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Blood pressure during resistance exercise is associated with 24-h ambulatory blood pressure and arterial stiffness

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Abstract Exaggerated blood pressure responses to aerobic and resistance exercise are associated with future cardiovascular disease. However, it remains unclear whether the excessive blood pressure responses induce these degenerative changes or are just an initial symptom of cardiovascular disease. The aim of this study was to test the hypothesis that exaggerated blood pressure responses to exercise and activities of daily living decrease vascular endothelial function and increase arterial stiffness. We investigated aortic pulse wave velocity (PWV, an index of arterial stiffness), blood pressure and heart rate at rest, during dynamic resistance (leg press) exercise and during 24-h ambulatory blood pressure monitoring (ABPM), one-repetition maximum of leg press exercise, maximal oxygen uptake and conventional cardiovascular risk factors such as serum cholesterol concentrations in 36 middle-aged and older individuals (mean age, 61.0 ± 1.3 years). Systolic blood pressure (SBP) during resistance exercise was correlated with aortic PWV, independent of resting SBP (partial $r = 0.399$). In the stepwise regression analysis, SBP during resistance exercise, age, body mass index, and 24-h ambulatory heart rate were used as significant predictors of aortic PWV, independent of other variables ($R^2 = 0.722$). Additionally, 24-h ambulatory SBP was correlated with SBP during resistance exercise ($r = 0.513$) and aortic PWV ($r = 0.472$). In conclusion, these results suggest that SBP during resistance exercise is an independent predictor of arterial stiffness. Repeated excessive rises in blood pressure during resistance exercise and activities of daily living may increase arterial stiffness.

Keywords : ambulatory blood pressure monitoring, arterial stiffness, endothelial function, pulse wave velocity, resistance exercise, systolic blood pressure

Introduction

A transient increase in blood pressure during exercise is a response to the increased demand for blood flow to the muscles. Individuals with left ventricular dysfunction or myocardial ischemia and users of β -blockers cannot achieve a sufficient blood pressure rise during exercise. On the other hand, exaggerated blood pressure responses to exercise are associated with future cardiovascular disease^{1,2)} and smaller brain volume³⁾. Although most of the related previous studies investigated blood pressure responses to aerobic exercise, one study reported that resistance exercise blood pressure is also a predictor for future hypertension⁴⁾. However, it remains unclear whether the excessive blood pressure responses induce the degenerative changes or are just an initial symptom of cardiovascular disease.

It is considered that hypertension adversely affects vascular endothelial function⁵⁾. Decreases in endothelial function increase arterial stiffness^{6,7)}, a well-established

cardiovascular risk factor⁸⁾. We hypothesized that exaggerated blood pressure responses to exercise and activities of daily living decrease vascular endothelial function and increase arterial stiffness. If so, arterial stiffness would be greater in individuals with exaggerated blood pressure responses to exercise than in counterparts with normal blood pressure responses. Indeed, a previous study reported that blood pressure during resistance exercise was correlated with 24-h ambulatory blood pressure and pulse wave velocity (PWV, a conventional index of arterial stiffness)⁹⁾. However, further studies are needed because 1) the correlation was not adjusted for resting blood pressure, levels of physical fitness, and conventional cardiovascular risk factors, 2) dynamic exercise was not conducted as an exercise test, and 3) participants were relatively young (mean age, 46.3 years) in the previous study⁹⁾. Accordingly, this study investigated aortic PWV, blood pressure and heart rate (HR) at rest, during dynamic leg press exercise and during 24-h ambulatory blood pressure monitoring (ABPM), one-repetition maximum (1RM) of leg press exercise, maximal oxygen uptake, and conventional cardiovascular risk factors such as serum

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cholesterol concentrations in individuals between 45 and 76 years of age.

Methods

Participants. We circulated advertisements to participants of a university extension course. Forty-five individuals volunteered to participate in this study. Inclusion criterion included the absence of any disorder that inhibits exercise. Participants on antihypertensive medication, smokers, and participants with missing blood pressure and HR data were excluded; the remaining 36 participants were analyzed (Table 1). Of the 36 participants, 30 individuals habitually did aerobic exercise (*e.g.*, walking and jogging) and 6 individuals habitually participated in other physical activities (*e.g.*, table tennis and yoga). In addition, 17 of the 36 participants were also engaged in habitual resistance exercise training at low or moderate intensity. Participants were instructed to refrain from alcohol consumption and intense physical activity starting the day before testing, and caffeine consumption on the day of testing. Experiments 1 (resistance exercise tests), 2 (PWV assessment and maximal oxygen uptake estimation), and 3 (24-h ABPM) were conducted in random order. The interval between the first and final experiments was 10.9 ± 1.2 d. Experiments 1 and 2 were conducted between 9:00 and 17:00. Additionally, these two experiments were performed at the same time as much as possible.

This study was approved by the Ethics Committee of Ryutsu Keizai University (approval number 1) and conformed to the principles of the Helsinki Declaration. All participants gave their written informed consent prior to

study participation.

Resistance exercise protocol. A cable-type resistance-training machine (Genesis Dual-Cable Cross; Freemotion Fitness, West Logan, USA) was customized for the resistance exercise test (Fig. 1). First, an expert instructor (TK) assessed 1RM during the leg press exercise. Participants performed a single repetition of the exercise with progressively heavier weights; the heaviest weight that subjects could lift once through a complete range of motion (*i.e.*, from a knee angle of 80° [180° at full extension] to a slightly flexed position) was considered their 1RM.

Five minutes after the 1RM assessment, participants performed two sets of 10 repetitions of the leg press exercise at 20% 1RM under the instruction of the resistance exercise expert. One repetition was performed for 8 seconds (*s*; 3 *s* of concentric contraction, 1 *s* of maintaining a slightly flexed position, 3 *s* of eccentric contraction, and 1 *s* of maintaining a knee angle of 80°) according to the Exercise Guide 2006 presented by the Ministry of Health, Labour and Welfare of Japan. Participants were asked ratings of perceived exertion (RPE, Borg's scale, range from 6 to 20) immediately after each set. The inter-set recovery period was 100 *s*. After completion of the 20% 1RM session, 160 *s* elapsed before the 40% 1RM session commenced in a similar fashion. The 60% 1RM session commenced 160 *s* after completion of the 40% 1RM session. Subjects were instructed not to interrupt their respiration while exercising.

Blood pressure and HR measurements. Resting systolic and diastolic blood pressure (SBP and DBP, respectively)

Table 1. Properties in subjects.

	Men	Women
<i>n</i>	11	25
Age, years	65.9 ± 1.7	58.8 ± 1.5
Height, m	1.68 ± 0.01	1.56 ± 0.01
Weight, kg	63.7 ± 2.1	54.3 ± 1.7
Body mass index, kg/m ²	22.6 ± 0.7	22.3 ± 0.8
LDL cholesterol, mg/dL	123 ± 8	133 ± 5
HDL cholesterol, mg/dL	65 ± 5	80 ± 4
Triglycerides, mg/dL	106 ± 15	94 ± 9
Glucose, mg/dL	106 ± 11	92 ± 1
Insulin, μ U/dL	3.9 ± 0.7	4.2 ± 0.3
1RM, arbitrary unit	228 ± 10	143 ± 10
Maximal oxygen uptake, mL/kg/min	27.2 ± 1.8	24.9 ± 1.4

Values are means $\pm$ SEs. LDL, low-density lipoprotein; HDL, high-density lipoprotein; 1RM, one-repetition maximum of leg press exercise.

Fig. 1 Leg press exercise in the present study.

A cable-type resistance exercise machine was customized and used for the exercise test.

in the seated position were measured in triplicate by oscillometry (DINAMAP Pro Care 300; GE Healthcare, Buckinghamshire, UK) before the exercises. Simultaneously, electrocardiograph (ECG) was recorded at 1,000 Hz and HR was calculated (LRR-03; GMS, Tokyo, Japan). During resistance exercise, SBP and DBP measurements were taken once per set by oscillometry 20 s after the onset of exercise until the end of the exercise. RR intervals were averaged every 8 s (*i.e.*, every repetition) and the highest value was used to determine the HR of each set. The mean value over two sets was calculated at 20%, 40% and 60% 1RM, respectively.

Aortic PWV assessment. Aortic PWV was measured as described in our previous study, with minor modifications^{10,11}. Briefly, carotid and femoral artery pulse waves were obtained in the supine position in triplicate by arterial applanation tonometry (BP-203RPE II; Omron Colin, Tokyo, Japan). Pulse wave transit time was automatically determined from the time delay between the proximal and distal ‘foot’ waveforms by this device. The distance traveled by the pulse wave was assessed over the surface of the body. Aortic PWV was calculated as the distance divided by the transit time.

24-h ABPM. 24-h ABPM was conducted with an automatic ABPM device (TM-2431; A&D, Tokyo, Japan) on the days that participants did not conduct habitual exercise training or do something unusual (*e.g.*, sightseeing). A cuff was attached to the nondominant arm. Participants were asked not to modify their lifestyle during ABPM and instructed to sit down if possible or at least stop physical activity during the measurements. Blood pressure and pulse rate were measured by oscillometry every 30 min. The recorded data were stored in the device and down-

loaded after the end of the ABPM. After invalid values were excluded, the 24-h mean values of SBP, DBP and HR were calculated under the assumption that pulse rate is equal to HR.

Maximal oxygen uptake estimation. Maximal oxygen uptake was estimated as described in our previous study¹². Subjects exercised using incremental cycling (4 min at 30 W, with a 20 W [men] or 15 W [women] increase every 2 min to 85% of age-predicted maximum HR [$208 - 0.7 \times \text{age}$]¹³). ECG and breath-by-breath oxygen uptake (AE300S; Minato Medical Science, Osaka, Japan) during the exercise were averaged every 30 s. The linear regression line between HR and oxygen uptake was determined using the values from the last 30 s of each workload. Oxygen uptake corresponding to age-predicted maximum HR was considered the maximal oxygen uptake.

Blood chemical analysis. Blood samples were collected in the morning after an overnight fast. Serum concentrations of cholesterol, triglycerides and insulin, as well as plasma concentrations of glucose, were determined using standard enzymatic techniques¹⁴.

Statistical analysis. Results are given as means $\pm$ SEs. First, relationships between two variables were investigated using Pearson’s correlation coefficients and partial correlation analysis. Second, stepwise regression analysis was conducted to determine independent factors associated with aortic PWV. Changes in blood pressure, HR and RPE from rest to exercise of 60% 1RM were evaluated by repeated measure analysis of variance (ANOVA). Comparisons in blood pressure and HR among resting value, mean value over three levels of exercise intensity, and 24-h ambulatory value were conducted using one-way

ANOVA. If a significant F value was found, a post hoc Fisher's protected least significant differences test was performed. P values < 0.05 were considered statistically significant. A statistical software (StatView; SAS Institute, Cary, NC) was used for these analyses.

Results

SBP, DBP, HR and RPE increased during resistance exercise in an exercise intensity-dependent manner (Table 2). Because there were strong correlations across three intensities in each variable (SBP; $r = 0.807$ - 0.899 ; DBP; $r = 0.781$ - 0.789 ; HR; $r = 0.797$ - 0.904), we used the mean values over three levels of exercise intensity in the following analyses. There were no differences in blood pressure between at rest and during 24-h ABPM. HR was

lower during 24-h ABPM compared to at rest. Blood pressure and HR during resistance exercise were higher than those at rest and during 24-h ABPM.

SBP and DBP at rest (range; 92-176 and 50-96 mmHg, respectively) were correlated with those during resistance exercise ($r = 0.726$ and $r = 0.610$, respectively) and during 24-h ABPM ($r = 0.656$ and $r = 0.648$, respectively). Blood pressure during resistance exercise were also correlated with 24-h ambulatory values (Fig. 2). However, in partial correlation analysis adjusting for resting value, there were no correlations between the exercise and 24-h values.

SBP and DBP at rest were correlated with aortic PWV ($r = 0.638$ and $r = 0.519$, respectively). Blood pressure during resistance exercise and during 24-h ABPM were also correlated with aortic PWV (Fig. 3 and 4, respectively).

Table 2. Blood pressure, heart rate and ratings of perceived exertion (Borg's 6—20 scale) at rest, during resistance exercise and during 24-h ambulatory monitoring.

	Rest	Leg press exercise				24-h
		20%	40%	60%	Mean (20—60%)	
Systolic blood pressure, mmHg	120 $\pm$ 3	147 $\pm$ 4*	160 $\pm$ 4*†	171 $\pm$ 4*†‡	159 $\pm$ 4*	124 $\pm$ 2#
Diastolic blood pressure, mmHg	72 $\pm$ 2	82 $\pm$ 2*	93 $\pm$ 2*†	97 $\pm$ 3*†‡	90 $\pm$ 2*	77 $\pm$ 1#
Heart rate, bpm	72 $\pm$ 2	80 $\pm$ 2*	91 $\pm$ 2*†	101 $\pm$ 3*†‡	91 $\pm$ 2*	64 $\pm$ 1*#
Ratings of perceived exertion	—	11.5 $\pm$ 0.2	14.9 $\pm$ 0.3†	17.3 $\pm$ 0.3†‡	—	—

Values are means $\pm$ SEs. 20%, 20% one-repetition maximum (1RM); 40%, 40% 1RM; 60%, 60% 1RM. *, $P < 0.05$ vs. rest; †, $P < 0.05$ vs. 20%; ‡, $P < 0.05$ vs. 40%; #, $P < 0.05$ vs mean value over three levels of exercise intensity.

Fig. 2 Relationship between blood pressure during resistance exercise and during 24-h ambulatory monitoring.

Systolic and diastolic blood pressure (SBP and DBP, respectively) during resistance exercise are demonstrated as mean value over three levels of exercise intensity (*i.e.*, 20, 40 and 60% one-repetition maximum). In partial correlation analysis, resting SBP and DBP were included as a covariate. * $P < 0.05$; ** $P < 0.005$.

Fig. 3 Relationship between blood pressure during resistance exercise and arterial stiffness.

Systolic and diastolic blood pressure (SBP and DBP, respectively) during resistance exercise are demonstrated as mean value over three levels of exercise intensity (*i.e.*, 20, 40 and 60% one-repetition maximum). In partial correlation analysis, resting SBP and DBP were included as a covariate. * $P < 0.05$; ** $P < 0.005$; *** $P < 0.0005$.

Fig. 4 Relationship between 24-h ambulatory blood pressure and arterial stiffness.

In partial correlation analysis, resting systolic and diastolic blood pressure (SBP and DBP, respectively) were included as a covariate. ** $P < 0.005$.

Particularly, the correlation between exercise SBP and aortic PWV was independent of resting SBP. Additionally, the correlation between exercise DBP and aortic PWV, adjusting for resting DBP, was close to statistical significance ($P = 0.06$). However, there were no correlations between 24-h ambulatory blood pressure and aortic PWV in partial correlation analysis adjusted for resting value. In the stepwise regression analysis (Table 3), SBP during resistance exercise, age, body mass index (BMI) and 24-h ambulatory HR were used as independent predictors of aortic PWV; sex, plasma and serum markers, 1RM of

leg press exercise, maximal oxygen uptake, resting blood pressure and HR, exercise DBP and HR and 24-h blood pressure did not reach statistical significance.

Discussion

The present study investigated aortic PWV and blood pressure at rest, during leg press exercise and during 24-h ABPM in middle-aged and older individuals. The salient findings of this study are that SBP during resistance exercise is an independent predictor of aortic PWV and

Table 3. Stepwise regression analysis to identify independent predictors of aortic pulse wave velocity.

$n = 36, R^2 = 0.722, P < 0.0005$	Aortic pulse wave velocity		
	RC	SE	β
Included variables			
Age	11.4	4.2	0.371
Body mass index	-15.2	7.2	-0.216
SBP during resistance exercise	3.7	1.3	0.380
24-h ambulatory HR	16.1	3.4	0.470
Excluded variables			
sex, serum concentrations of LDL and HDL cholesterol, triglycerides and insulin, plasma glucose concentrations, 1RM, maximal oxygen uptake, SBP, DBP and HR at rest, DBP and HR during resistance exercise, and SBP and DBP during 24-h ambulatory monitoring.			

RC, regression coefficient; SBP, systolic blood pressure; HR, heart rate; LDL, low-density lipoprotein; HDL, high-density lipoprotein; 1RM, one-repetition maximum of leg press exercise; DBP, diastolic blood pressure.

that individuals with higher blood pressure responses to resistance exercise have greater aortic PWV than those with lower responses. Additionally, 24-h ambulatory SBP was correlated with exercise SBP and aortic PWV. Exaggerated blood pressure responses to resistance exercise may increase arterial stiffness via blood pressure during activities of daily living such as climbing stairs and lifting objects.

Koletsos et al.⁹⁾ recently reported that blood pressure during isometric handgrip exercise was correlated with PWV and 24-h ambulatory blood pressure in middle-aged individuals (mean age, 46.3 years). However, the adjusted factors were only age and BMI⁹⁾, although there are many factors that can confound these relationships, such as sex, resting blood pressure and levels of physical fitness. Many dynamic physical activities are included in daily living, but blood pressure during dynamic resistance exercise was not measured⁹⁾. Finally, risk of hypertension and arterial stiffening increases with age. The present study demonstrated that the relationship between blood pressure during resistance exercise and arterial stiffness is independent of resting blood pressure and other factors, and expanded the research outcome to dynamic resistance exercise and older individuals.

One feature of resistance exercise is a transient elevation in blood pressure. A previous study reported that SBP during leg press exercises at 10-repetition maximum was higher than 300 mmHg in young participants¹⁵⁾. A human study demonstrated that a transient increase in plasma concentrations of endothelin-1 (ET-1), a vascular endothelium-derived vasoconstrictor peptide^{16,17)}, after resistance exercise was correlated with blood pressure during the exercise¹⁸⁾. In addition, we previously demonstrated that increased secretion of ET-1 might be impli-

cated in resistance training-induced arterial stiffening¹⁰⁾, although there is a conflicting report¹⁹⁾. Also in aerobic exercise, exercise SBP was associated with indices of vascular endothelial function such as flow-mediate vasodilation²⁰⁾ and plasma concentrations of nitrate/nitrite²¹⁾. An in vitro study showed that increased blood pressure thickens the arterial wall²²⁾. As a consequence of the intense blood pressure elevation, habitual high-intensity resistance training increases arterial stiffness²³⁾ possibly via decreases in vascular endothelial function and arterial thickening, although this type of training is beneficial for preventing sarcopenia and osteoporosis. About half of the participants in this study engaged in habitual resistance training to improve their health status. Additionally, physical activities similar to resistance exercise (*e.g.*, lifting objects, mopping, and climbing stairs) were included in daily living. These training exercises and activities were not intensive. However, repeated elevations in blood pressure may increase arterial stiffness in individuals with exaggerated blood pressure responses to habitual exercise training and activities of daily living.

This study demonstrated that dynamic resistance exercise SBP was correlated with arterial stiffness in agreement with a previous study that investigated static exercise SBP⁹⁾. Aerobic exercise SBP was also reported to be correlated with arterial stiffness^{20,24)}. To the best of our knowledge, it has been unexplored whether there is any difference in the relationship between blood pressure response to exercise and arterial stiffness when comparing resistance and aerobic exercises. However, a 14-year follow-up study reported that resistance exercise blood pressure is a better predictor of future hypertension than aerobic exercise blood pressure, although the difference was slight⁴⁾. The relationship between exercise blood

pressure and arterial stiffness also might be more significant in resistance exercise compared to aerobic exercise.

In this study, 24-h ambulatory blood pressure was correlated with aortic PWV. This result is in agreement with a previous study that an age-related increase in PWV was more pronounced among individuals with higher 24-h ambulatory blood pressure²⁵⁾. In addition, 24-h ambulatory blood pressure in this study was correlated with blood pressure during resistance exercise, in accord with a previous study⁹⁾. These results are consistent with our hypothesis that exaggerated blood pressure responses to exercise increase arterial stiffness via excessive blood pressure elevation during activities of daily living. However, relationships between 24-h and exercise blood pressure were dependent on resting blood pressure. This result implies that the effect of blood pressure responsiveness to exercise on 24-h blood pressure is not so large. Additionally, correlations between 24-h blood pressure and aortic PWV were also dependent on resting blood pressure. The mean values of 24-h SBP and DBP in this study were within the range of normotension²⁶⁾. In this case, each intensity of blood pressure elevation with activities of daily living may be more important than the 24-h mean value of blood pressure.

The present results suggest that SBP during resistance exercise is associated with arterial stiffness. In addition, we previously reported that decreases in resistance exercise SBP by 6-week aerobic training were correlated with those in arterial stiffness¹²⁾. However, it is difficult to determine the causal direction between blood pressure response to resistance exercise and arterial stiffness. Accordingly, the present results were interpreted not only as elevated exercise blood pressure increased arterial stiffness but also as increased arterial stiffness inducing excessive blood pressure elevation during exercise. Indeed, arterial stiffness is an important determinant of vascular load during exercise^{27,28)}. Based on the present and previous studies, we speculate that blood pressure during resistance exercise and arterial stiffness interact with each other. To date, it is difficult to directly test this causal relationship in humans. Comprehensive studies, including prospective studies and studies of the mechanisms underlying arterial stiffening induced by repeated blood pressure elevations, are warranted.

In the stepwise regression, age, 24-h ambulatory HR, and BMI were also significant predictors of aortic PWV. The significant correlation between age and arterial stiffness agrees with previous studies^{14,25)}. Increases in HR is also reported to increase arterial stiffness^{29,30)}. 24-h HR might be more similar to HR during the PWV measurement compared to resting HR, because sleep HR was included in 24-h HR and resting HR was measured in the seated position. On the other hand, we were surprised by the inverse correlation between BMI and aortic PWV. In general, arterial stiffness is higher in obese individuals than in their normal-weight counterparts³¹⁾. Height of

participants was used in the BMI calculation and would be correlated with the distance between the two recording sites in the PWV assessment. Additionally, the mean BMI in the present participants was within normal limits. These factors may underly the inverse correlation between BMI and aortic PWV.

Conclusions

The present results suggest that SBP during resistance exercise is an independent predictor of arterial stiffness. Additionally, 24-h ambulatory SBP is also correlated with resistance exercise SBP and arterial stiffness. Repeated excessive increases in blood pressure during resistance exercise and during activities of daily living may constitute a risk factor for central arterial stiffening.

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Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

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