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Morning blood pressure surge is associated with arterial stiffness and sympathetic baroreflex sensitivity in hypertensive seniors

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Okada Y, Galbreath MM, Shibata S, Jarvis SS, Bivens TB, Vongpatanasin W, Levine BD, Fu Q. Morning blood pressure surge is associated with arterial stiffness and sympathetic baroreflex sensitivity in hypertensive seniors. Am J Physiol Heart Circ Physiol 305: H793–H802, 2013. First published July 5, 2013; doi:10.1152/ajpheart.00254.2013.—Morning blood pressure (BP) surge is considered to be an independent risk factor for cardiovascular diseases. We tested the hypothesis that increased large-artery stiffness and impaired sympathetic baroreflex sensitivity (BRS) contribute to augmented morning surge in elderly hypertensive subjects. Morning surge was assessed as morning systolic BP averaged for 2 h just after waking up minus minimal sleeping systolic BP by using ambulatory BP monitoring (ABPM) in 40 untreated hypertensive (68 ± 1 (SE) yr) and 30 normotensive (68 ± 1 yr) subjects. Beat-by-beat finger BP and muscle sympathetic nerve activity (MSNA) were recorded in the supine position and at 60° upright tilt. We assessed arterial stiffness with carotid-to-femoral pulse wave velocity (cfPWV) and sympathetic BRS during spontaneous breathing. Awake and asleep ABPM-BPs and morning surge were higher in hypertensive than normotensive subjects (all P < 0.001). cfPWV was higher (P = 0.002) and sympathetic BRS was lower (P = 0.096) in hypertensive than normotensive subjects. Hypertensive subjects with morning surge ≥35 mmHg (median value) had higher cfPWV (11.9 ± 0.5 vs. 9.9 ± 0.4 m/s, P = 0.002) and lower sympathetic BRS (supine: −2.71 ± 0.25 vs. −3.73 ± 0.29, P = 0.011; upright: −2.62 ± 0.22 vs. −3.51 ± 0.35 bursts·100 beats−1·mmHg−1·s−1, P = 0.052) than those with morning surge <35 mmHg. MSNA indices were similar between groups (all P > 0.05), while upright total peripheral resistance was higher in hypertensive subjects with greater morning surge than those with lesser morning surge (P = 0.050). Morning surge was correlated positively with cfPWV (r = 0.59, P < 0.001) and negatively with sympathetic BRS (r = 0.51, P < 0.001) in hypertensive subjects only. Thus, morning BP surge is associated with arterial stiffness and sympathetic BRS, as well as vasoreactivity during orthostasis in hypertensive seniors.

In humans, blood pressure (BP) shows circadian variations; it decreases during sleep and increases in the morning (19, 36). Cardiovascular events also have a distinct circadian pattern with a peak incidence in the morning (5, 19). The degree of morning BP surge from the nadir during the night has been found to be an independent predictor for cardiovascular events (12, 15) and, therefore, elderly hypertensive patients who have poor morning BP control (26) may be at higher risk of these events. Thus, it is important to evaluate the pathophysiological mechanisms underlying the morning surge in elderly hypertensive subjects.

Some studies have demonstrated that the morning surge is associated with arterial stiffness and autonomic function. For example, hypertensive patients with an exaggerated morning surge ≥50 mmHg in systolic BP (SBP) or ≥22 mmHg in diastolic BP (DBP) had higher levels of carotid intima-media thickness and urinary catecholamine excretion than those with lesser morning surge (17). Cardiovascular baroreflex sensitivity (BRS), which regulates BP at the heart through the autonomic nervous system, was negatively correlated with morning SBP (4). Moreover, it was found that a decreased cardiovascular BRS was caused by a reduction in distensibility of the carotid artery, especially during the BP rise in the morning (33). Therefore, it seems that hypertensive patients with greater arterial stiffness have a lesser ability to buffer against BP increases in the morning. Based on the finding that the contribution of total peripheral resistance (TPR) to BP change by orthostasis became greater, while the contribution of heart rate (HR) decreased with age in hypertensive subjects (16), the sympathetic baroreflex, which regulates BP via vasodilation and constriction, may play a more important role in control of morning BP in elderly hypertensive subjects. The morning surge is actually assessed with night time BP and morning BP for 2 h after waking up (12), suggesting that the morning surge includes BP rises upon standing. Therefore, sympathetic control of BP during upright posture may also affect the magnitude of the morning surge. However, there is no information available regarding the effect of supine or upright sympathetic BRS on the morning surge in humans.

We recently reported that sympathetic BRS was correlated with the stiffness of the barosensory arteries, the carotid artery and aorta in elderly individuals (21). Because it seems that elderly hypertensive subjects with higher arterial stiffness have lower sympathetic BRS, we hypothesized that impaired sympathetic BRS and higher arterial stiffness would be observed in elderly hypertensive subjects with greater morning surge and that the level of morning surge would be correlated with sympathetic BRS. Additionally, elderly hypertensive subjects with enhanced α1-adrenergic responsiveness were found to have a greater increase in BP by norepinephrine infusion even with a similar increase of sympathetic nerve activity compared with elderly normotensive subjects (32). Therefore, we also evaluated muscle sympathetic nerve activity (MSNA) during
head-up tilt to test whether the efficacy of change in MSNA on TPR by head-up tilt is higher and/or upright sympathetic BRS is lower in elderly hypertensive subjects with greater morning surge than those with lesser morning surge or normotensive subjects.

METHODS

Subjects

Two hundred and ninety-four elderly individuals in the Dallas-Fort Worth area were contacted between August 2008 and May 2011, and 138 of them were interested in participating in research and were screened for our study. Ultimately, 70 elderly volunteers [40 hypertensive subjects (awake SBP: 135–159 and/or awake DBP: 85–99 mmHg according to 24-h ambulatory BP monitoring, ABPM) (2) and 30 normotensive subjects] participated in and completed the study. All participants were screened with a careful medical history, physical examination, 12-lead electrocardiogram, fasting blood samples, 24-h urine collection, and cardiovascular- and abdominal-echogram to confirm that they had no overt history of chronic diseases (e.g., cardiopulmonary, neurological, renal diseases, renal artery stenosis, primary aldosteronism, diabetes mellitus, and sleep apnea) that can cause secondary hypertension. They were excluded if they were smokers, regularly exercised at moderate- to high-intensity levels for >30 min/day for >3 times/wk, or their body mass index was >35 kg/m². Women taking hormone replacement treatment were also excluded. Subjects gave their written informed consent to a protocol approved by the Institutional Review Boards of University of Texas Southwestern Medical Center and Texas Health Presbyterian Hospital Dallas. Subjects’ characteristics are presented in Table 1.

Measurements

Muscle sympathetic nerve activity. MSNA signals were obtained with microneurography (30, 31). Briefly, a recording electrode was placed in the peroneal nerve at the popliteal fossa, and a reference electrode. The nerve signals were amplified (70,000 to 160,000-fold), electrocardiogram (lead II), and beat-by-beat BP was derived by finger photoplethysmography. The integrated neurogram was normalized by assigning a value of 100 by 10.220.33.6 on October 6, 2016 http://ajpheart.physiology.org/ Downloaded from

Table 1. Physical characteristics

<table>
<thead>
<tr>
<th>Variables</th>
<th>Hypertensive Subjects</th>
<th>Normotensive Subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>40</td>
<td>30</td>
</tr>
<tr>
<td>Men:women</td>
<td>20:20</td>
<td>15:15</td>
</tr>
<tr>
<td>Age, yr</td>
<td>68 ± 1</td>
<td>68 ± 1</td>
</tr>
<tr>
<td>Height, cm</td>
<td>169 ± 1</td>
<td>168 ± 2</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>77 ± 2</td>
<td>76 ± 3</td>
</tr>
<tr>
<td>Body surface area, m²</td>
<td>1.90 ± 0.03</td>
<td>1.90 ± 0.04</td>
</tr>
<tr>
<td>Body mass index, kg/m²</td>
<td>26.9 ± 0.4</td>
<td>26.8 ± 0.6</td>
</tr>
</tbody>
</table>

Values are means ± SE; n, no. of subjects.
SBP, systolic blood pressure; DBP, diastolic blood pressure; HR, heart rate.

The lowest nocturnal HR, beats/min 69
Morning HR, beats/min 122 ± 110 ± 1 <0.001
Asleep 70 ± 1 61 ± 1 <0.001
Morning SBP, mmHg 147 ± 2 121 ± 1 <0.001
The lowest nocturnal SBP, mmHg 111 ± 2 97 ± 1 <0.001
Nighttime dip in SBP, % 12 <0.001
ABPM-SBP, mmHg
24 h 142 ± 1 121 ± 1 <0.001
Awake 147 ± 2 124 ± 1 <0.001
Asleep 129 ± 2
24 h 79 ± 1 70 ± 1 <0.001
Awake 81 ± 1 73 ± 1 <0.001
Asleep 70 ± 1
Morning SBP, mmHg 147 ± 2 121 ± 1 <0.001
The lowest nocturnal SBP, mmHg 111 ± 2 97 ± 1 <0.001
Nighttime dip in SBP, % 12 <0.001
ABPM-HR, beats/min
24 h 69 ± 1 71 ± 2 0.461
Awake 72 ± 1 74 ± 2 0.369
Asleep 65 ± 1 63 ± 1 0.918
Morning HR, beats/min 69 ± 2 71 ± 2 0.539
The lowest nocturnal HR, beats/min 56 ± 1 56 ± 1 0.919

Values are means ± SE. ABPM, ambulatory blood pressure monitoring; SBP, systolic blood pressure; DBP, diastolic blood pressure; HR, heart rate.

methodology was employed to determine pressure wave transit time at the carotid and femoral artery in relation to the R-wave of the electrocardiogram. Pulse transit length was estimated by subtracting the distance between the sternal notch and the measuring point at the carotid artery from the distance between the sternal notch and the measuring point at the femoral artery. cfPWV was calculated from the transit length divided by the transit time.

Baroreflex sensitivity. Sympathetic BRS was assessed by using the slope of the linear correlation between MSNA and DBP during spontaneous breathing in each subject (6, 30) after confirming that the \( r \) value was >0.5 as described previously (27). MSNA burst incidence was calculated over a 3-mmHg DBP bin (6, 21) and statistically weighted to reduce the impacts of nonbaroreflex variability (e.g., respiration) and minor variation of bin width and position (13). Cardiovagal BRS was assessed by averaging the values of the slope of the linear correlation between R-R interval and beat-by-beat SBP during the two Valsalva maneuvers in each subject after confirming the \( r \) value was >0.8 (18). Values for SBP were linearly regressed against the corresponding R-R interval (lag 1) (18) during the hypertensive phase (phase IV), which was in the same direction of the BP change with the morning surge.

Statistical Analysis

Values are expressed as means ± SE. Linear regression analysis was used to evaluate the correlation between morning surge and arterial stiffness and sympathetic and cardiovagal BRS. Data between hypertensive and normotensive subjects were compared using unequal \( t \)-tests. If normality tests and/or equal variance tests failed, we compared the differences between groups using Mann-Whitney Rank Sum Tests. Multiple-regression analysis was used to assess factors related with morning surge in elderly hypertensive and normotensive subjects. A \( P \) value of <0.05 was considered statistically significant.

RESULTS

Ambulatory Blood Pressure and Heart Rate

ABPM-BPs were higher in hypertensive than normotensive subjects for all periods: 24 h, awake, and asleep (Table 2). Both the lowest nocturnal SBP and morning SBP were higher in hypertensive than normotensive subjects with no difference in night time dip in SBP. ABPM-HR was not different between groups in any period.

Supine Resting Variables

Table 3 depicts hemodynamics and MSNA indexes during supine rest. Supine BP was similar to asleep ABPM-BP in both hypertensive and normotensive subjects, whereas all supine BPs were still higher in hypertensive than normotensive subjects. There were no differences in HR, stroke volume, and cardiac output between groups, whereas TPR was higher in hypertensive than normotensive subjects (\( P = 0.081 \)). All MSNA indexes were similar between groups.

Morning Surge, Arterial Stiffness, and Baroreflex Sensitivity

Morning surge was greater in hypertensive than normotensive subjects, but morning HR increase was similar between groups (Fig. 1, A and B). cfPWV was higher in hypertensive than normotensive subjects (Fig. 1C). Sympathetic BRS was lower in hypertensive than normotensive subjects (\( P = 0.096 \)), but cardiovagal BRS was similar between groups (Fig. 1, D and E). To compare these variables between hypertensive subjects with greater and lesser morning surge, we set the median of morning surge (35 mmHg) as a threshold and divided hypertensive subjects into two subgroups (Fig. 2A): those with morning surge ≥35 mmHg (\( n = 20 \)) and <35 mmHg (\( n = 20 \)) [similar age and physical characteristics (all \( P > 0.050 \)) and the same men-to-women ratio (10:10) between subgroups]. Likewise, between subgroups, morning HR increase and cardiovagal BRS were similar (Fig. 2, B and E), whereas cfPWV was higher and sympathetic BRS was lower in hypertensive subjects with morning surge ≥35 mmHg than those with morning surge <35 mmHg (Fig. 2, C and D).

In hypertensive subjects, morning surge was positively correlated with cfPWV (Fig. 3A) and negatively correlated with sympathetic BRS (Fig. 3B). However, morning surge was not correlated with cardiovagal BRS (Fig. 3C). MSNA burst frequency (\( r = 0.10, P = 0.529 \)), or total activity (\( r = 0.08, P = 0.609 \)). In normotensive subjects, morning surge was not correlated with cfPWV (Fig. 3D), sympathetic BRS (Fig. 3F), or MSNA indexes (burst frequency: \( r = -0.29, P = 0.124 \); burst incidence: \( r = 0.08, P = 0.689 \); or total activity: \( r = -0.14, P = 0.689 \)). Multiple-regression analysis showed that cfPWV and sympathetic BRS

Table 2. Twenty-four-hour ambulatory blood pressure and heart rate

<table>
<thead>
<tr>
<th>Variables</th>
<th>Hypertensive Subjects</th>
<th>Normotensive Subjects</th>
<th>( P ) Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABPM-SBP, mmHg</td>
<td>142 ± 1 121 ± 1</td>
<td>&lt;0.001 124 ± 1</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>24 h</td>
<td>147 ± 2 124 ± 1</td>
<td>&lt;0.001 110 ± 1</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>
| Awake            | 129 ± 2
| ABPM-DBP, mmHg   | 79 ± 1 70 ± 1         | <0.001 81 ± 1       | <0.001        |
| 24 h             | 81 ± 1 73 ± 1         | <0.001 70 ± 1 61 ± 1 | <0.001        |
| Awake            | 70 ± 1 61 ± 1         | <0.001 147 ± 2 121 ± 1 | <0.001 |
| Asleep           | 69 ± 1 71 ± 2         | 0.461 72 ± 1 74 ± 2  | 0.369        |
| Morning SBP, mmHg| 147 ± 2 121 ± 1       | <0.001 111 ± 2 97 ± 1 | <0.001        |
| The lowest nocturnal SBP, mmHg | 56 ± 1 56 ± 1 | 0.919 |
| Nighttime dip in SBP, % | 12 ± 2 11 ± 1 | 0.767 |
| ABPM-HR, beats/min| 69 ± 1 71 ± 2 | 0.461 |
| 24 h             | 72 ± 1 74 ± 2         | 0.369 65 ± 1 63 ± 1  | 0.918        |
| Awake            | 65 ± 1 63 ± 1         | 0.918 69 ± 2 71 ± 2  | 0.539        |
| Asleep           | 56 ± 1 56 ± 1         | 0.919

Values are means ± SE. ABPM, ambulatory blood pressure monitoring; SBP, systolic blood pressure; DBP, diastolic blood pressure; HR, heart rate.

Table 3. Hemodynamic variables during supine rest on testing day in the laboratory

<table>
<thead>
<tr>
<th>Variables</th>
<th>Hypertensive Subjects</th>
<th>Normotensive Subjects</th>
<th>( P ) Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBP, mmHg</td>
<td>128 ± 2 112 ± 3</td>
<td>&lt;0.001 126 ± 2</td>
<td>0.006</td>
</tr>
<tr>
<td>DBCP mmHg</td>
<td>72 ± 2 66 ± 2</td>
<td>0.006 66 ± 2</td>
<td>0.374</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>1.708 ± 46 1,570 ± 66</td>
<td>0.081 40 ± 1 40 ± 2</td>
<td>0.986</td>
</tr>
<tr>
<td>Stroke volume, ml</td>
<td>61 ± 2 61 ± 3</td>
<td>0.744 4.0 ± 0.1 4.1 ± 0.2</td>
<td>0.653</td>
</tr>
<tr>
<td>Cardiac output, l/min</td>
<td>66 ± 1 68 ± 2</td>
<td>0.374</td>
<td></td>
</tr>
<tr>
<td>TPR, dyn·cm5</td>
<td>5 ± 0.1 6 ± 0.1</td>
<td>0.744 4.0 ± 0.1 4.1 ± 0.2</td>
<td>0.653</td>
</tr>
<tr>
<td>MSNA burst frequency, bursts/min</td>
<td>1,708 ± 46 1,570 ± 66</td>
<td>0.081</td>
<td></td>
</tr>
<tr>
<td>MSNA burst incidence, bursts/100 beats</td>
<td>40 ± 1 40 ± 2</td>
<td>0.986</td>
<td></td>
</tr>
<tr>
<td>Total activity, U/min</td>
<td>573 ± 24 591 ± 35</td>
<td>0.650</td>
<td></td>
</tr>
</tbody>
</table>

Values are means ± SE. TPR, total peripheral resistance; MSNA, muscle sympathetic nerve activity.
were relatively strong factors for morning surge in hypertensive subjects, whereas cardiovagal BRS and morning HR increase tended to be correlated with morning surge in normotensive subjects (Table 4).

Upright Sympathetic Baroreflex Sensitivity and Vasoreactivity

There was no difference in upright sympathetic BRS, %TPR/%MSNA, upright MSNA burst frequency, or TPR between elderly hypertensive and normotensive subjects (Fig. 4). Upright sympathetic BRS was smaller (P = 0.052, Fig. 5A) and %TPR/%MSNA by 60° head-up tilt was higher (P = 0.090, Fig. 5B) in hypertensive subjects with morning surge ≥35 mmHg than those with morning surge <35 mmHg. Although there was no difference in upright MSNA burst frequency between hypertensive subgroups (Fig. 5C), upright TPR was higher in hypertensive subjects with greater morning surge than those with lesser morning surge (Fig. 5D). Sympathetic BRS, but not %TPR/%MSNA, was correlated with cfPWV in hypertensive subjects (Fig. 6).

DISCUSSION

The major findings from this study are that 1) cfPWV was higher and sympathetic BRS was lower in elderly hypertensive subjects, especially those with greater morning surge than in elderly normotensive subjects; 2) morning surge was correlated with cfPWV and sympathetic BRS in hypertensive subjects only; and 3) there was no difference in supine or upright MSNA indexes between the groups, whereas the change in TPR for a given change in MSNA during head-up tilt was greater in hypertensive subjects with greater morning surge than those with lesser morning surge. These results suggest that
morning surge is associated with sympathetic BRS and vaso-reactivity to orthostasis, as well as arterial stiffness, in elderly hypertensive subjects.

Sympathetic Neural Control of Blood Pressure in the Morning

Morning surge has been proposed to be related to an excessive increase of sympathetic activity in the morning. This notion is supported by the Hypertension and Lipid Trial (22) indicating that \( \alpha \)-adrenergic blockade decreased morning BP. Kario et al. (11) demonstrated that original (baseline) morning surge had a strong correlation with a reduction of the morning surge by \( \alpha \)-adrenergic blockade, doxazosin. Conversely, we and others (8) found no correlation between morning surge and MSNA in hypertensive patients. This discrepancy suggests that other sympathetic neural control system(s), rather than absolute MSNA, may be responsible for the morning surge. If sympathetic baroreflex function were maintained in hypertensive subjects with greater morning surge, MSNA should have been reduced when BP increased markedly in the morning, and morning absolute MSNA should have been negatively correlated with morning surge. The absence of a relationship between morning surge and MSNA in hypertensive subjects suggests that sympathetic BRS in the patients with higher morning surge may be impaired and/or the baroreflex curve may be reset to a higher BP level in the morning. Indeed, hypertensive subjects with morning surge \( \geq 35 \) mmHg, which was similar to the median value for elderly hypertensive subjects in a previous study (39), had a lower sympathetic BRS than hypertensive subjects with morning surge \(< 35 \) mmHg.
whereas the latter had similar sympathetic BRS to that of normotensive subjects. Sympathetic BRS was found to decrease while sleeping and increase while awake (20). Moreover, it was found that the MSNA response was enhanced and the HR response was unchanged or lessened to the change in BP during orthostasis (16), mental stress (1), cold stress (9), and exercise (34) with age, especially in hypertensive subjects (3, 16). Therefore, in elderly hypertensive subjects, baroreflex control of TPR through MSNA seems to be predominant compared with baroreflex control of HR in the BP regulation at the time of awaking. The negative correlation between morning surge and sympathetic BRS and an exaggerated increase in TPR in the morning (36) in hypertensive subjects suggest that impaired sympathetic baroreflex function may result in the lack of a buffer system against morning surge in elderly hypertensive subjects.

There are some studies focusing on the circadian pattern of cardiovagal BRS. All of them demonstrated that a reduction of cardiovagal BRS occurred concomitant with BP increase in the morning, and it was suggested that cardiovagal BRS may be one of the determining factors for morning surge (4, 33, 36). Given the fact that a reduction of cardiovagal BRS and its correlation with morning BP was also observed in healthy normotensive subjects (4, 33) and that this relationship disappeared in hypertensive seniors in the current study, cardiovagal BRS may not be a predominant factor for morning BP increase in elderly hypertensive subjects. Indeed, multiple regression analysis showed that the lower cardiovagal BRS tended to be the factor for the higher morning surge in normotensive subjects, but not in elderly hypertensive subjects whose morning surge was significantly impacted by sympathetic BRS.

Orthostatic Effects

Morning surge includes the pressor response to orthostasis after awakening. The current study showed that upright sym-
pathetic BRS was also lower in hypertensive subjects with morning surge $\geq 35$ than those with morning surge $< 35$ mmHg, suggesting that impaired upright sympathetic baroreflex function may be, at least partially, related to the morning surge evoked by orthostasis. However, the difference of upright sympathetic BRS between hypertensive subgroups categorized by morning surge was weaker than the difference of supine sympathetic BRS between them ($P = 0.052$ vs. 0.011). This suggests that morning surge during orthostasis may be also affected by other mechanisms. One of the other possible sympathetic systems influencing morning surge may be vaso-reactivity to a change in MSNA. In this study, the efficacy of the increase in MSNA by head-up tilt on TPR was greater in hypertensive subjects with greater morning surge than those with lesser morning surge. Therefore, upright TPR was significantly higher in hypertensive subjects with greater morning surge despite upright MSNA being similar to those with lesser morning surge. This greater efficacy of MSNA on TPR during head-up tilt may be attributable to a greater sympathetic vascular transduction via augmented $\alpha_1$-adrenergic responsiveness observed in elderly hypertensive subjects in the previous study (32) and/or the enhanced renin-angiotensin-aldosterone system.

### Table 4. Determinant of morning blood pressure surge

<table>
<thead>
<tr>
<th></th>
<th>Hypertensive Subjects</th>
<th>Normotensive Subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\beta$</td>
<td>$P$</td>
</tr>
<tr>
<td>Multiple $r^2$</td>
<td>0.58</td>
<td>0.42</td>
</tr>
<tr>
<td>cfPWV, mmHg</td>
<td>0.458</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>The lowest nocturnal SBP, mmHg</td>
<td>excluded variable</td>
<td>-0.275</td>
</tr>
<tr>
<td>Morning SBP, mmHg</td>
<td>-0.047</td>
<td>0.834</td>
</tr>
<tr>
<td>Dip of night HR, beats/min</td>
<td>0.290</td>
<td>0.040</td>
</tr>
<tr>
<td>Morning HR increase, beats/min</td>
<td>0.093</td>
<td>0.660</td>
</tr>
<tr>
<td>Total activity, U/min</td>
<td>0.036</td>
<td>0.799</td>
</tr>
<tr>
<td>Sympathetic BRS, bursts $\cdot 100$ beats $^{-1} \cdot$ mmHg $^{-1}$</td>
<td>0.332</td>
<td>0.023</td>
</tr>
<tr>
<td>Cardiovagal BRS phase IV, ms/mmHg</td>
<td>0.057</td>
<td>0.668</td>
</tr>
</tbody>
</table>

cfPWV, carotid-to-femoral pulse wave velocity; BRS, baroreflex sensitivity.

### Arterial Stiffness and Morning Surge

To our knowledge, there are only two studies published evaluating the relationship between morning surge and cfPWV. Both studies demonstrated that morning surge was significantly correlated with cfPWV in subjects, including patients with type 2 diabetes and untreated and treated hypertension (23, 28). We found in elderly hypertensive subjects that morning surge was correlated with both sympathetic BRS and cfPWV and that there was a significant correlation between sympathetic BRS and cfPWV. There seems to be a close link between morning surge, arterial stiffening, and impaired sympathetic baroreflex function. Because baroreceptors are stretch receptors, the distortion of the barosensory artery is required to initiate neural firing. Taylor et al. (33) found that the decrease in cardiovagal BRS in the morning was the result of a reduced carotid artery distortion by the change in BP but not a blunted
neural response to the distortion. Because the mechanical change of the artery is a common component between the cardiovagal and sympathetic baroreflex, higher arterial stiffness could suppress the day time increase in sympathetic BRS. Conversely, no relationship between the efficacy of change in MSNA on TPR and cfPWV during upright posture was observed in this study, suggesting that vasoreactivity may be independent of arterial stiffness as a factor for the morning surge. Because this study was designed as a descriptive study, we cannot demonstrate cause-effect relationships; however, it is possible that stiffening of the arteries may cause enhanced morning surge via the lower sympathetic BRS.

**Perspectives**

The synergistic effects of a smaller decrease of MSNA even with a greater BP increase because of impaired supine and upright sympathetic BRS and greater vasoreactivity to MSNA by standing up may result in enhanced morning surge in elderly hypertensive subjects. This could place hypertensive patients at

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Fig. 5. Upright sympathetic BRS (A), efficacy of MSNA on TPR from supine to upright (B), upright MSNA burst frequency (C), and upright TPR (D) in elderly hypertensive subjects with morning surge ≥35 mmHg and those with morning surge <35 mmHg. Values are means ± SE.

Fig. 6. Linear regression analysis of the inter-individual relationships between sympathetic BRS and cfPWV (A) and between efficacy of MSNA on TPR and cfPWV (B) in elderly hypertensive subjects.
a higher risk for cardiovascular events. This study may provide some insight into the best treatment strategy for elderly hypertensive subjects with greater morning surge. Recently, the large-scale, international, multicenter SURGE study clearly demonstrated that morning BP was higher than lunch time and evening BP in elderly hypertensive subjects whose morning BP control was very poor (control rate 13.1%), even with antihypertensive drugs (26). Pharmacological and nonpharmacological approaches that can decrease large-artery stiffness, increase sympathetic BRS, and attenuate sympathetic vasoconstriction for 24 h may be particularly effective in reducing cardiovascular risks in these patients. Conversely, Verdecchia et al. (38) reported controversial relationships between morning surge and cardiovascular events; blunted morning surge was a predictor of cardiovascular events, whereas increased morning surge did not change the risk. This discrepancy seemed to be because of the interaction of morning BP rise and nocturnal BP dip; a smaller nocturnal dip in BP, another risk factor for cardiovascular events, resulted in a smaller morning surge. It seems to be necessary to distinguish morning surge caused by morning BP rise and that by nocturnal BP dip.

Limitations

First, consistent with the results of a previous study (39), the repeatability coefficient expressed as percentage of maximal variation was 39.7% for hypertensive and 62.9% for normotensive subjects. The relatively low reproducibility of the morning surge, especially in normotensive subjects, may obscure significant relationships between morning surge, cfPWV, and sympathetic BRS. However, even BP conventionally used in clinics exhibited a similar repeatability (~50%) to the morning surge (35), and many reports have indicated the significance of morning surge as a predictor for cardiovascular events in hypertensive subjects (12, 15). Therefore, we believe that our results are reliable and may provide insight into the underlying mechanisms of the increased morning surge for cardiovascular diseases in elderly hypertensive subjects. Second, we used cfPWV to assess arterial stiffness. It was found that cfPWV was affected by BP (29). However, cfPWV normalized by mean BP showed a similar relationship with morning surge (hypertensive subjects: \( r = 0.53, P < 0.001 \); normotensive subjects: \( r = -0.38, P = 0.040 \) as that with original cfPWV. Third, sympathetic BRS was evaluated during spontaneous breathing. Thus, the sensitivity was measured without assessing the entire baroreflex curve, which includes nonbaroreflex BP fluctuations. However, we used the binning method with MSNA burst incidence to reduce the impact of nonbaroreflex influence (30). Therefore, we can reveal the physiological modulation of sympathetic control around prevailing and operating point (6). Fourth, although we excluded patients with diagnosed sleep apnea, patients with unknown sleep apnea might have been included, because we did not perform polysomnography. However, it has been reported that patients with and without sleep apnea do not have any difference of the morning surge (24). Fifth, although we evaluated supine sympathetic BRS and cfPWV as factors of morning surge, they were measured at different time points from the period when a part of morning surge occurs, before waking up. Conversely, upright sympathetic BRS and \%TPR/\%MSNA were measured in a similar situation to when a part of morning surge occurs, orthostasis after waking up. Sixth, our subjects on average were considered overweight because of the difficulty to find elderly individuals who were healthy (except for stage I hypertension in the patient group), sedentary, but not overweight in the Dallas-Fort Worth area. However, there was no difference in weight or body mass index between groups in our study. Finally, we excluded patients with stage II hypertension for safety reasons. Although we found no difference in MSNA between hypertensive and normotensive subjects, which was similar to previous findings in borderline hypertensive patients (25), MSNA in moderate-to-severe middle-aged hypertensive subjects was found to be higher than that in normotensive subjects (7). Whether similar results can be obtained in elderly patients with stage II and white-coat hypertension needs to be determined.

In summary, elderly hypertensive subjects with greater morning surge had higher arterial stiffness and smaller sympathetic BRS than those with lesser morning surge. In addition, morning BP surge was positively correlated with arterial stiffness, whereas both variables were negatively correlated with sympathetic BRS in elderly hypertensive subjects. Furthermore, smaller sympathetic BRS and greater TPR with similar MSNA were observed in hypertensive subjects with greater morning surge during upright posture. These results suggest that morning surge may be associated with sympathetic BRS altering concomitantly with large-artery stiffness and vasoconstrictor sensitivity (e.g., sympathetic vascular transduction) during orthostasis in elderly hypertensive subjects.

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DISCLOSURES

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AUTHOR CONTRIBUTIONS


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