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ORIGINAL RESEARCH

Association of Sleep Characteristics With Nocturnal Hypertension and Nondipping Blood Pressure in the CARDIA Study

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BACKGROUND: Sleep characteristics and disorders are associated with higher blood pressure (BP) when measured in the clinic setting.

METHODS AND RESULTS: We tested whether self-reported sleep characteristics and likelihood of obstructive sleep apnea (OSA) were associated with nocturnal hypertension and nondipping systolic BP (SBP) among participants in the CARDIA (Coronary Artery Risk Development in Young Adults) study who completed 24-hour ambulatory BP monitoring during the year 30 examination. Likelihood of OSA was determined using the STOP-Bang questionnaire. Global sleep quality, habitual sleep duration, sleep efficiency, and midsleep time were obtained from the Pittsburgh Sleep Quality Index. Nocturnal hypertension was defined as mean asleep SBP ≥120 mm Hg or diastolic BP ≥70 mm Hg. Nondipping SBP was defined as a decline in awake-to-asleep SBP <10%. Among 702 participants, the prevalence of nocturnal hypertension and nondipping SBP was 41.3% and 32.5%, respectively. After multivariable adjustment including cardiovascular risk factors, the prevalence ratios (PRs) for nocturnal hypertension and nondipping SBP associated with high versus low likelihood of OSA were 1.32 (95% CI, 1.00–1.75) and 1.31 (95% CI, 1.02–1.68), respectively. The association between likelihood of OSA and nocturnal hypertension was stronger for white participants (PR: 2.09; 95% CI, 1.23–3.48) compared with black participants (PR: 1.11; 95% CI, 0.79–1.56). The PR for nondipping SBP associated with a 1-hour later midsleep time was 0.92 (95% CI, 0.85–0.99). Global sleep quality, habitual sleep duration, and sleep efficiency were not associated with either nocturnal hypertension or nondipping SBP.

CONCLUSIONS: These findings suggest that addressing OSA risk and sleep timing in a clinical trial may improve BP during sleep.

Key Words: ambulatory blood pressure monitoring ■ nocturnal hypertension ■ nondipping systolic blood pressure ■ obstructive sleep apnea ■ sleep quality

Sleep characteristics and disorders, including short sleep duration, obstructive sleep apnea (OSA), and insomnia with short sleep duration have been associated with an increased risk of developing hypertension based on blood pressure (BP) measured in the clinic setting.[1–3] Ambulatory BP phenotypes, including nocturnal hypertension and nondipping systolic BP (SBP), have been more strongly associated with cardiovascular morbidity and mortality than BP measured in the clinic.[4–6] Although the association between sleep characteristics and hypertension based on clinic BP measurements is well established,[1,7–9] few data exist on the association between sleep characteristics and asleep BP.[10–16] These existing studies have largely focused on OSA, included small sample sizes, recruited

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CLINICAL PERSPECTIVE

What Is New?

- This study is the first that is sufficiently powered to examine racial differences in the association between sleep characteristics across multiple domains, including sleep timing, habitual sleep duration, likelihood of obstructive sleep apnea, and asleep blood pressure.

What Are the Clinical Implications?

- These findings suggest that decreasing likelihood of obstructive sleep apnea, particularly among white individuals, and optimizing sleep timing may be targets for clinical trials with a goal of improving blood pressure during sleep.
- Given the high prevalence of nocturnal hypertension among black participants with low likelihood of obstructive sleep apnea, other mechanisms need to be considered.

Nonstandard Abbreviations and Acronyms

ABPM	ambulatory blood pressure monitoring
ACR	albumin-to-creatinine
CPAP	continuous positive airway pressure
eGFR	estimated glomerular filtration rate
OSA	obstructive sleep apnea
PR	prevalence ratio
PSQI	Pittsburgh Sleep Quality Index

patients from sleep clinics, or have not included both black and white participants. Therefore, their results may not generalize to broader populations. Studies have also demonstrated circadian control of BP,[17,18] wherein a circadian peak in BP occurs in the evening.[17] However, few studies have examined the impact of sleep timing, a proxy for endogenous circadian rhythms, on BP. We conducted an analysis of data from 702 participants in the CARDIA (Coronary Artery Risk Development in Young Adults) study to test the hypothesis that worse global sleep quality, shorter sleep duration, lower sleep efficiency, later midsleep time, and higher likelihood of having OSA would all be associated with nocturnal hypertension and nondipping SBP among both black and white participants.

METHODS

Data used in this analysis are available to the scientific community through the National Heart, Lung, and Blood Institute's Biological Specimen and Data Repository Information Coordinating Center (BioLINCC), and the analytical methods are described below.

Study Population

Detailed methods for the CARDIA study have been published previously.[19] Briefly, in 1985–1986, 5115 black and white men and women aged 18 to 30 years were enrolled in the CARDIA study from 4 field centers in the United States (Birmingham, AL; Chicago, IL; Minneapolis, MN; and Oakland, CA). Enrollment was performed to provide approximately equal numbers of participants by sex, self-reported race (black or white), age (18–24 or 25–30 years), and education (less than or equal to high school or more than high school) at each site. Participants have completed 9 study examinations that occurred at year 0 (baseline) and 2, 5, 7, 10, 15, 20, 25, and 30 years following the baseline examination. Participation at follow-up visits ranged from 90% (year 2 exam) to 71% (year 30 exam) of the surviving cohort. Contact is maintained with participants by telephone, mail, or email every 6 months, with annual interim medical history ascertainment. Over the past 5 years, >90% of the surviving cohort has been contacted directly, and follow-up for vital status is completed through related contacts and intermittent National Death Index searches. The institutional review board at the participating sites approved the human subjects protocol at each examination. All participants provided written informed consent at each study examination.

A total of 825 participants at the Birmingham and Chicago Field Centers were enrolled in an ambulatory BP monitoring (ABPM) ancillary study at the year 30 examination (2015–2016).[20] Among these participants, 781 (95%) had a complete ABPM recording (defined in Ambulatory BP Monitoring). We excluded 69 participants who did not complete both the Pittsburgh Sleep Quality Index (PSQI) and STOP-Bang questionnaires. We also excluded 10 participants who reported obtaining ≤2 hours of sleep each night over the past month. After these exclusions, 702 participants were included in the current cross-sectional analyses (Figure S1).

Data Collection

Sex and race were self-reported at baseline and confirmed at the year 2 exam. The remaining data used in this analysis were obtained at the year 30 exam. Self-administered questionnaires were used to collect information on age, education, cigarette smoking status, antihypertensive medication use, and continuous positive airway pressure use. Height

Table 1. Characteristics of Participants With and Without Nocturnal Hypertension

	Overall (N=702)	Nocturnal Hypertension		
		No (n=412)	Yes (n=290)	*P* Value
Age, y	54.7±3.7	54.7±3.7	54.7±3.8	0.946
Male, %	39.5	34.0	47.2	<0.001
Black, %	61.4	51.5	75.5	<0.001
Field center, %				>0.999
Birmingham	60.7	60.7	60.7	
Chicago	39.3	39.3	39.3	
Highest level of education, y	14.9±2.6	15.3±2.7	14.2±2.4	<0.001
Low physical activity, %	66.4	65.1	68.3	0.372
Alcohol intake, %				0.385
Nondrinker	52.4	50.7	54.8	
Moderate	34.3	34.7	33.8	
Heavy	13.3	14.6	11.4	
Current cigarette smoking, %	15.1	11.7	20.0	0.011
BMI, kg/m^2	31.5±6.9	30.6±6.9	32.7±7.0	<0.001
Depression symptoms, %	17.0	16.3	17.9	0.563
Diabetes mellitus, %	17.6	14.9	21.5	0.026
Reduced eGFR, %	4.4	4.4	4.5	0.942
Albuminuria, %	9.4	3.2	18.3	<0.001
CPAP use, %	14.1	12.4	16.6	0.120
Antihypertensive medication use, %	41.7	35.9	49.8	<0.001
CVD events, %	5.6	5.1	6.2	0.616
SBP, mm Hg				
Clinic	121.9±17.7	114.9±14.1	131.7±17.6	<0.001
Awake	129.7±15.5	122.7±11.4	139.6±15.1	<0.001
Asleep	112.5±15.6	102.6±8.3	126.5±12.6	<0.001
DBP, mm Hg				
Clinic	74.5±11.2	70.4±9.7	80.3±10.7	<0.001
Awake	80.7±9.2	76.9±7.4	86.0±8.9	<0.001
Asleep	67.0±9.4	61.2±5.6	75.3±7.2	<0.001
Decline from awake to asleep, mm Hg				
SBP	13.1±7.7	16.0±6.8	9.0±7.0	<0.001
DBP	16.7±8.3	20.0±7.4	12.1±7.1	<0.001
STOP-Bang components, %				
Snore loudly	27.5	22.4	34.6	0.001
Tired, fatigued, or sleepy	50.9	50.1	52.0	0.649
Observed apnea	16.8	15.4	18.8	0.264
High blood pressure	44.0	36.6	54.4	<0.001
BMI >35	26.8	23.4	31.5	0.016
Age >50 y	84.0	85.1	82.5	0.407
Large neck size	29.9	22.2	40.6	<0.001
Male	39.5	34.0	47.2	<0.001
Sleep characteristics				
Global sleep quality, score	6.9±3.7	6.8±3.8	7.0±3.6	0.412
Habitual sleep duration, min	391.5±79.7	396.3±79.0	384.6±80.2	0.055
Sleep efficiency, %	89.5±16.4	89.5±16.1	89.4±16.9	0.971

(Continued)

Table 1. Continued

	Overall (N=702)	Nocturnal Hypertension		
		No (n=412)	Yes (n=290)	*P* Value
Midsleep time, clock time	2:24±1:25	2:29±1:30	2:17±1:16	0.090
High likelihood of OSA, %	21.7	16.0	29.7	<0.001

Numbers in the table are mean±SD or percentage. BMI indicates body mass index; CPAP. continuous positive airway pressure; CVD, cardiovascular disease; DBP, diastolic blood pressure; eGFR, estimated glomerular filtration rate; MI, myocardial infarction; OSA, obstructive sleep apnea; PSQI, Pittsburgh Sleep Quality Index; and SBP, systolic blood pressure.

and weight were measured using a standardized protocol, and body mass index (BMI) was calculated as weight in kilograms divided by height in meters squared. Physical activity over the past year was assessed in exercise units using the validated CARDIA physical activity questionnaire.[21,22] Exercise units were calculated by summing the product of the frequency and duration of moderate (eg, walking or hiking) and vigorous (eg, running or biking) activities. Consistent with prior publications, we defined low activity as CARDIA exercise units <300.[22,23] Participants' alcohol intake was categorized as *none*, *moderate* (drinks per week: >0 to 14 for men and >0 to 7 for women), or *heavy* (drinks per week: >14 for men and >7 for women). Depressive symptoms were assessed using the 20-item Center for Epidemiologic Studies Depression (CES-D) scale.[24] Diabetes mellitus was defined as a fasting (≥8 hours) blood glucose ≥126 mg/dL or the use of anti–diabetes mellitus medication. Serum creatinine, measured from blood collected during the study examination, and the Chronic Kidney Disease Epidemiology Collaboration (CKD-EPI) equation were used to calculate estimated glomerular filtration rate. Reduced estimated glomerular filtration rate was defined as <60 mL/min per 1.73 m^2.[25] Using a spot urine specimen, albuminuria was defined as an albumin-to-creatinine ratio >30 mg/g. Clinic BP was measured by trained and certified staff following a standardized protocol. BP was measured on the right arm with an Omron HEM 907XL oscillometric device (Omron Healthcare). Three readings, each separated by at least 30 seconds, were performed with the participant's right arm positioned at heart level. The average of the second and third BP measurements was used in the current analyses. New cardiovascular disease events were assessed during scheduled study visits and yearly telephone interviews and verified by 2 physician members of the CARDIA end points surveillance and adjudication committee. For these analyses, cardiovascular disease events included myocardial infarction, non–myocardial infarction acute coronary syndrome, coronary artery disease, peripheral artery disease, congestive heart failure, stroke, and transient ischemic attacks.

Ambulatory BP Monitoring

ABPM was conducted over a 24-hour period using the validated OnTrak 90227 monitor (Spacelabs Healthcare) and an appropriately sized cuff.[26] BP was measured every 30 minutes on the nondominant arm. Readings outside the limits of SBP 70 to 250 mm Hg and DBP 40 to 150 mm Hg during the awake period and SBP readings <60 mm Hg and DBP readings <30 mm Hg during the asleep period were set to *missing*. Participants wore an Actiwatch activity monitor (Philips Respironics) on the same arm as the ABPM device. Participants were given a diary to record when they were awake and asleep, including naps. The time periods when participants were awake and asleep were determined using the activity monitor data in conjunction with the diary. Consistent with the criteria used by the International Database of Ambulatory Blood Pressure in relation to Cardiovascular Outcome (IDACO), participants with ≥10 valid awake and ≥5 valid asleep BP measurements were considered to have a complete ABPM recording.[27,28] Mean awake and asleep SBP and DBP were each defined based on the mean of all available readings obtained during the respective awake and asleep periods. The 24-hour mean BP was defined as the weighted mean of the awake and asleep BP measurements with weights equal to the proportion of the 24-hour period that each person reported being awake and asleep, respectively.[29] Nocturnal hypertension was defined as mean asleep SBP ≥120 mm Hg or mean asleep DBP ≥70 mm Hg.[30] These ambulatory BP thresholds are consistent with recommendations based on clinic BP cut points of SBP ≥140 mm Hg or DBP ≥90 mm Hg.[31] The percentage decline in SBP from awake to asleep was calculated as 1 minus the ratio of the mean asleep to mean awake SBP, and nondipping SBP was defined as <10% decline in SBP from awake to asleep.[30]

Sleep Characteristics

As part of the ABPM ancillary study conducted at the CARDIA year 30 examination (2015–2016), participants completed the PSQI and the STOP-Bang questionnaires. The PSQI is a validated 18-item self-report questionnaire that assesses sleep quality, latency,

Table 2. Adjusted PRs for Nocturnal Hypertension Associated With Each Sleep Characteristic

	PR (95% CI)
Global sleep quality, per 4 U	
Model 1	1.04 (0.92–1.18)
Model 2	1.02 (0.89–1.17)
Model 3	1.03 (0.89–1.18)
Habitual sleep duration, per 60 min	
Model 1	0.98 (0.92–1.04)
Model 2	0.97 (0.89–1.06)
Model 3	0.99 (0.90–1.08)
Sleep efficiency, per 15%	
Model 1	0.99 (0.92–1.07)
Model 2	1.02 (0.92–1.13)
Model 3	1.02 (0.92–1.14)
Midsleep time, per h	
Model 1	0.93 (0.87–0.99)
Model 2	0.94 (0.86–1.02)
Model 3	0.93 (0.85–1.01)
Likelihood of OSA*, high vs low	
Model 1	1.47 (1.22–1.75)
Model 2	1.45 (1.09–1.91)
Model 3	1.32 (1.00–1.75)
Model 4	1.08 (0.79–1.48)

Model 1 included adjustment for age, sex, race, and clinic site (Birmingham or Chicago). Model 2 included adjustment for the model 1 variables plus BMI, highest level of education obtained, alcohol consumption, cigarette smoking, physical activity, continuous positive airway pressure use, depressive symptoms, diabetes mellitus, albuminuria, and reduced estimate glomerular filtration rate. Model 3 included adjustment for the model 2 variables plus awake VP for the outcome of nocturnal hypertension or 24-hour BP for the outcome of nondipping BP. Model 4 included adjustment for the model 3 variables plus age, sex, and body mass index. High likelihood of having OSA was defined as a STOP-Bang questionnaire score ≥5. BMI indicates body mass index; BP, blood pressure; DBP, diastolic blood pressure; OSA, obstructive sleep apnea; PR, prevalence ratio; PSQI, Pittsburgh Sleep Quality Index; and SBP, systolic blood pressure.

*Age, sex, and BMI were not included in the models when risk of OSA was the exposure because these covariables are used to calculate the STOP-BANG score. Model 4 included these variables to determine the effect of their inclusion as covariables. Nocturnal hypertension is defined as mean sleep SBP ≥120 mm Hg or mean DBP ≥70 mm Hg.

duration, efficiency, disturbances, use of sleeping medication, and daytime dysfunction.[32] A total PSQI score >5 indicates poor global sleep quality. Additional details regarding scoring and interpretation of other PSQI variables are reported elsewhere.[32] Midsleep time, a proxy for sleep timing or chronotype, was calculated as the midpoint between habitual sleep onset and sleep offset reported in the PSQI. For example, an individual with a usual sleep period from 10 PM until 6 AM would have a midsleep time of 2 AM. The STOP-Bang is an 8-item questionnaire that has been validated against polysomnography and is used to screen for likelihood of having OSA.[33] The STOP-Bang questionnaire comprises the following items: self-reported snoring; feeling tired, fatigued, or sleepy; observed pauses in breathing during sleep; self-reported high BP or antihypertensive medication use; BMI >35; age >50 years; neck circumference for men ≥17 inches or women ≥16 inches, and male sex. Each response of *yes* results in 1 point, for a range of scores between 0 and 8, with higher scores reflecting higher likelihood of having OSA. Likelihood of OSA was categorized as high (STOP-Bang score ≥5) versus low (STOP-Bang score <5).

Statistical Analyses

Participant characteristics (mean±SD or numbers and percentages) were calculated overall and by nocturnal hypertension and nondipping SBP status, and stratified by race. The mean level of each sleep characteristic (ie, global sleep quality, habitual sleep duration, sleep efficiency, midsleep time) and the prevalence of a high likelihood of having OSA were calculated for participants with and without nocturnal hypertension and nondipping SBP, separately. Two-sample *t* tests and chi-square tests were used to evaluate the statistical significance of differences for continuous and categorical variables, respectively, across nocturnal hypertension and nondipping SBP status. The linearity of the association of each sleep characteristic with nocturnal hypertension and nondipping SBP status, separately, was assessed to determine the need for a nonlinear versus linear modeling term. All sleep characteristics, except likelihood of having OSA, were modeled as continuous variables and scaled so that prevalence ratios (PRs) would represent a 1-SD difference in risk-factor level (eg, 4 U for global sleep quality). Poisson regression models with robust variance estimators were used to calculate PRs with 95% CIs for nocturnal hypertension and nondipping SBP associated with each sleep characteristic. For each sleep characteristic except likelihood of having OSA, an initial model (model 1) included adjustment for age, sex, race, and field site (Birmingham or Chicago). Model 2 included adjustment for the variables in model 1 and BMI, highest level of education obtained, alcohol consumption, cigarette smoking, physical activity, continuous positive airway pressure use, depressive symptoms, diabetes mellitus, albuminuria, and reduced estimated glomerular filtration rate. Model 3 included adjustment for the variables in Model 2 and awake SBP and DBP for the outcome of nocturnal hypertension and 24-hour SBP and DBP for the outcome of nondipping SBP. Age, sex, and BMI were not included as covariates for adjustment in the above models when the likelihood of having OSA was the exposure because these characteristics are used in calculating the STOP-Bang score. Model 4 included adjustment for the variables in Model 3 and age, sex, and BMI

Table 3. Race-Stratified PRs for Nocturnal Hypertension Associated With Likelihood of Having OSA

	PR (95% CI)			
	White		Black	
	Low	High	Low	High
Prevalence, %	19.8	55.1	48.8	57.3
Model 1	1 (ref)	2.75 (1.90–3.98)	1 (ref)	1.19 (0.97–1.45)
Model 2	1 (ref)	2.55 (1.52–4.25)	1 (ref)	1.17 (0.84–1.65)
Model 3	1 (ref)	2.09 (1.23–3.48)	1 (ref)	1.11 (0.79–1.56)
Model 4	1 (ref)	1.66 (0.90–3.07)	1 (ref)	0.95 (0.65–1.39)

Model 1 included adjustment for clinic site (Birmingham or Chicago). Model 2 included adjustment for the model 1 variables plus highest level of education obtained, alcohol consumption, cigarette smoking, physical activity, continuous positive airway pressure use, depressive symptoms, diabetes mellitus, albuminuria, and reduced estimate glomerular filtration rate. Model 3 included adjustment for the model 2 variables plus awake BP for the outcome of nocturnal hypertension or 24-hour BP for the outcome of nondipping BP. Model 4 included adjustment for the model 3 variables plus age, sex, and BMI. BMI indicates body mass index; BP, blood pressure; DBP, diastolic blood pressure; OSA, obstructive sleep apnea; PR, prevalence ratio; ref, referent; and SBP, systolic blood pressure.

*Age, sex, and BMI were not included in the models when risk for OSA was the exposure because these covariables are used to calculate the STOP-BANG score. Model 4 included these variables to determine the effect of their inclusion as covariables.

to determine the effect of their inclusion as covariables. Wald tests were applied to evaluate interactions between race and, separately, sex and each sleep characteristic on nocturnal hypertension and nondipping SBP. In sensitivity analyses, we repeated the above analyses using the 2017 American College of Cardiology/American Heart Association (ACC/AHA) BP guideline definition of nocturnal hypertension (mean asleep SBP ≥110 mm Hg or mean asleep DBP ≥65 mm Hg).[34] Analyses were conducted using SAS software (v9.4; SAS Institute) and R (v3.5.1 or higher).

RESULTS

Nocturnal Hypertension

Of the 702 participants, 290 (41.3%) had nocturnal hypertension. Participants with nocturnal hypertension were more likely to be male and black, to smoke cigarettes, to have diabetes mellitus and albuminuria, and to take antihypertensive medication than their counterparts without nocturnal hypertension (Table 1). Participants with nocturnal hypertension had fewer years of education and higher BMI; clinic, awake, asleep SBP and DBP; and a smaller decline in SBP and DBP from being awake to asleep. Characteristics of participants with and without nocturnal hypertension stratified by race are presented in Table S1.

Participants with nocturnal hypertension had a higher likelihood of having OSA compared with their counterparts without nocturnal hypertension (Table 1). After multivariable adjustment, higher likelihood of having OSA was associated with a higher probability of nocturnal hypertension (PR: 1.32; 95% CI, 1.00–1.75; Table 2). There was no statistically significant evidence of an association between global sleep quality (PR: 1.03; 95% CI, 0.89–1.18), habitual sleep duration (PR: 0.99; 95% CI, 0.90–1.08), sleep efficiency (PR: 1.02; 95% CI, 0.92–1.14), or midsleep time (PR: 0.93; 95% CI: 0.85–1.01) and nocturnal hypertension in fully adjusted models. There was a statistically significant interaction between race and likelihood of having OSA on nocturnal hypertension (P=0.01), with a stronger association between likelihood of having OSA and nocturnal hypertension for white participants (PR: 2.09; 95% CI, 1.23–3.48) compared with black participants (PR: 1.11; 95% CI, 0.79–1.56; Table 3). When age, sex, and BMI were added into the models, there was no association between likelihood of OSA and nocturnal hypertension. There were no interactions between race and other sleep characteristics on nocturnal hypertension (all P>0.12). In addition, there were no interactions between sex and any sleep characteristic on nocturnal hypertension (all P>0.32).

The characteristics of participants with and without nocturnal hypertension using the 2017 ACC/AHA BP guidelines definition of nocturnal hypertension (ie, mean sleep SBP ≥110 mm Hg or mean DBP ≥65 mm Hg) are presented in Table S2. Although not statistically significant, the association between a high likelihood of OSA and nocturnal hypertension was similar (PR: 1.22; 95% CI, 0.97–1.54) using the 2017 ACC/AHA BP guidelines definition in a fully adjusted model (Table S3). When age, sex, and BMI were added into the models, there was no association between likelihood of OSA and nocturnal hypertension. There were no interactions between either sex or race and any of the sleep characteristics on nocturnal hypertension (all P>0.5).

Nondipping Systolic BP

Of the 702 participants, 228 (32.5%) had nondipping SBP. Compared with participants without nondipping SBP, those with nondipping SBP were more likely to be black, to have fewer years of education, not to drink alcohol, to have diabetes mellitus and albuminuria, to

Table 4. Characteristics of Participants Without and With Nondipping SBP

	Overall (N=702)	Nondipping SBP		
		No (n=474)	Yes (n=228)	*P* Value
Age, y	54.7±3.7	54.6±3.7	55.1±3.8	0.105
Male, %	39.5	40.7	36.8	0.324
Black, %	61.4	54.2	76.3	<0.001
Field center, %				0.443
Birmingham	60.7	59.7	62.7	
Chicago	39.3	40.3	37.3	
Highest level of education, y	14.9±2.6	15.1±2.7	14.4±2.4	0.001
Low physical activity, %	66.4	64.1	71.1	0.067
Alcohol use, %				0.002
Nondrinker	52.4	47.9	61.8	
Moderate	34.3	37.8	27.2	
Heavy	13.3	14.4	11.0	
Current cigarette smoking, %	15.1	14.8	15.8	0.940
BMI, kg/m^2	31.5±6.9	30.4±6.4	33.7±7.4	<0.001
Depression symptoms, %	17.0	16.7	17.5	0.772
Diabetes mellitus, %	17.6	13.2	26.9	<0.001
Reduced eGFR, %	4.4	4.2	4.8	0.717
Albuminuria, %	9.4	7.2	14.0	0.005
CPAP use, %	14.1	11.8	18.9	0.014
Antihypertensive medication use, %	41.7	37.6	50.2	0.002
CVD events, %	5.6	5.7	5.3	0.862
SBP, mm Hg				
Clinic	121.9±17.7	121.8±17.2	122.0±18.7	0.857
Awake	129.7±15.5	130.4±15.2	128.2±16.1	0.082
Asleep	112.5±15.6	107.9±13.3	122.1±15.8	<0.001
DBP, mm Hg				
Clinic	74.5±11.2	74.5±11.1	74.5±11.4	0.986
Awake	80.7±9.2	81.5±9.0	78.9±9.4	<0.001
Asleep	67.0±9.4	64.7±8.5	71.8±9.3	<0.001
Decline from awake to asleep, mm Hg				
SBP	13.1±7.7	17.2±5.2	4.7±4.7	<0.001
DBP	16.7±8.3	20.5±6.3	8.9±6.0	<0.001
STOP-Bang components, %				
Snore loudly	27.5	24.3	33.9	0.008
Tired, fatigued, or sleepy	50.9	49.7	53.4	0.381
Observed apnea	16.8	15.5	19.5	0.202
High blood pressure	44.0	38.6	55.1	<0.001
BMI >35	26.8	21.0	38.6	<0.001
Age >50 y	84.0	83.2	85.6	0.449
Large neck	29.9	27.9	33.9	0.100
Male	39.5	40.7	36.8	0.324
Sleep characteristics				
Global sleep quality, score	6.9±3.7	6.8±3.5	7.2±4.0	0.149
Habitual sleep duration, min	391.5±79.7	395.9±78.4	382.3±81.7	0.035
Sleep efficiency, %	89.5±16.4	90.0±15.7	88.3±17.7	0.204

(*Continued*)

Table 4. Continued

	Overall (N=702)	Nondipping SBP		
		No (n=474)	Yes (n=228)	*P* Value
Midsleep time, clock time	2:24 (1:25)	2:29 (1:28)	2:14 (1:16)	0.063
High likelihood of OSA, %	21.7	17.7	29.8	<0.001

Numbers in the table are mean±SD or percentage. BMI indicates body mass index; CPAP. continuous positive airway pressure; CVD, cardiovascular disease; DBP, diastolic blood pressure; eGFR, estimated glomerular filtration rate; MI, myocardial infarction; OSA, obstructive sleep apnea; PSQI, Pittsburgh Sleep Quality Index; and SBP, systolic blood pressure.

use continuous positive airway pressure, and to be taking antihypertensive medication (Table 4). Participants with nondipping SBP had higher BMI and asleep SBP and DBP, lower awake DBP, and a smaller decline in SBP and DBP from awake to asleep. Characteristics of participants with and without nondipping SBP stratified by race are presented in Table S4.

Participants with nondipping SBP had a shorter habitual sleep duration and a higher likelihood of having OSA compared with their counterparts without nondipping SBP (Table 4). After multivariable adjustment, later midsleep time was associated with a lower probability of nondipping SBP (PR: 0.92; 95% CI, 0.85–0.99), and a higher likelihood of having OSA was associated with a higher probability for nondipping SBP (PR: 1.31; 95% CI, 1.02–1.68; Table 5). There was no evidence of an association between global sleep quality (PR: 1.03; 95% CI, 0.91–1.17), habitual sleep duration (PR: 0.97; 95% CI, 0.90–1.05), or sleep efficiency (PR: 0.99; 95% CI, 0.90–1.09) and nondipping SBP after multivariable adjustment. When age, sex, and BMI were added into the models, there was no association between likelihood of OSA and nondipping SBP. There was a statistically significant interaction between race and likelihood of having OSA on nondipping SBP ($P<0.01$), with a stronger association between likelihood of having OSA and nondipping SBP for white participants (PR: 2.07; 95% CI, 1.23–3.48) but not black participants (PR: 1.08; 95% CI, 0.81–1.43; Table 6). There were no interactions between race and other sleep characteristics on nondipping SBP (all $P>0.30$). There were also no interactions between sex and any sleep characteristic on nondipping SBP (all $P>0.12$).

DISCUSSION

In the current analysis, white but not black participants with a high likelihood of having OSA had a higher relative probability of nocturnal hypertension and nondipping SBP. In addition, participants with later midsleep time (later sleep onset and sleep offset) had a lower probability of nondipping SBP. These associations were present even after adjusting for multiple potential confounders, including awake BP for nocturnal hypertension and 24-hour BP for nondipping SBP. There was no evidence of associations between global sleep quality, habitual sleep duration, or sleep efficiency and nocturnal hypertension or nondipping SBP after multivariable adjustment.

Studies have consistently demonstrated an association between OSA and hypertension based on BP measured in the clinic.[1,7–9] However, few data are available on the association between OSA and nocturnal hypertension or nondipping SBP.[35] Moderate to severe OSA was associated with higher nighttime SBP, daytime and nighttime DBP, and lower percentage dipping in a case–control study of 90 patients recruited from a sleep clinic.[10] In a sample of 54 sleep clinic patients, higher severity of OSA was associated with higher mean 24-hour, nocturnal, and nondipping SBP and DBP profiles.[12] However, another study reported no association between sleep quality and BP dipping status despite a high prevalence (84%) of nondipping BP among individuals with OSA.[11] The sample sizes were small in these studies, and patients were recruited from sleep clinics or had symptoms of OSA, which may limit generalizability to the general population. In a prospective community-based cohort of 186 participants, poor sleep quality was associated with nondipping BP.[13] In the Wisconsin Sleep Cohort, a prospective population-based study comprised almost exclusively of white participants, OSA, poor sleep quality, and insomnia were associated with nondipping BP.[14–16] In the current study, a high likelihood of having OSA was associated with a higher relative probability of both nocturnal hypertension and nondipping SBP in white but not black participants. The lack of an association between the likelihood of having OSA and nocturnal hypertension and nondipping SBP among black participants suggests that other factors, including salt sensitivity,[36] may be a stronger contributor to high asleep BP in this population and may result in the relative high prevalence of nocturnal hypertension (48.8%) and nondipping BP (38.4%) observed among black participants with a low likelihood of OSA. Although the STOP-Bang questionnaire is validated and sensitive to OSA severity,[33] future population-based studies should include home sleep testing or polysomnography to more precisely estimate and understand the association between OSA and asleep

BP. For example, it has been shown that OSA severity and the percentage of sleep time with <90% oxyhemoglobin saturation are both associated with resistant hypertension.[37] OSA severity and hypoxemia may also be associated with higher asleep BP.

Other sleep characteristics, including sleep quality, sleep duration, and sleep efficiency, have been associated with an increased risk of hypertension based on BP measured in the clinic.[2,3] Using CARDIA study data from years 15 and 20, shorter sleep duration and lower sleep efficiency measured using actigraphy were associated with higher clinic SBP and DBP and an increase in clinic SBP and DBP over 5 years of follow-up.[3] However, ABPM was not conducted at the CARDIA year 15 and 20 study visits and, therefore, could not assess BP measured outside of the clinic setting. In the current study, no association was present between self-reported global sleep quality, habitual sleep duration, sleep efficiency, and either nocturnal hypertension or nondipping SBP. Both participants with and without nocturnal hypertension or nondipping SBP reported mean global PSQI scores >5, mean habitual sleep duration <7 hours, and mean sleep efficiency <90%, suggesting overall poor sleep among both groups. Furthermore, compared with white participants, black participants had higher prevalence of nocturnal hypertension and nondipping SBP.[20] The relatively high prevalence of poor sleep in the full sample and nocturnal hypertension and nondipping SBP among black participants may have resulted in an attenuated association between these sleep characteristics and both nocturnal hypertension and nondipping SBP. There were no interactions by race for these particular sleep characteristics. Both shorter and longer sleep durations are associated with adverse cardiovascular outcomes.[38,39] We considered examining sleep duration as a categorical variable; however, the association between sleep duration and both nocturnal hypertension and nondipping SBP was linear. Furthermore, only 13 participants reported longer habitual sleep durations (ie, >9 hours).

Table 5. Adjusted PRs for Nondipping SBP Associated With Each Sleep Characteristic

	PR (95% CI)
Global sleep quality, per 4 U	
Model 1	1.06 (0.95–1.19)
Model 2	1.03 (0.91–1.17)
Model 3	1.03 (0.91–1.17)
Habitual sleep duration, per 60 min	
Model 1	0.96 (0.89–1.03)
Model 2	0.97 (0.90–1.04)
Model 3	0.97 (0.90–1.05)
Sleep efficiency, per 15%	
Model 1	0.96 (0.88–1.05)
Model 2	0.99 (0.90–1.09)
Model 3	0.99 (0.90–1.09)
Midsleep time, per h	
Model 1	0.91 (0.84–0.99)
Model 2	0.92 (0.85–0.99)
Model 3	0.92 (0.85–0.99)
Risk for OSA*, high vs low	
Model 1	1.46 (1.17–1.83)
Model 2	1.33 (1.04–1.70)
Model 3	1.31 (1.02–1.68)
Model 4	1.13 (0.86–1.48)

Model 1 included adjustment for age, sex, race, and clinic site (Birmingham or Chicago). Model 2 included adjustment for the model 1 variables plus BMI, highest level of education obtained, alcohol consumption, cigarette smoking, physical activity, continuous positive airway pressure use, depressive symptoms, diabetes mellitus, albuminuria, and reduced estimate glomerular filtration rate. Model 3 included adjustment for the model 2 variables plus awake BP for the outcome of nocturnal hypertension or 24-hour BP for the outcome of nondipping BP. Model 4 included adjustment for the model 3 variables plus age, sex, and BMI. BMI indicates body mass index; BP, blood pressure; OSA, obstructive sleep apnea; PR, prevalence ratio; PSQI, Pittsburgh Sleep Quality Index; and SBP, systolic blood pressure.

*Age, sex, and BMI were not included in models 1–3 when risk for OSA was the exposure because these covariables are used to calculate the STOP-BANG score. Model 4 included these variables to determine the effect of their inclusion as covariables. Nondipping BP was defined as a decline in sleep BP relative to awake BP <10%.

Table 6. Race-Stratified PRs for Nondipping SBP Associated With Risk for OSA

	PR (95% CI)			
	White		Black	
	Low	High	Low	High
Prevalence, %	15.3	40.8	38.4	46.6
Model 1	1 (ref)	2.62 (1.65–4.15)	1 (ref)	1.22 (0.95–1.56)
Model 2	1 (ref)	2.37 (1.39–4.04)	1 (ref)	1.07 (0.81–1.41)
Model 3	1 (ref)	2.07 (1.23–3.48)	1 (ref)	1.08 (0.81–1.43)
Model 4	1 (ref)	2.09 (1.00–4.38)	1 (ref)	0.92 (0.61–1.40)

Model 1 included adjustment for clinic site (Birmingham or Chicago). Model 2 included adjustment for the model 1 variables plus highest level of education obtained, alcohol consumption, cigarette smoking, physical activity, continuous positive airway pressure use, depressive symptoms, diabetes mellitus, albuminuria, and reduced estimate glomerular filtration rate. Model 3 included adjustment for the model 2 variables plus awake BP for the outcome of nocturnal hypertension or 24-hour BP for the outcome of nondipping BP. Model 4 included adjustment for the model 3 variables plus age, sex, and BMI. High likelihood of having OSA was defined as a STOP-Bang questionnaire score ≥5. BMI indicates body mass index; BP, blood pressure; DBP, diastolic blood pressure; OSA, obstructive sleep apnea; PR, prevalence ratio; ref, referent; and SBP, systolic blood pressure.

*Age, sex, and BMI were not included in the models when risk for OSA was the exposure because these covariables are used to calculate the STOP-BANG score. Model 4 included these variables to determine the effect of their inclusion as covariables.

Studies have demonstrated circadian control of BP,[17,18] wherein a circadian peak in BP occurs in the evening.[17] Knockout of circadian clock genes in mouse models has resulted in a reduction and/or elimination of circadian variation in BP.[40–43] Taken together, these findings suggest potential circadian involvement in nocturnal hypertension and/or nondipping SBP. In the current study, a later midsleep time, a proxy for chronotype, was associated with a lower PR for nondipping SBP but not nocturnal hypertension. We calculated dipping status based on both self-reported and actigraphically measured sleep; this approach decreases misclassification of dipping status and strengthens the finding that timing of sleep is associated with nondipping SBP. These results suggest that an underlying circadian mechanism may be implicated in dipping status, albeit in the opposite direction we hypothesized, but not necessarily nocturnal hypertension. However, the magnitude of the PRs suggests that, compared with midsleep time, the likelihood of OSA is more strongly associated with nondipping SBP. Aligning sleep behaviors with endogenous circadian rhythms may be important in increasing percentage SBP dipping, particularly if a part of the sleep period overlaps with the aforementioned circadian peak in BP that occurs early in the evening.

The current study has several strengths. ABPM was conducted as part of an ancillary study of a large, population-based cohort that included both black and white participants. Both actigraphy and self-reported data were used to determine awake and asleep times. Sleep characteristics across multiple domains, including sleep quality, duration, and chronotype, were assessed. Extensive data collection permitted adjustment for multiple confounders. Despite these strengths, the results should be interpreted in the context of potential limitations. Data on sleep characteristics were self-reported, and objective measures of sleep may yield different results. However, all sleep measures used in the current study are widely used in sleep research and have been validated. Only a single 24-hour ABPM was performed, which may result in misclassification of participants' nocturnal hypertension and nondipping SBP status, given their relatively low reproducibility.[44–46]

In conclusion, a higher likelihood of having OSA was associated with a higher relative probability of both nocturnal hypertension and nondipping SBP among white but not black participants. Midsleep time, a proxy for chronotype, was associated with nondipping SBP. The current results suggest that risk of OSA, particularly among white individuals, and sleep timing may be targets for clinical trials seeking to improve BP during sleep.

ARTICLE INFORMATION

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Disclosures

None.

Supplementary Materials

Tables S1–S4
Figure S1

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SUPPLEMENTAL MATERIAL

Table S1. Characteristics of participants with and without nocturnal hypertension stratified by race.

	White			Black		
	Nocturnal hypertension			Nocturnal Hypertension		
	No (N=200)	Yes (N=71)	p-value	No (N=212)	Yes (N=219)	p-value
Age, years	55.5 ± 3.2	55.3 ± 3.6	0.641	54.0 ± 4.0	54.5 ± 3.8	0.207
Male, %	38.0	59.7	0.002	30.2	43.4	0.005
Field center, %						0.230
Birmingham	54.5	61.1	0.406	66.5	60.7	
Chicago	45.5	38.9		33.5	39.3	
Highest level of education, years	16.1 ± 2.6	15.6 ± 2.4	0.169	14.5 ± 2.4	13.8 ± 2.2	0.001
Low physical activity, %	54.0	59.7	0.411	75.9	78.5	0.566
Alcohol intake, %			0.021			
Non-drinker	40.5	56.9		60.5	54.0	0.337
Moderate	39.5	34.7		30.2	33.6	
Heavy	20.0	8.3		9.3	12.4	
Current cigarette smoking, %	6.5	13.9	0.058	16.3	22.1	0.237
Body mass index, kg/m^2	28.0 ± 5.6	31.6 ± 5.6	<0.001	33.0 ± 6.9	33.0 ± 7.4	0.922
Depression symptoms, %	13.5	16.7	0.557	19.5	19.5	1.00
Diabetes, %	6.5	18.1	0.008	23.1	22.7	1.00
Cardiovascular disease event, %	3.0	4.2	0.703	7.0	7.1	1.00
Reduced eGFR, %	2.5	2.8	1.00	6.0	5.8	1.00
Albuminuria, %	2.5	8.3	0.04	3.7	21.7	<0.001
CPAP use, %	8.5	11.1	0.485	16.3	17.7	0.706
Antihypertensive medication use, %	21.5	33.3	0.056	50.2	55.1	0.340
Systolic blood pressure, mm Hg						
Clinic	112.0 ± 12.2	127.8 ± 14.0	<0.001	117.6 ± 15.2	132.7 ± 18.3	<0.001
Awake	122.4 ± 11.5	138.5 ± 15.4	<0.001	123.0 ± 11.2	139.9 ± 14.9	<0.001
Asleep	100.8 ± 8.8	124.6 ± 13.8	<0.001	104.5 ± 7.5	127.3 ± 12.3	<0.001
Diastolic blood pressure, mm Hg						
Clinic	68.4 ± 9.0	78.4 ± 9.9	<0.001	72.4 ± 9.9	80.6 ± 11.0	<0.001
Awake	77.2 ± 7.2	84.4 ± 8.9	<0.001	76.5 ± 7.6	86.3 ± 8.7	<0.001
Asleep	60.9 ± 5.4	74.1 ± 6.3	<0.001	61.5 ± 75.7	75.7 ± 7.5	<0.001
Decline from awake to asleep, mm Hg						
Systolic blood pressure	17.4 ± 6.0	9.7 ± 7.1	<0.001	14.6 ± 7.3	8.6 ± 7.0	<0.001
Diastolic blood pressure	20.8 ± 6.5	11.7 ± 7.2	<0.001	19.1 ± 8.2	12.0 ± 7.2	<0.001
STOP-Bang components, %						
Snore loudly	19.0	40.3	0.001	25.6	32.7	0.116
Tired, fatigued, or sleepy	47.5	56.9	0.216	52.6	50.4	0.703
Observed apnea	12.5	23.6	0.035	18.1	17.3	0.901
High blood pressure	20.5	36.1	0.011	51.6	60.2	0.084
BMI >35 kg/m^2	11.0	23.6	0.017	34.9	34.1	0.920
Age >50 years	95.0	87.5	0.055	75.8	81.0	0.203
Large neck size	24.5	51.4	<0.001	20.0	37.2	<0.001
Male	38.0	59.7	0.002	30.2	43.4	0.005
High likelihood of OSA, %	20.2	55.1	<0.001	49.5	56.6	0.221

Numbers in the table are mean ± standard deviation or percentage.
eGFR: Estimated glomerular filtration rate; CPAP: Continuous positive airway pressure; OSA: Obstructive sleep apnea.
Low physical activity is defined as less than 300 exercise units.
Cardiovascular disease events include myocardial infarction (MI), non-MI acute coronary syndrome, coronary artery disease, peripheral artery disease, congestive heart failure, stroke, and transient ischemic attacks.
Reduced estimated glomerular filtration rate (eGFR) was defined as an eGFR <60 mL/min/1.73 m^2.
Albuminuria was defined as albumin-to-creatinine ratio (ACR) >30 mg/g.
High risk for obstructive sleep apnea was defined as a STOP-Bang questionnaire score ≥5.
Nocturnal hypertension was defined as mean sleep systolic blood pressure ≥120 mm Hg or mean diastolic blood pressure ≥70 mm Hg.

Table S2. Characteristics of participants without and with nocturnal hypertension defined using 2017 ACC/AHA blood pressure guidelines.

	Overall (N=702)	Nocturnal hypertension		
		No (N=257)	Yes (N=445)	p-value
Age, years	54.7 ± 3.7	54.7 ± 3.7	54.8 ± 3.8	0.761
Male, %	39.5	30.0	44.9	<0.001
Black, %	61.4	46.7	69.9	<0.001
Field center, %				0.265
Birmingham	60.7	58.0	62.3	
Chicago	39.3	42.0	37.7	
Highest level of education, years	14.9 ± 2.6	15.4 ± 2.7	14.6 ± 2.5	<0.001
Low physical activity, %	66.4	63.4	68.1	0.209
Alcohol intake, %				0.512
Non-drinker	52.4	51.8	52.8	
Moderate	34.3	33.1	35.1	
Heavy	13.3	15.2	12.1	
Current cigarette smoking, %	15.1	12.5	16.7	0.217
Body mass index, kg/m^2	31.5 ± 6.9	29.7 ± 6.4	32.5 ± 7.0	<0.001
Depression symptoms, %	17.0	18.3	16.2	0.475
Diabetes, %	17.6	12.1	20.8	0.003
Reduced eGFR, %	4.4	5.1	4.0	0.533
Albuminuria, %	9.4	2.3	13.5	<0.001
CPAP use, %	14.1	89.9	83.6	0.019
Antihypertensive medication use, %	41.7	68.1	52.7	<0.001
CVD events, %	5.6	4.3	6.3	0.307
Systolic blood pressure, mm Hg				
Clinic	121.9 ± 17.7	112.0 ± 13.6	127.5 ± 17.3	<0.001
Awake	129.7 ± 15.5	120.0 ± 11.0	135.3 ± 14.9	<0.001
Asleep	112.5 ± 15.6	98.4 ± 6.7	120.6 ± 13.4	<0.001
Diastolic blood pressure, mm Hg				
Clinic	74.5 ± 11.2	68.1 ± 9.4	78.1 ± 10.5	<0.001
Awake	80.7 ± 9.2	75.3 ± 7.3	83.8 ± 8.8	<0.001
Asleep	67.0 ± 9.4	58.4 ± 4.8	72.0 ± 7.6	<0.001
Decline from awake to asleep, mm Hg				
Systolic blood pressure	13.1 ± 7.7	17.5 ± 6.6	10.6 ± 7.1	<0.001
Diastolic blood pressure	16.7 ± 8.3	22.0 ± 7.4	13.7 ± 7.2	<0.001
STOP-Bang components, %				
Snore loudly	27.5	19.8	31.9	<0.001
Tired, fatigued, or sleepy	50.9	50.0	51.4	0.755
Observed apnea	16.8	13.9	18.5	0.145
High blood pressure	44.0	32.2	50.8	<0.001

BMI >35 kg/m^2	26.8	19.4	31.0	0.001
Age >50 years	84.0	85.3	83.3	0.525
Large neck size	29.9	15.1	38.2	<0.001
Male	39.5	30.0	44.9	<0.001
Sleep characteristics				
Global sleep quality, score	6.9 ± 3.7	6.7 ± 3.8	7.0 ± 3.8	0.339
Habitual sleep duration, minutes	391.5 ± 79.7	397.9 ± 82.7	387.7 ± 77.7	0.102
Sleep efficiency, %	89.5 ± 16.4	89.0 ± 16.1	89.8 ± 16.6	0.536
Mid-sleep time, clock time	2:24 ± 1:25	2:27 ± 1:14	2:22 ± 1:30	0.492
High likelihood of OSA, %	21.7	12.1	27.2	<0.001

Numbers in the table are mean ± standard deviation or percentage.
eGFR: Estimated glomerular filtration rate; CPAP: Continuous positive airway pressure; OSA: Obstructive sleep apnea; CVD: cardiovascular disease.
Low physical activity was defined as less than 300 exercise units.
Reduced estimated glomerular filtration rate was defined as less than 60 mL/min/1.73 m^2.
Albuminuria was defined as albumin-to-creatinine ratio greater than 30 mg/g.
Cardiovascular disease events include myocardial infarction (MI), non-MI acute coronary syndrome, coronary artery disease, peripheral artery disease, congestive heart failure, stroke, and transient ischemic attacks.
Global sleep quality is represented by the total score on the Pittsburgh Sleep Quality Index. The total score ranges from 0 – 21 with higher scores indicative of poorer global sleep quality.
Sleep efficiency was calculated as the habitual (number of hours slept per night/time in bed) expressed as a percentage.
Mid-sleep times were calculated as the midpoint between the habitual bedtime and wake time reported on the Pittsburgh Sleep Quality Index. Mid-sleep time reflects clock time (a.m.) ± time elapsed in hours and minutes.
High likelihood of having obstructive sleep apnea was defined as a STOP-Bang questionnaire score ≥5.
Nocturnal hypertension is defined as mean sleep systolic blood pressure ≥110 mm Hg or mean diastolic blood pressure ≥65 mm Hg.

Table S3. Adjusted prevalence ratios for nocturnal hypertension, as defined by 2017 ACC/AHA blood pressure guideline, associated with each sleep characteristic.

	Prevalence ratio (95% confidence interval)
Global sleep quality, per 4 units	
Model 1	1.03 (0.93-1.14)
Model 2	1.04 (0.93-1.16)
Model 3	1.03 (0.92-1.16)
Habitual sleep duration, per 60 minutes	
Model 1	0.99 (0.95-1.03)
Model 2	0.98 (0.91-1.06)
Model 3	0.99 (0.92-1.07)
Sleep efficiency, per 15%	
Model 1	1.01 (0.97-1.06)
Model 2	1.02 (0.94-1.11)
Model 3	1.03 (0.94-1.02)
Mid-sleep time, per minute	
Model 1	0.98 (0.94-1.02)
Model 2	0.98 (0.92-1.05)
Model 3	0.97 (0.91-1.04)
Risk for OSA*, high versus low	
Model 1	1.31 (1.18-1.46)
Model 2	1.30 (1.04-1.64)
Model 3	1.22 (0.97-1.54)
Model 4	1.06 (0.82-1.37)

OSA: Obstructive sleep apnea.
Model 1 included adjustment for age, sex, race, and clinic site (Birmingham or Chicago).
Model 2 included adjustment for the Model 1 variables plus body mass index, highest level of education obtained, alcohol consumption, cigarette smoking, physical activity, continuous positive airway pressure use, depressive symptoms, diabetes, albuminuria, and reduced estimate glomerular filtration rate.
Model 3 included adjustment for the Model 2 variables plus awake blood pressure for the outcome of nocturnal hypertension or 24-hour blood pressure for the outcome of non-dipping blood pressure.
Model 4 included adjustment for the Model 3 variables plus age, sex and body mass index.
*Age, sex, and body mass index were not included in the models when risk for obstructive sleep apnea was the exposure because these covariables are used to calculate the STOP-BANG score. Model 4 included these variables to determine the effect of their inclusion as covariables.
Nocturnal hypertension is defined as mean sleep systolic blood pressure ≥110 mm Hg or mean diastolic blood pressure ≥65 mm Hg.

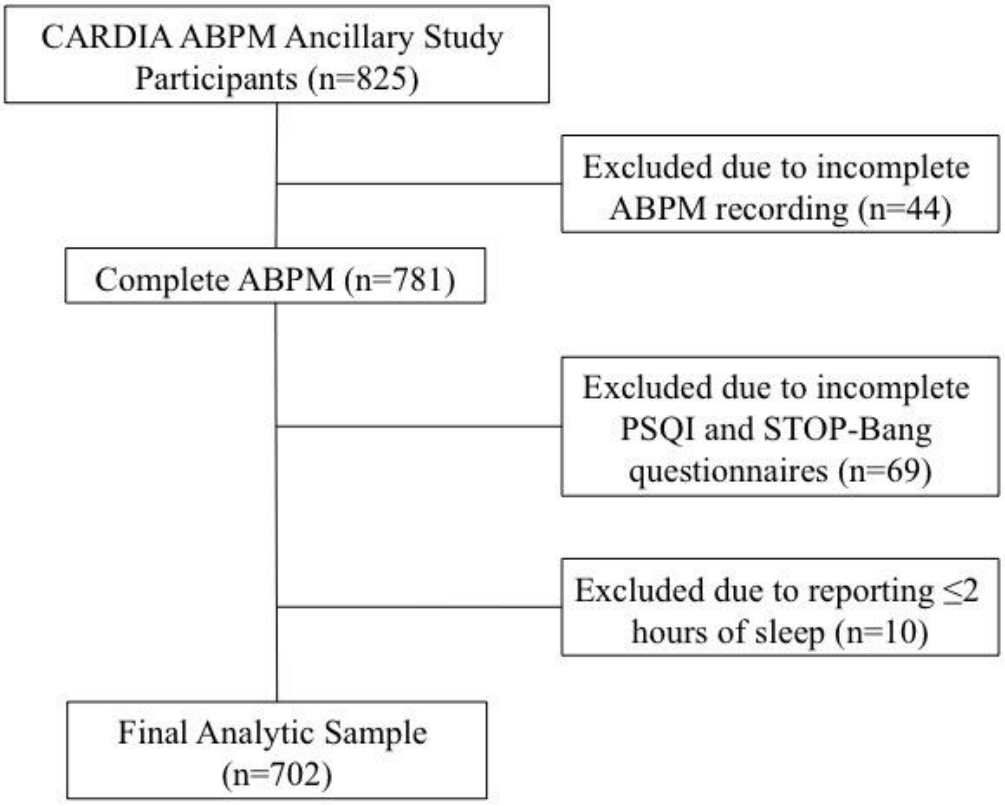
Table S4. Characteristics of participants with and without non-dipping systolic blood pressure stratified by race.

	White			Black		
	Non-dipping SBP			Non-dipping SBP		
	No (N=217)	Yes (N=54)	p-value	No (N=257)	Yes (N=174)	p-value
Age, years	55.3 ± 3.3	56.0 ± 3.5	0.159	53.9 ± 3.9	54.7 ± 3.8	0.032
Male, %	43.6	44.4	1.00	38.6	34.6	0.423
Field center, %			0.287			0.920
Birmingham	54.6	63.0		63.7	63.2	
Chicago	45.4	37.0		36.3	36.8	
Highest level of education, years	16.2 ± 2.5	15.3 ± 2.8	0.019	14.1 ± 2.4	14.1 ± 2.2	0.936
Low physical activity, %	53.2	64.8	0.130	73.7	73.6	1.00
Alcohol intake, %			0.175			0.059
Non-drinker	42.2	55.6		52.9	63.2	
Moderate	39.4	33.3		36.3	25.8	
Heavy	18.4	11.1		10.8	11.0	
Current cigarette smoking, %	7.4	13.0	0.195	20.8	17.0	0.315
Body mass index, kg/m^2	28.4 ± 5.2	31.4 ± 7.3	0.005	32.1 ± 7.0	34.3 ± 7.2	0.002
Depression symptoms, %	13.3	18.5	0.385	19.7	19.2	1.00
Diabetes, %	7.3	18.5	0.019	18.0	29.8	0.005
Cardiovascular disease event, %	4.1	0.0	0.212	6.9	7.1	1.00
Reduced eGFR, %	2.7	1.8	1.00	5.4	6.6	0.683
Albuminuria, %	3.7	5.6	0.461	10.0	17.0	0.043
CPAP use, %	8.3	13.0	0.295	15.1	19.8	0.200
Antihypertensive medication use, %	23.8	27.8	0.597	51.0	42.0	0.066
Systolic blood pressure, mm Hg						
Clinic	116.5 ± 14.4	115.2 ± 15.1	0.564	126.2 ± 18.1	124.1 ± 18.9	0.250
Awake	126.8 ± 13.2	126.1 ± 19.1	0.793	133.5 ± 16.0	129.1 ± 14.9	0.004
Asleep	103.9 ± 11.6	120.1 ± 18.4	<0.001	111.3 ± 13.7	123.1 ± 15.0	<0.001
Diastolic blood pressure, mm Hg						
Clinic	71.5 ± 10.0	69.4 ± 10.9	0.182	77.0 ± 11.4	75.9 ± 11.0	0.314
Awake	79.9 ± 7.9	75.8 ± 9.1	0.001	82.8 ± 9.6	79.8 ± 9.2	0.001
Asleep	63.1 ± 7.4	69.5 ± 8.9	<0.001	66.1 ± 9.2	72.6 ± 9.3	<0.001

Decline from awake to asleep, mm Hg						
Systolic blood pressure	18.0 ± 4.9	4.7 ± 4.6	<0.001	16.5 ± 5.3	4.6 ± 4.8	<0.001
Diastolic blood pressure	20.9 ± 5.8	8.2 ± 6.1	<0.001	20.1 ± 6.7	8.9 ± 6.0	<0.001
STOP-Bang components, %						
Snore loudly	22.5	33.3	0.113	25.9	34.1	0.071
Tired, fatigued, or sleepy	48.6	55.6	0.447	50.6	52.7	0.699
Observed apnea	13.3	24.1	0.059	17.4	18.1	0.899
High blood pressure	22.5	33.3	0.113	52.1	61.5	0.052
BMI >35 kg/m^2	10.5	29.6	0.001	29.7	41.2	0.015
Age >50 years	93.6	90.7	0.479	74.5	84.1	0.018
Large neck size	28.9	42.6	0.071	27.0	31.3	0.338
Male	43.6	44.4	0.999	38.6	34.6	0.423
High likelihood of OSA, %	13.3	37.0	<0.001	39.4	47.2	0.175

Numbers in the table are mean ± standard deviation or percentage.
CPAP: Continuous positive airway pressure.
OSA: Obstructive sleep apnea.
Low physical activity is defined as less than 300 exercise units.
Cardiovascular disease events include myocardial infarction (MI), non-MI acute coronary syndrome, coronary artery disease, peripheral artery disease, congestive heart failure, stroke, and transient ischemic attacks.
Reduced estimated glomerular filtration rate (eGFR) was defined as an eGFR <60 mL/min/1.73 m^2.
Albuminuria was defined as albumin-to-creatinine ratio (ACR) >30 mg/g.
High risk for obstructive sleep apnea was defined as a STOP-Bang questionnaire score ≥5.
Non-dipping blood pressure was defined as a decline in sleep systolic blood pressure relative to awake systolic blood pressure <10%.

Figure S1. Flow diagram for the analytic sample.



CARDIA: Coronary Artery Risk Development in Young Adults; ABPM: ambulatory blood pressure monitoring; PSQI: Pittsburgh Sleep Quality Index