ORIGINAL ARTICLE

Impact of outdoor temperature on prewaking morning surge and nocturnal decline in blood pressure in a Japanese population

Shougo Murakami¹, Kuniaki Otsuka², Tatsuji Kono¹, Akiko Soyama¹, Tatsuya Umeda¹, Naomune Yamamoto², Hideaki Morita¹, Gaku Yamanaka² and Yasushi Kita¹

Seasonal variations in blood pressure (BP) have often been attributed to meteorological factors, especially changes in outdoor temperature. We evaluated the direct association between meteorological factors and circadian BP variability. Twenty-four-hour ambulatory BP was monitored continuously for 7 days in 158 subjects. Mean awake, asleep, morning (first 2 h after waking) BP, prewaking morning BP surge (morning systolic BP (SBP)–mean SBP during the 2-h period before waking) and nocturnal BP decline were measured each day. We compared BP values for the lowest and highest days with regard to the daily mean outdoor temperature and mean atmospheric pressure. Morning BP and prewaking morning BP surge on the coldest day were significantly higher than those on the warmest day (morning SBP, 136.6 ± 1.6 vs. 133.1 ± 1.5 mm Hg, $P=0.002$; morning diastolic BP, 84.4 ± 0.9 vs. 82.6 ± 0.9 mm Hg, $P=0.02$; and prewaking morning BP surge, 20.8 ± 1.3 vs. 15.3 ± 1.3 mm Hg, $P=0.0004$). The magnitude of nocturnal BP decline on the coldest day was significantly greater than that on the warmest day (15.8 ± 0.7 vs. $13.9 \pm 0.7\%$, $P=0.01$). Outdoor temperature is an important determinant of morning BP, prewaking morning BP surge and the magnitude of nocturnal BP decline. These findings may have important implications in management of hypertension and prevention of cardiovascular events.

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Keywords: ambulatory blood pressure monitoring; cold pressure stress; outdoor temperature; prewaking morning blood pressure surge

INTRODUCTION

Previous studies have indicated that the onset of cardiovascular events show circadian, weekly and seasonal variations.^{1–3}

Many studies have demonstrated an increased incidence of acute cardiovascular events in winter compared with other seasons. Blood pressure (BP) has also been reported to be higher in winter than in the other three seasons.^{4–8} This seasonal variation in BP has often been attributed to meteorological factors, especially changes in outdoor temperature. However, direct effects of outdoor temperature and atmospheric pressure on BP have yet to be established conclusively, as seasonal changes in other factors such as diet,⁹ physical activity¹⁰ and psychological status¹¹ that may affect BP have also been observed.

In this study, we evaluated the effect of outdoor temperature and atmospheric pressure on BP variability in a Japanese population using continuous 24-h ambulatory BP (ABP) monitoring for a 7-day period.

METHODS

Subjects

This study is a part of the longitudinal observational study about the association between BP and lifestyle in 'T-town', a Japanese rural town. All

subjects were residents of 'T-town', and had visited and used the free health screening, counseling and educational services offered by the town office. This study was performed from April 2004 to January 2009 during a relatively cold season (October–April). Subjects with definite neurological diseases such as Parkinson disease and stroke were excluded from the study.

A total of 165 subjects who agreed to perform ABP monitoring for 7 days were initially recruited in this study. Seven subjects (4%) were excluded from this study because of incomplete ABP recording. Overall, 158 subjects (96%) were eligible for inclusion in this study. Informed consent was obtained from all subjects before their participation in this study. Smokers were defined as current smokers. The body mass index was calculated as weight (kg)/height (m)².

Seven-day (24-h) ABP monitoring

Non-invasive ABP monitoring was performed using an oscillometric monitor (TM-2431, A&D, Tokyo, Japan) to record the systolic BP (SBP) and diastolic BP (DBP). The recorder was programmed to take readings at 30-min intervals between 07:00 and 22:00 hours and at 60-min intervals between 22:00 and 07:00 hours for 7 days. All subjects were fitted with the recorder at the town office and asked to revisit the office 7 days later. Subjects were taught how to attach and remove the recorder and were instructed to remove the recorder while taking a bath. Individuals were asked to keep a diary noting the times they went to sleep and woke up.

¹Third Division, Department of Internal Medicine, Osaka Medical College, Osaka, Japan and ²Department of Internal Medicine, Tokyo Women's Medical University, Medical Center East, Tokyo, Japan

Correspondence: Dr S Murakami, Third Division, Department of Internal Medicine, Osaka Medical College, 2-7, Daigakumachi, Takatsuki, Osaka 569-8686, Japan.

E-mail: shougo17@gb3.so-net.ne.jp

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Stored data were retrieved on a personal computer using commercially available software for the oscillometric monitor (TM-2430-15, A&D).

Data from the 7-day (24-h) ABP monitoring were divided into 7 intervals. The first interval lasted from the time of fitting of the recorder until the subject's bedtime (day 1). The second interval lasted from bedtime on the first day to that of the next (day 2). The third to seventh intervals were defined in the same manner as the second interval. As indicated by our previous study,¹² BP on day 1 was significantly higher than those on other days of monitoring (novelty effect in BP), and hence, the data obtained on day 1 were eliminated from the analysis.

We defined the mean of BP results obtained while the subject was awake as awake BP and the mean of the BP results obtained while the subject was asleep as asleep BP. Morning BP was defined as average BP during the first 2 h after waking.

Awake and asleep time BP variability were estimated using average real variability index. Mena *et al.*¹³ showed average real variability as a more reliable measure of BP variability than the standard deviation of average BP values.

Prewaking morning BP surge for each day was defined as the rise in BP during morning (morning BP – mean BP during the 2-h period before waking).

Nocturnal BP decline for each day was defined as the decrease in BP at night, calculated as (awake BP – asleep BP)/awake BP × 100.

SBP was used to calculate prewaking morning BP surge and nocturnal BP decline.

Meteorological data

Daily mean outdoor temperature and daily mean atmospheric pressure were obtained from the local meteorological office of Japan Meteorological Agency. In this study, outdoor temperature was measured in degrees Celsius (°C) and atmospheric pressure was measured in hectopascals (hPa).

Data analysis

Data are expressed as mean ± s.e.m. To investigate the effect of meteorological factors on BP, the paired *t*-test was used to compare the mean values of BP on the lowest and highest days with regard to daily mean outdoor temperature and mean atmospheric pressure. Univariate linear regression and multivariate regression analyses were performed to determine the variables that had a significant influence on differences in morning BP surge between the coldest and warmest days (Δ morning BP surge). Differences with a value of $P < 0.05$ were considered significant.

RESULTS

Population characteristics

The mean age of the participants was 58 ± 1 (range: 28–74) years, average body mass index was 23.7 ± 0.3 (range: 15.7–32.1) kg m⁻² and proportion of men was 41.1%. Of the subjects, 23 (14.6%) were classified as smokers, and 48 (30.4%) were receiving antihypertensive medications.

The effect of outdoor temperature on BP

Mean difference in outdoor temperature between the coldest and warmest days was 5.0°C (5.5 ± 0.4 vs. $10.5 \pm 0.5^\circ\text{C}$, $P < 0.0001$).

Table 1 compares mean BP and BP variability between the coldest and warmest days. Awake SBP and DBP on the coldest day tended to be higher than those on the warmest day (SBP, 135.1 ± 1.4 vs. 133.6 ± 1.3 mm Hg, $P = 0.06$; DBP, 82.8 ± 0.8 vs. 81.8 ± 0.7 mm Hg, $P = 0.06$). Morning SBP and DBP on the coldest day were significantly higher than those on the warmest day (SBP, 136.6 ± 1.6 vs. 133.1 ± 1.5 mm Hg, $P = 0.002$; DBP, 84.4 ± 0.9 vs. 82.6 ± 0.9 mm Hg, $P = 0.02$). Variability in awake SBP and DBP on the warmest day was significantly greater than that on the coldest day (SBP, 15.6 ± 0.4 vs. 14.8 ± 0.4 mm Hg, $P = 0.04$; DBP, 11.7 ± 0.4 vs. 11.0 ± 0.3 mm Hg, $P = 0.03$). On the coldest day, prewaking morning BP surge was significantly higher than that measured on the warmest day (20.8 ± 1.3 vs. 15.3 ± 1.3 mm Hg, $P = 0.0004$) (Figure 1a). The magnitude

Table 1 A comparison of mean blood pressure and blood pressure variability between the lowest and highest days with regard to outdoor temperature

	Lowest day	Highest day	
Outdoor temperature (°C)	5.5 ± 0.4	10.5 ± 0.4	P-values
Awake SBP (mm Hg)	135.1 ± 1.4	133.6 ± 1.4	0.06
Awake DBP (mm Hg)	82.8 ± 0.8	81.8 ± 0.7	0.06
Asleep SBP (mm Hg)	113.2 ± 1.3	114.8 ± 1.4	0.11
Asleep DBP (mm Hg)	69.8 ± 0.8	70.3 ± 0.8	0.42
Morning SBP (mm Hg)	136.6 ± 1.6	133.1 ± 1.5	0.002
Morning DBP (mm Hg)	84.4 ± 0.9	82.6 ± 0.9	0.02
Awake SBP variability	14.8 ± 0.4	15.6 ± 0.4	0.03
Awake DBP variability	12.8 ± 0.4	13.3 ± 0.4	0.12
Asleep SBP variability	14.3 ± 0.5	14.0 ± 0.5	0.61
Asleep DBP variability	9.6 ± 0.4	9.9 ± 0.4	0.52

Abbreviations: BP, blood pressure; DBP, diastolic blood pressure; SBP, systolic blood pressure.

of nocturnal BP decline on the coldest day was significantly greater than that measured on the warmest day (15.8 ± 0.7 vs. $13.9 \pm 0.7\%$, $P = 0.01$) (Figure 1b).

To clarify the effect of outdoor temperature on prewaking morning BP surge, we examined factors that contributed to the difference in this surge between the coldest and warmest days (Δ prewaking morning BP surge). A univariate regression analysis was performed to examine the relation between Δ prewaking morning BP surge and clinical variables. Differences in outdoor temperature and age both correlated with Δ prewaking morning BP surge (Table 2). A multiple regression analysis also showed that differences in outdoor temperature and age were independent determinants for Δ prewaking morning BP surge (Table 3).

The effect of atmospheric pressure on BP

Mean difference in atmospheric pressure between the lowest and highest days was 10.0 hPa (1013.6 ± 0.4 vs. 1023.6 ± 0.3 hPa, $P < 0.0001$). We found no association between atmospheric pressure and any of the BP variables (Table 4).

DISCUSSION

Although seasonal variations in BP have been observed in many studies, the effect of meteorological factors on circadian BP variability remains unclear due to the confounding influence of seasonal variations on other factors, such as diet, physical activity and psychological stress. In this study, we demonstrated that outdoor temperature had an influence on morning BP, morning BP surge, nocturnal BP decline and variability in awake BP.

The most important finding in this study was that cold temperature had a significant impact on prewaking morning BP surge. Modesti *et al.*¹⁴ also demonstrated that morning BP surge was augmented in the cold seasons. A surge in morning BP is associated not only with target organ damage¹⁵ but also with increased risk of cardiovascular disease.^{16,17} Several pathophysiological mechanisms such as circadian neurohormonal rhythms, sympathetic nerve activation and systemic vasoconstriction associated with arousal reaction have been suggested to contribute to this surge in morning BP. In addition, a recent study showed a relation between morning BP surge and the structure of small resistance arteries.¹⁸ Activation of the sympathetic nervous system induced in response to cold pressor stress increases vascular tone in resistance arteries, and therefore, may augment prewaking

Figure 1 A comparison of prewaking morning BP surge (a) and nocturnal BP decline (b) between the coldest and warmest days.

Table 2 A univariate regression analysis of determinants for Δ prewaking morning blood pressure surge

	<i>r</i>	<i>P</i> -values
Difference in outdoor temperature (°C)	0.182	0.02
Age (year)	0.176	0.03
Gender (men=1)	0.137	0.09
Hypertensive medication (yes=1)	0.043	0.60
Body mass index (kg m ⁻²)	-0.048	0.56
Smoking (yes=1)	0.038	0.64

Table 3 A multiple regression analysis of determinants for Δ prewaking morning blood pressure surge

	β	<i>t</i>	<i>P</i> -values
Difference in outdoor temperature (°C)	0.186	2.29	0.02
Age (year)	0.211	2.38	0.02
Gender (men=1)	0.154	1.75	0.08

morning BP surge. Previous studies showed bedtime administration of an α -adrenergic blocker suppressed morning BP surge by reducing the resistance of peripheral vessels.^{19,20} This finding suggests that bedtime administration of an α -adrenergic blocker during cold seasons may also have the beneficial effect of preventing cardiovascular diseases.

Our data showed that the magnitude of nocturnal decline in BP was greater on the coldest day than on the warmest day. This finding may reflect higher levels of awake BP on the cold day than that measured on the warm day. Previous studies showed that the level of physical activity,²¹ sleep activity²² and psychological factors²³ are known to affect the magnitude of nocturnal decline in BP. Outdoor temperature may also be a determining factor in the magnitude of nocturnal decline in BP.

Variability in awake BP was greater on the warmest day than on the coldest day. Although the underlying mechanisms responsible for this difference are not clear, a possible explanation is that physical activity is a major determinant of diurnal BP variation. A previous study demonstrated that variability in awake BP correlated positively with awake activity.²¹ As this study was performed during a relatively cold season, the level of physical activity might be lesser on the coldest day than on the warmest day.

Table 4 A comparison of mean blood pressure and blood pressure variability between the lowest and highest days with regard to atmospheric pressure

	<i>Lowest day</i>	<i>Highest day</i>	<i>P</i> -values
Atmospheric pressure (hPa)	1013.6 ± 0.3	1023.6 ± 0.3	
Awake SBP (mm Hg)	134.0 ± 1.3	134.2 ± 1.3	0.94
Awake DBP (mm Hg)	82.6 ± 0.8	82.3 ± 0.7	0.61
Asleep SBP (mm Hg)	113.0 ± 1.3	114.4 ± 1.4	0.14
Asleep DBP (mm Hg)	69.6 ± 0.8	70.1 ± 0.8	0.31
Morning SBP (mm Hg)	132.3 ± 1.6	133.1 ± 1.7	0.58
Morning DBP (mm Hg)	83.3 ± 0.9	82.3 ± 1.0	0.28
Awake SBP variability	16.1 ± 0.5	16.4 ± 0.4	0.33
Awake DBP variability	12.8 ± 0.4	13.3 ± 0.4	0.12
Asleep SBP variability	14.2 ± 0.4	14.6 ± 0.6	0.42
Asleep DBP variability	10.0 ± 0.4	9.9 ± 0.4	0.85
Prewaking MBP surge (mm Hg)	16.3 ± 1.3	15.9 ± 1.5	0.73
Nocturnal BP decline (%)	15.1 ± 0.7	14.5 ± 0.8	0.32

Abbreviations: BP, blood pressure; DBP, diastolic blood pressure; MBP, morning blood pressure; SBP, systolic blood pressure.

Although some studies have demonstrated an association between atmospheric pressure and cardiovascular events,^{24,25} this relation is not consistent. Our data showed no effect of atmospheric pressure on circadian BP variables. Jehn *et al.*²⁶ also reported no relation between atmospheric pressure and BP. On the other hand, Weinbacher *et al.*²⁷ demonstrated a negative correlation between atmospheric pressure and BP. Further evaluations are therefore needed to better understand the relationship between atmospheric pressure and BP.

There were some potential limitations of this study. First, as this study was performed during a relatively cold season (October–April), the relation between outdoor temperature and circadian BP variability in the hot season has yet to be established. Second, meteorological conditions vary according to locality; therefore, it is necessary to confirm the relationship between meteorological factors in different regions and BP. Third, we did not examine the effect of alcohol intake on BP in this study. Previous studies demonstrated that habitual alcohol intake was associated with increased BP in the morning.²⁸ Therefore, further study is necessary to clarify the effect of alcohol intake on Δ prewaking morning BP surge. Finally, we could not obtain information regarding the indoor temperature. As most houses have a heating system in Japan, there might be a difference in the morning temperature between outdoor and indoor.

Despite these limitations, our data may have important implications for achieving adequate BP control and prevention of cardiovascular events.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DISCLAIMER

We certify that no portion of this paper has been previously published.

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