ORIGINAL ARTICLE

Stress-Induced Blood Pressure Elevation Self-Measured by a Wearable Watch-Type Device

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BACKGROUND
Psychological stress contributes to blood pressure (BP) variability, which is a significant and independent risk factor for cardiovascular events. We compared the effectiveness of a recently developed wearable watch-type BP monitoring (WBPM) device and an ambulatory BP monitoring (ABPM) device for detecting ambulatory stress-induced BP elevation in 50 outpatients with 1 or more cardiovascular risk factors.

METHODS
The WBPM and ABPM were both worn on the subject's nondominant arm. ABPM was measured automatically at 30-minute intervals, and each ABPM measurement was followed by a self-measured WBPM measurement. We also collected self-reported information about situational conditions, including the emotional state of subjects at the time of each BP measurement. We analyzed 642 paired BP readings for which the self-reported emotional state in the corresponding diary entry was happy, calm, anxious, or tense.

RESULTS
In a mixed-effect analysis, there were significant differences between the BP values measured during negative (anxious, tense) and positive (happy, calm) emotions in both the WBPM (systolic BP [SBP]: 9.3 ± 2.1 mm Hg, $P < 0.001$; diastolic BP [DBP]: 8.4 ± 1.4 mm Hg, $P < 0.001$) and ABPM (SBP: 10.7 ± 2.1 mm Hg, $P < 0.001$; DBP: 5.6 ± 1.4 mm Hg, $P < 0.001$). The absolute BP levels induced by emotional stress self-measured by the WBPM were similar to those automeasured by the ABPM (SBP, WBPM: 141.1 ± 2.7 mm Hg; ABPM: 140.3 ± 2.7 mm Hg; $P = 0.724$). The subject's location at the BP measurement was also significantly associated with BP elevation.

CONCLUSIONS
The self-measurement by the WBPM could detect BP variability induced by multiple factors, including emotional stress, under ambulatory conditions as accurately as ABPM.

Keywords: ambulatory blood pressure; blood pressure; blood pressure variability; emotional stress; hypertension; wearable watch-type wrist blood pressure monitor

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Blood pressure (BP) variation is necessary for human survival. Such variation arises from homeostatic and allostatic circulatory processes in response to changes in the body's internal physiological status and external environmental conditions.[1,2] Excessive BP variability has been described as a strong risk factor for cardiovascular events independent of the average BP values.[3]

Psychological and physical stress are known to contribute to both acute and long-lasting BP variability. Studies conducted in laboratory settings have shown that the acute BP reactivity to emotional stress differs among individuals.[4,5] A Chinese cohort study reported that a long-term psychological intervention improved the BP, health-related quality of life, and stroke prevalence of subjects.[6] These findings suggest that for the goal of personalized hypertension management, it is necessary to determine the levels of stress-induced BP elevation in individual patients. A relationship between emotional states and BP variability measured by ambulatory BP monitoring (ABPM) has been described,[7,8] but further investigations of BP variability in real-life contexts rather than laboratory settings will be needed to identify the "true" risk in our daily lives, which are characterized by exposure to a wide range of internal and external stresses. Because the levels and types of daily stress vary widely on different days, a single day's BP measurement by ABPM is not sufficient to assess the true BP variability in an individual subject.

A newly developed wearable wrist-type BP monitoring (WBPM) device, the "HeartGuide," measures absolute BP

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values using the oscillometric method.[9] The HeartGuide enables wearers to self-measure their BP on a daily basis, whenever they want by setting their wrist at heart level. In our previous comparison study, we observed that the BP values measured by a WBPM in out-of-office setting were acceptable agreement with those measured by an ABPM.[10] The primary aim of the present study was to determine whether stress-induced BP variation can be self-measured by a WBPM as accurately as by ABPM.

SUBJECTS AND METHODS

Study design

This was a *post hoc* analysis of our comparison study of a WBPM, i.e., the HeartGuide device, and traditional ABPM. Details of the study design have been published previously.[10] Briefly, 50 outpatients (mean age 66.1 ± 10.8 years) were asked to simultaneously wear the WBPM and an ABPM device on the same nondominant arm for 24 hours and to write a daily self-report of their situation at the time of each WBPM measurement. The measurements using the WBPM device were conducted only during the daytime throughout the measurement period. The study protocol was approved by the institutional review board of Jichi Medical University School of Medicine (rin-B18-030). The study protocol was registered with the University Hospital Medical Information Network Clinical Trials Registry (UMIN000036689). All of the outpatients provided their written informed consent to participate.

BP measurements

The WBPM was performed by the HeartGuide device (HEM-6410T: Omron Healthcare, Kyoto, Japan), which is a watch-type wearable and automatic oscillometric device for self-measurement of BP at the wrist.[9] ABPM was performed by the TM-2441 (A&D, Tokyo, Japan), an automatic oscillometric device with a BP cuff worn on the upper arm.[11]

The WBPM and ABPM devices were worn on the same nondominant arm by each subject. The ABPM device was set to measure systolic BP (SBP) and diastolic BP (DBP) every 30 minutes for 24 hours. The subjects were instructed to stop moving their arms once the automatic measurement of ABPM was initiated.[12,13] In addition, they were instructed to self-measure their BP with the WBPM device just after each automatic ABPM measurement ≥10 times while awake. When measuring BP with a WBPM device, the worn wrist should be at heart level to reduce the hydrostatic effect.

The previous study demonstrated that the 1st and 2nd BP values self-measured by the WBPM device were significantly higher than those measured by ABPM, suggesting that, in clinical practice, the first 2 self-measurements by WBPM should be discarded.[10] In the present analysis, the first 2 paired BP values from the WBPM and ABPM were discarded.

Self-report diary at the time of BP measurement

The subjects were provided a diary in which they were asked to answer questions about several situational conditions (the location, intensity of physical activity, behavior, emotional state, and body position) at the time of each WBPM measurement during the 24-hour monitoring period (Supplementary Figure S1 online).

Dataset for analysis and emotional state categories defined by self-report diary

In total, 956 paired readings of ABPM followed by WBPM in the out-of-office setting were successfully obtained from the 50 subjects and analyzed in the previous report. The first 2 measurements (n = 100) were excluded due to the instability of BP readings.[10] Another 139 paired readings were excluded due to the lack of a self-reported emotional state at the time of WBPM measurements. As shown in Supplementary Table S2 online, most recordings had the emotional state as "tense," "anxious," "happy," "calm," or "tired." In this *post hoc* analysis, we focused on stress-induced BP and split data into the stressful negative emotion and the positive emotion with less stress. We excluded "tired" from the analysis because we could not determine which of these 2 emotional categories it belongs to. In addition, 18 readings which had uncertain emotional state were also excluded, resulting in 642 paired readings for which the self-reported emotional state in the corresponding diary entry was happy, calm, anxious, or tense were used for the present study. We grouped these reports into 2 emotional states: positive (happy and/or calm; n = 575, with some patients reporting both) and negative (anxious and/or tense: n = 67, with some patients reporting both).

Statistical analyses

All statistical analyses were performed using SAS ver. 9.4 (SAS Institute, Cary, NC). Mixed-effect repeated measures models were used to compare the BP readings measured by the 2 devices and in negative and positive emotional states. All of the data processing and analyses were independently conducted in the Global Analysis Center of BP (GAP) at the Jichi Medical University COE Cardiovascular Research and Development (JCARD) Center. OMRON Healthcare employees were not involved in any of the data collection, processing, or analysis.

RESULTS

The characteristics of the subjects are summarized in Supplementary Table S1 online.[10] The subjects' mean age was 66.1 ± 10.8 years, 60% were male, and the average body mass index was 23.4 ± 4.8 kg/m^2. The prevalence of regular alcohol use was 30%; current smoking, 4%; hypertension, 98%; antihypertensive medication use, 94%; and history of cardiovascular disease (any of angina, myocardial infarction, aortic dissection, stroke, or heart failure), 26%.

Table 1 provides the least square means delivered from the unadjusted mixed-effect model. The BP values measured during the negative emotions were significantly higher than those measured during positive emotions by both the WBPM device (SBP: 9.3 ± 2.1 mm Hg, P < 0.001;

Table 1. Changes in blood pressure and heart rate in response to emotional stress analyzed with an unadjusted mixed-effect model (n = 642)

	Negative[a] (n = 67)	Positive[a] (n = 575)	Negative–positive difference	P for emotional difference
SBP, mm Hg				
WBPM	141.1 ± 2.7	131.7 ± 2.0	9.3 ± 2.1	<0.001
ABPM	140.3 ± 2.7	129.6 ± 2.0	10.7 ± 2.1	<0.001
Device difference	0.8 ± 2.3	2.2 ± 0.8	−1.4 ± 2.4	0.575
P for device difference	0.724	0.006	0.575	
DBP, mm Hg				
WBPM	85.8 ± 1.9	77.5 ± 1.4	8.4 ± 1.4	<0.001
ABPM	86.7 ± 1.9	81.1 ± 1.4	5.6 ± 1.4	<0.001
Device difference	−0.9 ± 1.5	−3.6 ± 0.5	2.7 ± 1.6	0.092
P for device difference	0.564	<0.001	0.092	
HR, bpm				
WBPM	74.2 ± 1.7	72.4 ± 1.4	1.8 ± 1.1	0.107
ABPM	73.5 ± 1.7	73.1 ± 1.4	0.3 ± 1.1	0.766
Device difference	0.8 ± 1.2	−0.7 ± 0.4	1.5 ± 1.3	0.259
P for device difference	0.541	0.089	0.259	

Data are mean ± SE. Abbreviations: ABPM, ambulatory blood pressure monitoring; DBP, diastolic blood pressure; HR, heart rate; SBP, systolic blood pressure; WBPM, wearable blood pressure monitoring.
[a]Negative: self-reported "anxious" or "tense"; positive: self-reported "happy" or "calm."

DBP: 8.4 ± 1.4 mm Hg, P < 0.001) and the ABPM device (SBP: 10.7 ± 2.1 mm Hg, P < 0.001; DBP: 5.6 ± 1.4 mm Hg, P < 0.001). There was no significant difference in heart rate between the positive and negative emotion categories. The elevations of BP in response to negative emotion as self-measured by WBPM were not statistically different from those automeasured by ABPM (SBP: WBPM, 141.1 ± 2.7 mm Hg; ABPM, 140.3 ± 2.7 mm Hg; P = 0.724; DBP: WBPM, 85.8 ± 1.9 mm Hg; ABPM, 86.7 ± 1.9 mm Hg; P = 0.564). During positive emotions the SBP values were slightly higher (by 2.2 ± 0.8 mm Hg, P = 0.006) and DBP values were lower (by 3.6 ± 0.5 mm Hg, P < 0.001) when measured by WBPM than by ABPM. The negative–positive differences of SBP, DBP, and heart rate measured by WBPM were not significantly different from those measured by ABPM. In the present analysis, BP readings with the emotional state as "tired," "sad," "excited," and "surprised" were excluded, as described in the Subjects and methods section. When "tired" and "sad" were categorized in the negative emotion and "excited" and "surprising" were categorized in the positive emotion, the BP values measured during the negative emotions (n = 121) were significantly higher than those measured during the positive emotions (n = 578) by both WBPM (SBP: 4.9 ± 1.6 mm Hg, P = 0.002; DBP: 5.2 ± 1.0 mm Hg, P < 0.001) and ABPM (SBP: 4.6 ± 1.6 mm Hg, P = 0.004; DBP: 3.1 ± 1.0 mm Hg, P = 0.003). When "sad" was categorized in the negative emotion and "tired," "excited," and "surprising" were categorized in the positive emotion, the BP values measured during the negative emotions (n = 72) were also significantly higher than those measured during the positive emotions (n = 627) by both WBPM (SBP: 6.9 ± 1.9 mm Hg, P < 0.001; DBP: 6.7 ± 1.3 mm Hg, P < 0.001) and ABPM (SBP: 4.5 ± 1.6 mm Hg, P = 0.004; DBP: 2.9 ± 1.0 mm Hg, P = 0.005). These results were similar to the present results.

In addition, another analysis was performed to examine the agreement of emotional stress-induced BP difference between devices at individual level. The average of mean SBP for an individual patient was 130.6 ± 15.1 mm Hg measured by ABPM and 132.9 ± 15.2 mm Hg measured by WBPM, and the correlation between devices was high (r = 0.703, P < 0.01). Among the 15 patients who had BP readings measured during both negative and positive emotion, the within individual negative–positive difference of SBP was significantly correlated between devices (r = 0.814, P < 0.01).

The SBP changes in response to emotional stress in the separate mixed-effect models adjusted for covariates are presented in Table 2. Even after adjustment for age, sex, body mass index, location, measurement time, body position, and intensity of physical activity, the BP difference between negative and positive emotions remained significant in both the WBPM (5.5 ± 2.1 mm Hg, P = 0.010) and ABPM (6.9 ± 2.1 mm Hg, P = 0.001). Even when we added 18 types of behavior reported in the subjects' diaries as covariates to Model 3, the difference still remained significant for both WBPM (5.1 ± 2.2 mm Hg, P = 0.022) and ABPM (6.2 ± 2.2 mm Hg, P = 0.006) (P for device difference = 0.651).

A mixed-effect model adjusted for selected variables (age, sex, body mass index, emotional state, location, body position, and the intensity of physical activity) was used to examine the predictive effects on the SBP value measured by WBPM (Table 3). Negative emotions and outside-home location were significantly and independently associated with an increase in SBP (all P < 0.01), and reclining posture

Table 2. Changes in SBP values against emotional stress analyzed with a mixed-effect model adjusted for different variables (*n* = 642)

Device	Negative–positive SBP difference (mm Hg)	*P* for emotional difference	*P* for device difference
Model 1: age, sex, BMI			
WBPM	9.3 ± 2.1	<0.001	0.575
ABPM	10.7 ± 2.1	<0.001	
Model 2: Model 1 + location[a]			
WBPM	7.4 ± 2.1	<0.001	0.572
ABPM	8.7 ± 2.1	<0.001	
Model 3: Model 2 + measurement time (hour), body position[b], and physical activity[c]			
WBPM	5.5 ± 2.1	0.010	0.531
ABPM	6.9 ± 2.1	0.001	

Data are mean ± SE. Abbreviations: ABPM, ambulatory blood pressure monitoring; BMI, body mass index; SBP, systolic blood pressure; WBPM, wearable blood pressure monitoring.

[a]Location was categorized as home, worksite, and others (commuting and outside).

[b]Body position was categorized as sitting, standing, and reclining.

[c]Physical activity was categorized as rest, mild, and ≥moderate (moderate and high strength).

Table 3. Predictors of SBP measured by WBPM derived from a mixed-effect model adjusted for age, sex, BMI, emotional state, location, body position, and intensity of physical activity (*n* = 642)

Variable	Coefficient	95% CI (lower, upper)	*P*
Intercept	129.2		
Male	2.8	−6.3, 11.9	0.536
Age, 1 SD, years	−1.1	−5.5, 3.4	0.627
BMI, 1 SD, kg/m^2	0.8	−3.6, 5.2	0.707
Emotion			
Positive	Ref.	—	—
Negative	7.9	4.1, 11.6	<0.001
Location			
Home	Ref.	—	—
Worksite	4.6	1.5, 7.8	0.004
Others[a]	4.1	1.1, 7.0	0.007
Body position			
Sitting	Ref.	—	—
Standing	−2.0	−4.8, 0.8	0.169
Reclining	−5.6	−10.2, −0.9	0.018
Physical activity			
Rest	Ref.	—	—
Mild	1.9	−0.7, 4.4	0.150
≥Moderate[b]	4.5	−0.4, 9.3	0.074

Age, 1 SD = 10.8 years; BMI, 1 SD = 4.8 kg/m^2. Abbreviations: BMI, body mass index; CI, confidence interval; SBP, systolic blood pressure; WBPM, wearable blood pressure monitoring.

[a]"Others" includes commuting and outside.

[b]"≥Moderate" includes moderate and high strength.

was inversely associated with SBP. Similar associations were observed for DBP measured by the WBPM device (Supplementary Table S3 online).

DISCUSSION

This is the first study to determine the influences of emotional stress, location, body position, and other related factors on BP self-measured by a validated wearable watch-type BP monitoring device in an ambulatory situation. The WBPM successfully detected negative emotion-induced BP elevation as accurately as ABPM. In addition, the subjects' location at the time of the BP measurement was significantly associated with BP change.

Stress-induced BP elevation detected by self-measured WBPM

The elevated SBP values affected by negative emotions and stress-induced SBP elevation detected by WBPM were similar to those detected by ABPM (SBP, WBPM: 141.1 ± 2.7 mm Hg; ABPM: 140.3 ± 2.7 mm Hg; *P* for device difference = 0.724, stress-induced SBP elevation, WBPM: 9.3 ± 2.1 mm Hg; ABPM: 10.7 ± 2.1 mm Hg; *P* for device difference = 0.575). Even when examined at individual level, the stress-induced BP elevation measured by WBPM and ABPM was significantly correlated. However, the number of data was insufficient for this intraindividual analysis because only 15 patients had BP readings measured during both negative and positive emotion. Further studies are needed to verify the inter- and intraindividual BP differences measured by WBPM.

The BP values measured during positive emotions were significantly different between devices, however, these differences were close to those calculated from the total data. The difference may be partly explained by the different BP algorithms used in the 2 devices. The negative emotion-induced BP increase remained significant even after adjustment for multiple factors which may contribute to BP, including location, intensity of physical activity, behavior, emotional state, and body position at the time of each WBPM measurement.

Other studies using ABPM reported that the BP of subjects rose during angry or anxious state[7,14] and neutral state, which is similar emotion of "calm" in our study, was associated with lower BP.[14] Our present findings are in line with those reports. Although BP values measured by wrist-type BPM are known to be affected by the position of the device from the heart level and by the angle and rotation of the wrist at the time of BP measurement, our results herein demonstrated that a wrist-type WBPM device detected emotional stress-induced BP changes as accurately as ABPM even in ambulatory situations.

Our study population consisted of outpatients with cardiovascular risk factors (98% of the subjects were hypertensive), and their SBP increase in response to emotional stress was 9.3 mm Hg when self-measured by the WBPM device and 10.7 mm Hg when automatically measured by the ABPM device. In a study of normotensive subjects, the SBP increase measured by ABPM during an angry state was 4 mm Hg.[14] Another investigation also indicated that the effect of emotional stress on BP might be greater in individuals with labile BP.[7] This discrepancy in results might therefore be due to the difference in the subjects' hypertension status, concomitant risk factors, and vascular conditions.

Effects of different ambulatory conditions

The location of subjects (worksite, home, and outside home) was also significantly associated with the SBP difference, independently of emotional factors, body position, and other confounding factors. The results shown in Table 3 indicate that the SBP level could increase by approximately 12.5 mm Hg when hypertensive subjects were exposed to emotional stress at a worksite (worksite: 4.6 mm Hg; negative: 7.9 mm Hg).

In the laboratory setting, an excessive BP response to psychological stress, *per se*, is a risk factor for cardiovascular disease.[15,16] A study of healthy young adults revealed that BP reactivity to psychological stress is associated with cardiovascular risk.[15] A meta-analysis demonstrated that greater reactivity to stress is associated with future poor cardiovascular status.[16] The Chinese cohort study mentioned earlier reported that 2 years of psychological intervention could lower BP.[6] Stress could therefore be both an acute and a chronic risk factor for the cardiovascular state, and adequate management of stress-induced BP variability is important.

We speculated that the BP-related cardiovascular risk conferred by psychological stress might be more sensitively detected under real-world ambulatory conditions than specific laboratory conditions. In individuals who experience a greater response to psychological stress, the stress-induced elevation in BP in an ambulatory setting might be exaggerated in combination with other pressor conditions such as location, physical activity, smoking status, and air conditioning, resulting in more exaggerated BP variability under real-world daily ambulatory conditions. These personal characteristics of stress-induced BP elevation could be detected repeatedly using self-measured WBPM.

Clinical implications of WBPM

By using the present validated WBPM device, which self-measures stress-induced BP levels as accurately as ABPM, the quality of BP control could be significantly improved in several ways. First, by collecting an increased number of ambulatory BP measurements under different ambulatory conditions, the WBPM device would increase the accuracy of hypertension diagnosis, especially for masked hypertension, as well as the accuracy of the ambulatory BP status and daily BP control status, which are essentially based on the average of BP measurements. Second, the increased number of repeated BP measurements afforded by WBPM also enables the detection of various types of ambulatory and day-by-day BP variability under different daily conditions.

There is accumulating evidence indicating that increased BP variability poses a risk of cardiovascular disease and organ damage.[17] Some research groups have evaluated diurnal BP variability using ABPM,[18,19] and others evaluated day-by-day variability using home blood pressure monitoring[20–22] to unveil the risk of BP variability in different time phases. As the cardiovascular risk of BP variability is greater in high-risk patients, the early detection of exaggerated BP variability is clinically important in such patients.[23,24] Because the ability of a WBPM device to self-measure BP anytime and anywhere allows the measurement of BP at each moment under stressful conditions—which is impossible with the scheduled measurements by ABPM and home blood pressure monitoring—the use of WBPM will provide important information for the individual management of BP and BP variability in everyday life.

Study limitations

There are several possible limitations to the present study. First, the present *post hoc* analysis on stress-induced BP elevation used about two-thirds of all 956 paired BP readings to compare BP values in the stressful negative emotion and the positive emotion with less stress. Because the 314 paired readings were omitted from the present analysis, the results could be limited. However, the additional analysis using the dataset which exclude minimal data demonstrated the similar results to the present results. Second, we analyzed the BP measurements of ABPM and WBPM only over a 24-hour period. A previous study reported that the effects of mental stress (especially in working adults) exhibit day-by-day variability.[25] Data from multiple days are required to detect the precise BP variability of an individual. Finally, the self-measurements by WBPM were obtained just after the ABPM measurements at 30-minute intervals, although the HeartGuide device is designed to be able to measure BP anytime. With this study protocol using a fixed time interval, the WBPM measurements might not detect the maximum stress-induced BP elevation. However, our findings demonstrated that stress-induced BP elevation could be detected even by scheduled measurements. Further studies with a self-measuring protocol under stressful conditions would more accurately detect stress-induced BP increases.

Self-measurement of BP by a new wearable watch-type device was found to detect elevated ambulatory BP levels and BP variability triggered by emotional stress and location with an accuracy comparable to that of automatic measurements by ABPM. The new WBPM device, which measures BP frequently at any location to detect abnormal BP elevations induced by multiple factors under ambulatory and daily conditions, will facilitate personalized hypertension management in the near future.

SUPPLEMENTARY MATERIAL

Supplementary data are available at *American Journal of Hypertension* online.

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DISCLOSURE

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