_{sv}$ obtained by VC and $K_{at}$ obtained by AT recorded at the same time and also the values were in good agreement. However, although there were significantly high correlation between SAC$_{sv}$ and SAC$_{at}$ calculated based on SV measured by VC, K obtained by each blood pressure waveform and blood pressure difference between ventricular end systole and end diastole, the degree of the agreement was not so high.

In case of VC, after winding up of inflatable cuff stored infrared plethysmograph and maintaining the constant arterial vessel volume by adjusting the inner pressure of cuff by servo system, the change of the volume is transformed into the blood pressure and recorded [Wesseling et al. (1985)]. But the blood pressure waveform of peripheral artery is different from that of central artery due to the distortion caused by reflection wave [Bos et al. (1996)]. Therefore, with regard to the blood pressure waveforms of central artery and peripheral artery, the area under arterial blood pressure waveform to be used for SAC calculation by the area method [Liu et al. (1986)] and the blood pressure difference at left ventricular end systole and at left ventricular end diastole may be different. However, with regard to Portapres and Beat scope, blood pressure waveform of finger artery is transformed into blood pressure waveform of brachial artery with a modification of distortion and as a result, the transformed blood pressure waveform will be in good agreement with invasively recorded waveform at brachial artery [Bos et al. (1996); Gizdulich et al. (1996); Gizdulich et al. (1997)]. However, the error of about 9 (14) mmHg and about 7 (12) mmHg in the absolute value of the blood pressure are observed at ventricular systole and at ventricular diastole respectively [Bos et al. (1996); Gizdulich et al. (1997)]. Hence, by correcting this using the relationship between the error and the blood pressure, the absolute value of blood pressure was found to be resulted in good agreement with the invasively recorded value at brachial artery [Bos et al. (1996); Gizdulich et al. (1997)]. The recent study [Westerhof et al. (2002)] of 24 hour continuous blood pressure measurement in daily routine life showed the blood pressure difference of 1 (11) mmHg and -2 (7) mmHg for VC and invasive method at brachial artery respectively, and both were in good agreement. Although there is a difference between the blood pressure waveform at brachial artery and the blood pressure waveform at central artery, its difference is said to be small for the elderly [Nichols and O’Rourke (1988)]. Therefore, if the blood pressure waveform of finger artery is transformed into the blood pressure waveform of brachial artery, it can be used at least for the elderly in place of blood pressure waveform of central artery.

Cameron and Dart (1994) have verified the validity of the method the noninvasively recorded blood pressure at carotid artery for SAC calculation. In their study, total 74 heart beat blood pressure waveforms of 3 subjects were recorded at carotid artery by AT and also invasively recorded by manometry using catheter. They were in good agreement, although damping speed of carotid arterial pressure was slightly higher at ventricular diastole. When compared the area under the arterial blood pressure waveform at left ventricular diastole calculated from each of them, high correlation was found among them, and examination for bias using the method of Bland and Altman (1986) was negative. In our study, the finger arterial blood pressure waveform for 47 elderly patients was recorded and then transformed into brachial arterial blood pressure waveform and at the same time carotid arterial blood pressure waveform was recorded. Mean values for 15 seconds of each ratio of area under the arterial blood pressure waveform was compared and significantly high correlation was observed. Agreement was also good. Therefore, as far as the area method is used, the method using brachial arterial blood pressure waveform transformed by transfer function from peripheral arterial blood pressure waveform is suggested to have the equivalent validity to the method using the
blood pressure waveform of carotid artery.

There was a high correlation between $K_{BC}$ and $K_{SV}$ and agreement of the value was also good. However, although there was a high correlation between $SAC_{BC}$ and $SAC_{SV}$, the agreement was not so high. For calculation of SAC, not only area ratio but also the blood pressure difference at ventricular end systole and at ventricular end diastole, and SV are required [Liu et al. (1986)]. In this study, the common value obtained from the blood pressure waveform of VC was used as SV. But blood pressure difference was obtained from each blood pressure waveform. As the blood pressure waveform by VC is recorded as an absolute value at each heart beat, the blood pressure difference can be easily obtained. But as the blood pressure waveform by AT is recorded as a relative value, the blood pressure difference obtained by correcting the mean blood pressure measured at brachial artery can be used for SAC calculation [Cameron and Dart (1994)]. In this study, the mean blood pressure measured at brachial artery was used for calibration of the blood pressure by AT. When compared the blood pressure difference obtained in this way with the blood pressure difference measured as absolute value by VC, correlation coefficient and degree of agreement was relatively poor. While the blood pressure difference by VC was a mean of the absolute values obtained at each heart beat, the blood pressure difference by AT was a corrected one of mean value of the relative value of the blood pressure difference by the mean blood pressure of brachial artery. Mean blood pressure at brachial artery was based on one measurement, and it was not measured at the same time. This may be attributed to the blood pressure difference, and to also relatively poor agreement of SAC. This result suggests that VC is more reliable than AT in SAC calculation.

In this study, SV was obtained from the blood pressure waveform of VC by using Modelflow Method [Wesseling et al. (1993)]. Modelflow Method is a technique to calculate SV from the blood pressure waveform by simulating the relationship of arterial characteristics between the blood flow volume and the blood pressure. The validity of the measurement of SV by Modelflow Method for the elderly at rest position is already verified by the previous study [Wesseling et al. (1993)]. With regard to VC, SV at one heart beat by Modelflow Method, the area ratio and the blood pressure difference can be at the same time calculated from the record of the same blood pressure waveform. In case of SAC calculation by AT, SV is required to be measured by using ultrasonic Doppler method [Cameron and Dart (1994); Cameron et al. (1999); Kingwell et al. (1995); Kingwell et al. (1997); Kingwell et al. (2002); Rajkumar et al. (1997a); Rajkumar et al. (1997b); Waddell et al. (2001)]. Although the recording of the blood pressure waveform by AT requires supine position, the recording of the blood pressure waveform by VC requires only sitting position. Therefore, in comparison with the conventional AT, the method used in this study has an advantage of short time required for measuring, labor saving and limited space. These advantages are important for the measurement of a number of subjects, for the measurement during the exercise. Therefore, it is very significant that the validity of SAC measurement by this method has been verified. By applying this method, further development of study areas such as the relationship between SAC and life style related diseases and the relationship between SAC and the exercise can be expected to be pursued.

5. Conclusion

The validity of the method using the blood pressure waveform at brachial artery transformed from the recorded blood pressure waveform at peripheral artery has been verified as a simple and noninvasive estimate of systemic arterial compliance.

Acknowledgments

This work was supported by grants-in-aid for scientific research (14380008) and Special Coordination Funds of the Ministry of Education, Culture, Sports, Science and Technology, the Japanese Government.

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International Journal of Sport and Health Science
Vol.1 No.1, March 2003