Noninvasive Estimate of Systemic Arterial Compliance by Using Peripheral Arterial Blood Pressure Waveform during Light Exercise in Elderly People

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Systemic arterial compliance (SAC) for the aged is a very important index in hemodynamics during exercise. In this study, the blood pressure waveform used for calculation of SAC was noninvasively recorded at finger artery by volume clamp method (VC) and compared with the method recorded by applanation tonometry (AT) at carotid artery, and usefulness and validity of this method were investigated. Continuous blood pressure waveform was recorded using VC at finger artery and AT at carotid artery during the light exercise for 22 elderly patients. The blood pressure waveform by VC was transformed by transfer function into the waveform of brachial artery. The ratio of the subjects recorded with stable waveform was 64% by AT while that of VC is 100%. Significantly high correlation-ship ($r=0.89$) between the measured values of the ratio of the area under the arterial blood pressure waveform at one heart beat cycle and at left ventricular diastole by VC and AT was observed, and its agreement was very good. As a consequence, it is supposed to be valid to use the method using blood pressure waveform recorded at peripheral artery by VC as a noninvasive estimate method of SAC for the elderly people during light exercise.

Keywords: volume clamp method, applanation tonometry, area method

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1. Introduction

SAC (Systemic Arterial Compliance) is an index of Windkessel function of aorta and central artery [Keucherer et al. (2000)]. When SAC reduces, left ventricular afterload increases due to the increase of systolic pressure, and following the increase of pulse pressure with the reduction of diastolic pressure results in the reduction of coronary blood flow [Belz (1995)]. In case of endurance exercise in which increase of cardiac output and coronary blood flow are required, increase of systolic pressure and pulse pressure is supposed to be a critical factor in hemodynamics. SAC can be defined as an index of arterial distensibility and the change in blood volume relative to a given change in distending pressure. Since the arterial distensibility is said to be degraded by aging [Avolio et al. (1983); Avolio et al. (1985); Kanda et al. (2000)], the influence of SAC on hemodynamics during exercise is espe-

cially important for the elderly people. Therefore, if the method to evaluate SAC non-invasively during exercise for the elderly is developed, very important and useful information on exercise physiology will be obtained.

SAC can be calculated from the blood pressure waveform of central artery and SV (Stroke Volume) at one heart beat by using Windkessel Model [Liu et al. (1986)]. Since it is not possible to record the blood pressure waveform of central artery non-invasively, especially, aorta, it was used to be replaced by the record of blood pressure waveform at carotid artery by non-invasive way, such as AT (Applanation Tonometry). The validity of this method was verified by comparing the invasively recorded aortic blood pressure waveform by manometry with the area under the arterial blood pressure waveform [Cameron and Dart (1994)]. The record of carotid arterial blood pressure waveform by AT can be made by percutaneous contact of the

sensor on the subject's artery. However, it is not easy to place the sensor exactly at the right position of carotid artery and to record the blood pressure waveform when the subcutaneous fat of the subject is thick or the subject is during exercise. Therefore, there is no study reported on investigating SAC during exercise. This is because of its difficulty of its measurement. It is necessary to develop noninvasive recording method of the blood pressure waveform in place of AT in order to study SAC of the elderly during exercise. One of the noninvasive recording method of blood pressure waveform is VC (Volume Clamp method) using Portapres (TNO-TPD Biomedical Instrumentation) [Staessen et al. (1995); Langewouters et al. (1998)]. We [Otsuki et al. (in press)] have transformed the blood pressure waveform of peripheral artery (finger artery) by VC into the blood pressure waveform of brachial artery by a transfer function [Bos et al. (1996); Gizdulich et al. (1996); Gizdulich et al. (1997)] and investigated the validity of this method on SAC calculation at rest position. As Portapres is a measurement instrument developed to measure the blood pressure continuously in daily life, it is thought to be applied to evaluate SAC during exercise, however, no investigation on its validity is ever reported.

The purpose of this study was to investigate the validity of the blood pressure waveform of finger artery recorded by VC as a noninvasive estimate of SAC for the elderly during exercise. 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 during the exercise, and its easiness of recording and the ratio of the area under the blood pressure waveform calculated from each waveform were compared after the blood pressure waveform of finger artery by VC was transformed into the blood pressure waveform of brachial artery.

2. Materials and Methods

2.1. Subjects

Subjects were 11 elderly males (61~78 years old) and 11 elderly females (60~76 years old). Males were mean (standard deviation) age of 68.8 (5.5) years old, height of 163.7 (3.4) cm, weight of 59.7 (3.4) kg, body mass index (BMI) of 22.3 (1.2) kg/m². Females were age of 66.8 (5.4) years old, height of 150.3 (3.3) cm, weight of 56.8 (7.1) kg and BMI of 25.1 (3.0) kg/m². 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 confirmed by the monitor to obtain the stable blood pressure waveform at finger artery by VC using continuous recording instrument (Portapres, TNO-TPD Biomedical Instrumentation) and then SBP (Systolic Blood Pressure), DBP (Diastolic Blood Pressure), MBP (Mean Blood Pressure) and HR (Heart Rate) were measured. Also it was confirmed that stable blood pressure waveform at carotid artery were available by the monitor of the recording instrument according to AT (form PWV/ABI, Colin).

Then the subjects performed a light exercise (30 W, 5 minutes) by putting inferior limb on bicycle ergometer (232CXL, Combi Wellness) in supine position. During exercise, the record of blood pressure waveform by VC at finger artery and measurement of SBP, DBP, MBP and HR was continuously made. Just before the finish of the exercise, continuous blood pressure waveform by AT at carotid artery was recorded.

The finger arterial blood pressure waveform by VC was numerically taken into computer at 100 Hz and transformed into brachial arterial blood pressure waveform by analysis software (Beat scope, TNO-TPD Biomedical Instrumentation). By using Beat scope, correction of the blood pressure waveform difference between central and peripheral arteries due to the distortion with transfer was performed [Gizdulich et al. (1997)]. The blood pressure waveform at carotid artery by AT was numerically taken into computer at 1200 Hz (BTFC 1.1, Colin).

2.3. Data Analysis

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

$$SAC = SV / K \times dP$$

Where : K = area under the arterial blood pressure waveform at left ventricular systole and at left ventricular diastole / area under the arterial blood pressure waveform at left ventricular diastole

dP = left ventricular end systolic blood pressure
- left ventricular end diastolic blood pressure

K was 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.

Table 1. Number of subjects in whom favorable or poor record of carotid arterial blood pressure waveform was obtained.

		n	rate (%)	age (years old)
Male	Total	11	100	68.8 (5.5)
	Favorable record	10	91	69.1 (5.7)
	Poor record	1	9	66.0 (-)
Female	Total	11	100	66.8 (5.4)
	Favorable record	4	36	65.8 (6.6)
	Poor record	7	64	67.4 (5.0)

Values of age are mean (S. D.)

Table 2. Hemodynamics of subjects at rest and during exercise.

Parameters	Subjects	n	Rest	Exercise
SBP (mmHg)	Total	14	125 (20)	161* (22)
	Male	10	123 (19)	157* (23)
	Female	4	132 (14)	171 (17)
DBP (mmHg)	Total	14	66 (8)	78* (8)
	Male	10	69 (9)	79* (8)
	Female	4	61 (6)	75* (6)
MBP (mmHg)	Total	14	89 (11)	110* (12)
	Male	10	89 (12)	109* (14)
	Female	4	88 (7)	112* (10)
HR (beat / min)	Total	14	64 (12)	84* (11)
	Male	10	69 (16)	83* (13)
	Female	4	59 (9)	87* (7)
% HRreserve (%)	Total	14	0 (0)	20.8* (9.1)
	Male	10	0 (0)	17.6* (4.6)
	Female	4	0 (0)	28.7* (13.4)

SBP, systolic blood pressure; DBP, diastolic blood pressure; MBP, mean blood pressure; HR, heart rate; *, p < 0.05 vs rest; values are mean (S. D.).

SBP, DBP, MBP and HR at rest and during exercise were measured by VC at each heart beat and mean value for 15 seconds were obtained. In order to evaluate the degree of exercise load, % HRreserve (the ratio of increased HR during exercise against HR reserve for the age) was calculated from the following formula.

$$\% \text{ HRreserve} = (\text{HR during exercise} - \text{HR at rest}) \times 100 / \{ (220 - \text{Age}) - \text{HR at rest} \}$$

2.4. Statistics

Measured values are shown in mean $\pm$ standard deviation. The degree of the correlation and agreement of K (K_{VC} and K_{AT} , respectively) calculated from the blood pressure waveform recorded by VC and AT 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 $\pm$ (1.96 $\times$ standard deviation of the difference)] and 95% confidence interval for the bias [mean of the difference $\pm$ (standard error of the difference $\times$ t) : t is a t distribution of freedom (number of specimen -1)] were calculated. For com-

Fig. 1. Relationship between ratios of area under the arterial blood pressure waveform during exercise measured by using volume clamp method (K_{VC}) and applanation tonometry (K_{AT}).

parison of SBP, DBP, MBP and HR at rest and during exercise, the paired t-test was used. Stat View 5.0 J (SAS Institute Inc.) was used for every statistical analysis in this study.

3. Results

Stable continuous blood pressure waveform were recorded for all the subjects by VC, but in case of AT, stable waveform were recorded for only 64% (14/22) of the subjects (**Table 1**). Among them, stable record was obtained for a majority (91%:10/11) of male. On the other hand, stable record was obtained for only 36% (4/11) of female (**Table 1**). **Table 2** shows the hemodynamics of the subjects at rest and during exercise with stable recording. Although the increase of the blood pressure and HR were observed, % HRreserve during exercise was 20.8 (9.1)%, 17.6 (4.6)% and 28.7 (13.4)% for all the subjects, male and female respectively. This is supposed to be light exercise.

A significant correlation ($r = 0.89$, **Fig.1**) was observed between K_{VC} (2.07 ± 0.21) and K_{AT} (2.00 ± 0.19) and the difference of both values was 0.07 ± 0.10 (95% confidence interval of the difference: - 0.12 ~ 0.26, 95% confidence interval for the bias: 0.01 ~ 0.13), and degree of agreement of both values was very good (**Fig.2**).

4. Discussion

Continuous and stable recording of blood pressure waveform at finger artery by VC during exercise was possible for all the subjects, but it was not possible to

Fig. 2. Degree of agreement of ratios of area under the arterial blood pressure waveform during exercise measured by using volume clamp method (K_{VC}) and applanation tonometry (K_{AT}). CI, confidence interval.

record stable blood pressure waveform at carotid artery by AT for 40% of the subjects. Especially for 60% of female, it was not possible to obtain the continuous and stable blood pressure waveform at carotid artery during exercise. From the standpoint of obtaining stable blood pressure waveform during exercise, recording blood pressure waveform at finger artery by VC is superior to that at carotid artery by AT, and is considered to be useful. On the other hand, the ratio of the area under arterial blood pressure waveform calculated from each blood pressure waveform obtained by VC and AT had a significant correlation and the degree of agreement of values was good. Therefore, the validity of the procedures where finger arterial blood pressure waveform by VC will be recorded for the elderly during exercise and then the waveform will be transformed into brachial arterial blood pressure waveform for calculation of SAC is suggested.

At the time of continuous recording of blood pressure waveform using AT at carotid artery, it is necessary to place the sensor through skin on the top of artery and maintain the proper pressure of the sensor against the skin. Hence, it is not easy to record stable and continuous blood pressure waveform when movement of the body is accompanied during exercise. In this study, the exercise was performed in supine position in order to avoid the movement of the body. Also, as % HRreserve during exercise is shown, degree of the exercise was set to be modest. But, although it was confirmed before the start-up of exercise that stable blood pressure waveform at carotid was available, it was not easy to record continuous blood pressure

waveform during exercise, especially, for female, there were more cases where the stable record could not be available. Although the degree of obesity was not extreme among the subjects, it was with more difficulty for the female who had more subcutaneous fat than male to record the blood pressure waveform at carotid artery during exercise. That means there are more restrictions for the subjects and experimental conditions when evaluating SAC at carotid artery by using AT during exercise. On the other hand, with regard to VC at finger artery, stable and continuous blood pressure waveform can be easily obtained during exercise at the low exercise level in this study, therefore, it is thought to be more useful.

The validity of using the blood pressure waveform recorded at carotid artery into calculation of SAC was verified by the previous study [Cameron and Dart (1994)]. In their study, the area under the arterial blood pressure waveform at diastole calculated from the blood pressure waveform of carotid artery and the blood pressure waveform of aorta recorded invasively by manometry were compared. Total 74 heart beat blood pressure waveforms of 3 subjects were analysed. Significant correlation was observed between both waveforms. Examination for bias using the method of Bland and Altman (1986) was negative in their study. We [Otsuki et al. (in press)] referred to their study [Cameron and Dart (1994)]. The blood pressure waveform of finger artery was recorded at rest and then transformed into the blood pressure waveform of brachial artery by a transfer function. The area ratio calculated from the waveform (the area under the blood pressure waveform at one heart beat cycle/ area under the blood pressure waveform at diastole) was compared with the area ratio calculated from the blood pressure waveform of carotid artery recorded at the same time as a reference. As a result, significant correlation was observed between the mean values of area ratio and degree of agreement was also good. In this study, it was suggested that if the blood pressure waveform of finger artery is transformed into blood pressure waveform of brachial artery and then SAC is calculated from the transformed waveform, the value can be equivalent to that calculated from the blood pressure waveform of carotid artery during exercise.

The 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)] where SAC was noninvasively evaluated by AT, blood flow volume was measured by ultrasonic Doppler method. However, it is not easy to measure continuously blood flow volume during exercise. In the previous study [Sugawara et al. (2001)], it was shown

that it is possible to record stable blood pressure waveform up to the ventilatory threshold during exercise by using VC and also the validity of the value of blood flow volume calculated from the recorded blood pressure waveform in comparison with electrical impedance cardiography method was verified. Although absolute value of carotid arterial blood pressure by AT should be calibrated by the measured blood pressure value at brachial artery, the blood pressure is recorded in absolute value in VC [Bos et al. (1996); Gizdulich et al. (1996); Gizdulich et al. (1997)]. That means, in comparison with AT, VC enables to calculate SAC at ease and also enables to measure a number of subjects and to record stable blood pressure waveform, therefore, it is said to be more useful testing method.

The limitation of this study is the level of exercise to be performed. Evaluation during exercise means in this study only about 20% of % HRreserve. Evaluation during more severe exercise condition will be the issue to be further studied. Whether this method is valid or not as a recording method of blood pressure waveform for calculation of SAC under more severe exercise conditions, it is necessary to compare directly with invasively recorded blood pressure waveform of aorta. Also, with regard to blood flow volume used for calculation of SAC, it is required to compare with the blood flow volume measured by other method.

5. Conclusion

The method using the blood pressure waveform at brachial artery transformed from the recorded blood pressure waveform by volume clamp method at peripheral artery was studied as a noninvasive estimate of systemic arterial compliance for the elderly during exercise and then compared with the conventional method in this study. As a result, the method using peripheral arterial blood pressure waveform was found to be useful as an estimate of systemic arterial compliance and the calculated value was suggested to be valid.

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