JACC: ADVANCES VOL. 4, NO. 4, 2025

ORIGINAL RESEARCH

Gestational Blood Pressure Trajectories and 5-Year Postpartum Hypertension Risk in the MADRES Study

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ABSTRACT

BACKGROUND Blood pressure (BP) changes during pregnancy, but less is known about heterogeneous changing patterns within a population and long-term hypertension risk.

OBJECTIVES The purpose of this study was to identify distinct gestational systolic blood pressure (SBP) trajectories and examine their association with postpartum hypertension risk.

METHODS The MADRES (Maternal and Developmental Risks from Environmental and Social Stressors) (2015-present) cohort followed 854 pregnant individuals from early pregnancy to 5 years postpartum and collected information on demographics, lifestyle, and medical records, including BP at each prenatal visit. Latent class growth modeling was used to identify gestational SBP trajectories. Incident postpartum hypertension was identified from interviews and BP measurements. Cox modeling was used to assess the association of trajectory groups with the risk of hypertension at 2 to 5 years postpartum.

RESULTS We identified 3 distinct gestational SBP trajectory groups. The majority (n = 685, 80.2%) had a "consistently low" trajectory over pregnancy. A "consistently elevated" trajectory group (n = 106, 12.4%) was characterized by modestly elevated SBP within a clinically normal range but lacked a midpregnancy dip. A "high-drop-high" trajectory group (n = 63, 7.4%) consisted of most cases of gestational hypertension or pre-eclampsia. Risk of hypertension in 5 years postpartum was 4.91 (95% CI: 2.01-12.0) fold higher in the "consistently elevated" group and 5.44 (95% CI: 1.89-15.7) fold higher in the "high-drop-high" group than the "consistently low" group, after adjusting for covariates.

CONCLUSIONS Pregnant individuals with consistently elevated SBP yet within the subclinical range face longer-term risk of hypertension but may not be captured by standard prenatal clinical guidelines. (JACC Adv. 2025;4:101660)

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The authors attest they are in compliance with human studies committees and animal welfare regulations of the authors' institutions and Food and Drug Administration guidelines, including patient consent where appropriate. For more information, visit the Author Center.

Manuscript received November 24, 2024; revised manuscript received January 22, 2025, accepted February 14, 2025.

ISSN 2772-963X https://doi.org/10.1016/j.jacadv.2025.101660

ABBREVIATIONS AND ACRONYMS

BMI = body mass index

BP = blood pressure

CVD = cardiovascular disease

DBP = diastolic blood pressure

GH/PE = gestational hypertension or pre-eclampsia

HDP = hypertensive disorders of pregnancy

SBP = systolic blood pressure

Hypertension, a leading cause of cardiovascular disease (CVD), was prevalent among 43.0% of U.S. females ≥20 years in 2023.[1] In addition to hypertension's common risk factors such as smoking and obesity, childbearing individuals face unique risk factors related to pregnancy, such as hypertensive disorders of pregnancy (HDP)—a gestational complication characterized by blood pressure (BP) elevation and other vascular dysfunction that typically resolve after delivery.[1,2] Indeed, BP fluctuates during normal pregnancy, with levels decreasing in the first half of pregnancy and returning to prepregnancy levels shortly after delivery.[3] These BP changes are driven by cardiovascular and hormonal adaptation to accommodate the growth of the placenta and fetus.[3] However, dysregulated elevations in BP during pregnancy, even within the subclinical range and thus not diagnosed of HDP, have been linked with poor pregnancy and birth outcomes.[4] Additionally, the patterns of BP changes, such as the absence of a decrease in BP in the first half of pregnancy,[5] have also been associated with adverse pregnancy outcomes.[6-10] Thus, gestational BP trajectory, a combination of BP levels and changing patterns over time, not only varies in a population but can also provide valuable insights into an individual's underlying cardiovascular health from a life course perspective. Because most cases of female hypertension occur in years after pregnancy, prospective evaluation of BP trajectories during pregnancy can advance early identification of pregnancy individuals who are at risk of future hypertension. Identifying heterogeneous BP trajectories in a population can also improve our understanding of cardiovascular adaptation during pregnancy.

Therefore, we aimed to first characterize potentially different gestational BP trajectories in a predominately low-income, Hispanic population, who have been less studied, yet may be at elevated risk of hypertension.[1] Furthermore, we investigated the association of BP trajectories with the risk of hypertension up to 5 years postpartum. We hypothesized that there are distinct BP trajectories, and some BP trajectories are associated with increased risk of longer-term postpartum hypertension.

METHODS

STUDY POPULATION. The study is based on the ongoing MADRES (Maternal and Developmental Risks from Environmental and Social Stressors) pregnancy cohort, established in 2015 in Los Angeles, California.[11] Participants were recruited in early to midpregnancy and actively followed in each trimester of pregnancy, at delivery, and twice a year up to 5 years postpartum. Eligibility criteria included ≥18 years of age at enrollment, having a gestational age ≤30 weeks, carrying a singleton pregnancy, and fluency in English/Spanish. Exclusion criteria included HIV infection, having disabilities that would prevent participation, or incarceration. All participants signed informed consent at recruitment. The Institutional Review Board at the University of Southern California approved all aspects of the study.

A total of 854 participants delivered by July 16, 2023, and constituted the study population to construct BP trajectories during pregnancy. Because participants were enrolled on a rolling basis, follow-up visits in later postpartum years had smaller numbers of participants. Overall, 384 participants had been followed up at least once between 2 and 5 years postpartum. After excluding 25 participants who had stage I or higher hypertension before pregnancy (systolic blood pressure [SBP] >130 mm Hg or diastolic blood pressure [DBP] >80 mm Hg), 359 participants were eligible to assess postpartum incidence of newly occurred hypertension. Comparison of key characteristics between these 359 participants and the other 308 participants who were lost to follow-up during postpartum years (Supplemental Table 1) indicated that most characteristics were comparable, including age, education, prepregnancy body mass index (BMI), and HDP (ie, pre-eclampsia and gestational hypertension).

BLOOD PRESSURE DURING PREGNANCY AND POSTPARTUM FOLLOW-UP VISITS. BP during pregnancy was measured by a medical assistant at each prenatal clinic visit and abstracted from electronic medical records after delivery. Mean BP did not materially differ across the recruitment sites. Participants had a mean of 11.6 ± 4.3 SBP measures during pregnancy (all between 4 and 41 gestational weeks), contributing to a total of 9,862 SBP measures after removing 1 unrealistic value (30 mm Hg). These BP measures were used to identify BP trajectories (details in Statistical Methods).

BP at postpartum annual follow-up study visits was measured by trained research staff. Participants rested for 5 minutes in an upright, supported sitting position prior to measurement with a validated automated digital oscillometric sphygmomanometer (Carescape V100, GE Healthcare) with appropriate cuff size. BP was measured 3 times with a 1-minute rest between measures, and the average value was used. We calculated pulse pressure by subtracting

DBP from SBP. Mean arterial pressure was read from the machine. The number of measurements and average SBP at each gestational week and at postpartum visits are shown in Supplemental Figure 1 and Supplemental Table 2.

ASSESSMENT OF POSTPARTUM HYPERTENSION. Incident postpartum hypertension was identified by combining information from twice-yearly phone interviews and yearly BP measurement during in-person study visits from 24 to 60 months postpartum. Every 6 months, participants were interviewed by telephone to ascertain new diagnosis and/or treatment by a doctor for hypertension, along with other CVDs. Participants were also classified as having hypertension if their SBP was ≥130 mm Hg or DBP was ≥80 mm Hg at any postpartum study visit. Time-to-hypertension was coded as the month postpartum when hypertension was first diagnosed or censored at the last follow-up.

MEASUREMENT OF COVARIATES. Potential confounders were a priori selected based on a review of the literature and analyses of the causal structure (Supplemental Figure 2),[12] including age, recruitment site, gestational age at the time of recruitment, ethnicity by country of birth, education, family income, prepregnancy BMI, total gestational weight gain, parity, and newborn sex. Standing height was measured twice by a stadiometer, and prepregnancy BMI was calculated using self-reported prepregnancy weight (kg) divided by the square of measured height (m^2). Parity was coded with 3 categories: first, second, and third or more. Newborn sex was abstracted from birth records. Prepregnancy active smoking was reported among 21 (2.5%) participants and thus only included in a sensitivity analysis to avoid potential sparse data issue in regression models. Additional adjustment models (details below) included HDP, which was abstracted from medical records and included preeclampsia and gestational hypertension.[13]

STATISTICAL METHODS. The analyses had 2 steps. The first step estimated distinct SBP trajectory groups among the overall population (N = 854), then the second step assessed the associations of SBP trajectories with the primary outcome—incident hypertension during the 5 years postpartum (N = 359). We chose to estimate trajectories of SBP, rather than DBP, because both SBP and DBP could reflect BP changes during pregnancy but SBP is a stronger predictor of long-term CVD risk than DBP.[14] Secondary outcomes were longitudinal measures of BP between 2 and 5 years postpartum.

To estimate SBP trajectory groups, we used the latent class growth model,[15] a data-driven approach to identify a finite number of longitudinal changing patterns (trajectories) in SBP throughout pregnancy when each participant had different number and timing of repeated BP measures. We followed the Guidelines for Reporting on Latent Trajectory Studies to specify the number and shape of the trajectory group, using a set of criteria, including minimizing the Bayesian Information Criteria.[16] A comparison of these criteria across different model specifications is summarized in Supplemental Table 3. For each trajectory, a linear and quadratic term of time, random intercept and slope were included with group-specific variance-covariance. For each individual, membership in a trajectory group was assigned based on the maximum estimated posterior trajectory probability.[17] A comparison of population characteristics by trajectory group was tested by chi-square test or ANOVA.

To analyze the association of SBP trajectory groups with postpartum incident hypertension, we first used Kaplan-Meier plots to visualize hypertension-free survival curves, with log-rank test for the difference among trajectory groups. We then used a Cox proportional hazard model to assess the association of trajectory groups with the hazard of hypertension at 2 to 5 years postpartum, adjusting for abovementioned covariates. To assess whether BP trajectories provide more information than clinical diagnosis, we further included GH and PE in the adjustment set. For a sensitivity analysis, we excluded PE and GH cases from the Cox model. Notably, such analysis completely removed participants who met current guidelines on diagnosis of hypertension before or during pregnancy, thus can separate trajectories' predictive value for postpartum risk of hypertension from direct readings of BP or HDP diagnosis during pregnancy. During postpartum follow-up, 65 participants reported another pregnancy. For a sensitivity analysis, we further adjusted for additional pregnancies. For the secondary aim, we examined longitudinal changes in postpartum BP from 12 to 60 months using a linear mixed effects model. The model incorporated an unstructured covariance matrix to account for the within-subject correlation of BP over time. We also included an interaction term between postpartum months (treated as a continuous variable) and pregnancy BP trajectory groups to

TABLE 1 Characteristics of MADRES Participants by Pregnancy Systolic Blood Pressure Trajectories (N = 854)

	Overall (N = 854)	"Consistently Low" (n = 685, 80.2%)	"Consistently Elevated" (n = 106, 12.4%)	"High-Drop-High" (n = 63, 7.4%)	*P* Value
Baseline characteristics					
Maternal age (y)	28.36 (5.95)	28.27 (5.9)	28.07 (6.04)	29.75 (6.3)	0.15
Recruitment site					0.20
LA County Hospital	209 (24%)	162 (24%)	34 (32%)	13 (21%)	
Eisner Clinics	559 (65%)	453 (66%)	60 (57%)	46 (73%)	
USC OBGYN	58 (6.8%)	48 (7.0%)	9 (8.5%)	1 (1.6%)	
Community Recruit	4 (0.5%)	2 (0.3%)	1 (0.9%)	1 (1.6%)	
South Central Clinic	24 (2.8%)	20 (2.9%)	2 (1.9%)	2 (3.2%)	
Recruitment cohort					0.50
Regular entry	596 (70%)	474 (69%)	79 (75%)	43 (68%)	
Late entry	258 (30%)	211 (31%)	27 (25%)	20 (32%)	
Annual household income					0.08
<$15,000	184 (22%)	147 (21%)	20 (19%)	17 (27%)	
$15,000-$30,000	195 (23%)	156 (23%)	19 (18%)	20 (32%)	
≥$30,000	170 (20%)	134 (20%)	31 (29%)	5 (7.9%)	
Unknown	261 (31%)	212 (31%)	31 (29%)	18 (29%)	
Missing	44 (5.2%)	36 (5.3%)	5 (4.7%)	3 (4.8%)	
Ethnicity by birthplace					0.14
Non-Hispanic	163 (19%)	124 (18%)	26 (25%)	13 (21%)	
Hispanic, U.S. born	270 (32%)	207 (30%)	40 (38%)	23 (37%)	
Hispanic, non-U.S. born	305 (36%)	258 (38%)	30 (28%)	17 (27%)	
Missing	116 (14%)	96 (14%)	10 (9.4%)	10 (16%)	
Maternal education					0.13
Below high school	203 (24%)	168 (25%)	19 (18%)	16 (25%)	
High school	257 (30%)	210 (31%)	24 (23%)	23 (37%)	
Some college	217 (25%)	165 (24%)	36 (34%)	16 (25%)	
College or higher	132 (15%)	105 (15%)	22 (21%)	5 (7.9%)	
Missing	45 (5.3%)	37 (5.4%)	5 (4.7%)	3 (4.8%)	
Prepregnancy BMI					<0.001
Normal	275 (32%)	251 (37%)	14 (13%)	10 (16%)	
Overweight	269 (31%)	224 (33%)	27 (25%)	18 (29%)	
Obese	308 (36%)	208 (30%)	65 (61%)	35 (56%)	
Missing	2 (0.2%)	2 (0.3%)	0 (0%)	0 (0%)	
Parity					0.14
0	272 (32%)	212 (31%)	42 (40%)	18 (29%)	
1	231 (27%)	180 (26%)	35 (33%)	16 (25%)	
2	215 (25%)	179 (26%)	18 (17%)	18 (29%)	
≥3	136 (16%)	114 (17%)	11 (10%)	11 (17%)	
Prepregnancy smoking					0.20
Never smoker	749 (88%)	598 (87%)	95 (90%)	56 (89%)	
Ever smoker	66 (7.7%)	49 (7.2%)	10 (9.4%)	7 (11%)	
Current smoker	21 (2.5%)	21 (3.1%)	0 (0%)	0 (0%)	
Missing	18 (2.1%)	17 (2.5%)	1 (0.9%)	0 (0%)	
Birth outcomes					
Gestation duration	38.99 (1.88)	39.15 (1.73)	38.67 (2.14)	37.82 (2.41)	<0.001
Newborn sex					0.06
Male	430 (50%)	349 (51%)	54 (51%)	27 (43%)	
Female	419 (49%)	333 (49%)	52 (49%)	34 (54%)	
Missing	5 (0.6%)	3 (0.4%)	0 (0%)	2 (3.2%)	
Preterm birth					<0.001
No	768 (90%)	627 (92%)	92 (87%)	49 (78%)	
Yes	86 (10%)	58 (8.5%)	14 (13%)	14 (22%)	
Small for gestational age					0.03
No	751 (88%)	610 (89%)	93 (88%)	48 (76%)	
Yes	85 (10.0%)	63 (9.2%)	11 (10%)	11 (17%)	
Missing	18 (2.1%)	12 (1.8%)	2 (1.9%)	4 (6.3%)	

Continued on the next page

TABLE 1 Continued

	Overall (N = 854)	"Consistently Low" (n = 685, 80.2%)	"Consistently Elevated" (n = 106, 12.4%)	"High-Drop-High" (n = 63, 7.4%)	*P* Value
Pregnancy characteristics					
Average SBP, mm Hg					
4-8 wk	113.0 (10.7)	110.4 (8.9)	122.3 (9.2)	127.2 (13.1)	<0.001
20-24 wk	108.3 (10.2)	105.3 (7.8)	122.4 (8.1)	114.7 (12.1)	<0.001
37-41 wk	113.7 (10.8)	110.8 (7.8)	120.1 (8.9)	136.0 (13.4)	<0.001
Average DBP, mm Hg					
4-8 wk	69.5 (7.9)	68.0 (7.3)	74.6 (6.8)	78.3 (7.7)	<0.001
20-24 wk	66.3 (7.5)	64.6 (6.5)	73.5 (7.3)	71.25 (8.3)	<0.001
37-41 wk	71.3 (7.9)	69.7 (6.7)	75.1 (7.7)	83.53 (8.6)	<0.001
Total weight gain (kg)	10.8 (6.9)	10.7 (6.8)	11.5 (7.4)	10.48 (7.7)	0.81
Hypertensive status					<0.001
Nonhypertensive	668 (78%)	589 (86%)	67 (63%)	12 (19%)	
Preeclampsia	77 (9.0%)	40 (5.8%)	10 (9.4%)	27 (43%)	
Chronic hypertension	26 (3.0%)	13 (1.9%)	7 (6.6%)	6 (9.5%)	
Superimposed pre-eclampsia	16 (1.9%)	2 (0.3%)	7 (6.6%)	7 (11%)	
Gestational hypertension	58 (6.8%)	33 (4.8%)	15 (14%)	10 (16%)	
Postpartum pre-eclampsia	1 (0.1%)	0 (0%)	0 (0%)	1 (1.6%)	
Missing	8 (0.9%)	8 (1.2%)	0 (0%)	0 (0%)	
Diabetic status					<0.001
Nondiabetic	735 (86%)	605 (88%)	81 (76%)	49 (78%)	
Gestational diabetes	78 (9.1%)	56 (8.2%)	17 (16%)	5 (7.9%)	
Type 2 diabetes	41 (4.8%)	24 (3.5%)	8 (7.5%)	9 (14%)	

BMI = body mass index; DBP = diastolic blood pressure; MADRES = Maternal and Developmental Risks from Environmental and Social Stressors; SBP = systolic blood pressure; US OBGYN = Department of Obstetrics and Gynecology at University of Southern California.

investigate whether the trajectory groups differentially influenced the trend of postpartum BP over time. This interaction allows us to assess whether the slope of postpartum BP change varies across different pregnancy BP trajectory groups.

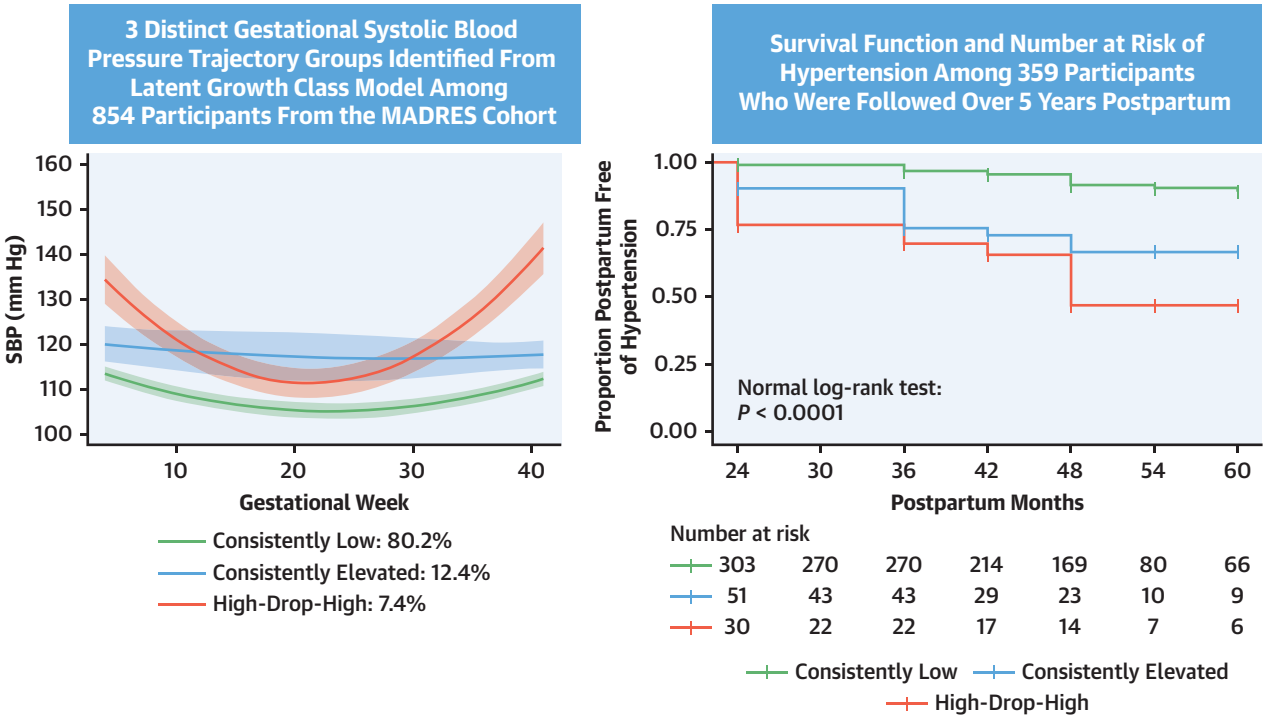
Although stage 1 or higher hypertension cases were excluded when examining postpartum hypertension risk, they could shift population BP trajectories during pregnancy. Therefore, we conducted a sensitivity analysis by excluding participants with stage 1 or higher hypertension to reconstruct SBP trajectories. We compared the trajectory groups with and without excluding stage 1 or higher hypertension cases and reran all the association analyses. All analyses were conducted in R (4.3.1, Vienna, Austria), with package "lcmm" (2.0.2) for trajectory analysis, "survival" (3.5.5) for survival analysis, "geepack" (1.3.9) for mixed effects analysis, and "mediation" (4.5.0) for mediation analysis. The significance level was set at 0.05.

RESULTS

Of the 854 participants, a majority were Hispanic (n = 575, 68%), with very low income (n = 379, 45% below $30,000/year) and low education (n = 460, 54% high school or lower, Table 1). Twenty-six (3.0%) participants had prepregnancy hypertension, while 77 (9.0%) developed PE and 58 (6.8%) developed GH. Mean gestational duration was 39.0 ± 1.9 weeks, with 86 (10.0%) cases of preterm birth.

We identified 3 trajectory groups that have distinct SBP levels and changing patterns over pregnancy (Central Illustration). The majority group of 685 (80.2%) participants was characterized by a "consistently low" SBP trajectory over pregnancy. Their SBP levels (mean ± SD) were, for example, 110.4 ± 8.9 mm Hg at 4 to 8 gestational weeks, 105.3 ± 7.8 mm Hg at 20 to 24 gestational weeks, and 110.8 ± 7.8 mm Hg at 37 to 41 gestational weeks (Table 1). Another 106 (12.4%) participants had a "consistently elevated" SBP trajectory with modestly elevated BP levels within a clinically normal range and lacked a midpregnancy drop (eg, SBP: 122.3 ± 9.2, 122.4 ± 8.1, 120.1 ± 8.9 mm Hg at 4-8, 20-24, and 37-41 gestational weeks, respectively). There were 63 (7.4%) who had a "high-drop-high" SBP trajectory (eg, SBP: 127.2 ± 13.1, 114.7 ± 12.1, 136.0 ± 13.4, mm Hg at 4-8, 20-24, and 37-41 gestational weeks, respectively). There were higher percentages of obesity in the "consistently elevated" group (65, 61%) and the "high-drop-high" group (35, 56%) compared to the "consistently low" group (208, 30%, $P < 0.001$). Across groups from "consistently low" to "consistently elevated" to "high-drop-high," there is an increasing trend in the risk of preterm birth (8.5%, 13%, 22%),

CENTRAL ILLUSTRATION Gestational Blood Pressure Trajectories and Postpartum Risk of Hypertension



Pregnant individuals with consistently elevated blood pressure (shown in blue), yet within the subclinical range, face longer-term risk of hypertension that may not be captured by standard guidelines for prenatal and postpartum clinical care

Niu Z, et al. JACC Adv. 2025;4(4):101660.

MADRES = Maternal and Developmental Risks from Environmental and Social Stressors.

pre-eclampsia (5.8%, 9.4%, 43%), gestational hypertension (4.8%, 14%, 16%), and type 2 diabetes (3.5%, 7.5%, 14%). Gestational diabetes was highest in "consistently elevated" (16%), followed by "consistently low" (8.2%) and "high-drop-high" (7.9%). These differences did not change meaningfully after adjusting for potential confounders (Supplemental Table 4).

Incidence rate of hypertension over the 5 years postpartum was the highest among the "high-drop-high" group (11.22 per 1,000 person-month), followed by the "consistently elevated" group (6.93) and "consistently low" group (1.53) (**Table 2**), and these differences were statistically significant (log-rank test $P < 0.001$) (**Central Illustration**). From confounder-adjusted Cox models, the risk of 5-year postpartum hypertension was 4.91 (95% CI: 2.01-12.0) fold higher in the "consistently elevated" group than the "consistently low" group. Adjusting for PE/GH attenuated the HR for the "consistently elevated" group to 3.42 (95% CI: 1.30-9.02), while removing individuals with PE/GH from the analysis strengthened the HR to 6.21 (95% CI: 0.93-41.4). The adjusted HR for the "high-drop-high" group with the risk of 5-year postpartum hypertension was 5.44 (95% CI: 1.89-15.7), which was not significant after adjusting for PE/GH (HR: 2.15, 95% CI: 0.61-7.54), and failed convergence after removing individuals with PE/GH from the analysis (due to a high number of individuals with PE/GH in this group).

The "consistently elevated" group and the "high-drop-high" group had significantly higher BP measures up to 5 years postpartum than the "consistently low" group (**Figure 1**, Supplemental Table 5). The interaction term of postpartum month and the "high-drop-high" group were generally not statistically significant for postpartum BP measures. However, the interaction term between postpartum month and the "high-drop-high" group was significant for DBP (adjusted $\beta = -0.21$; $P = 0.03$), suggesting that individuals in the "high-drop-high" trajectory group

TABLE 2 Risk Rate and Hazard Ratio of Incident Hypertension in 5 Years of Postpartum Follow-Up by Pregnancy Systolic Blood Pressure Trajectories

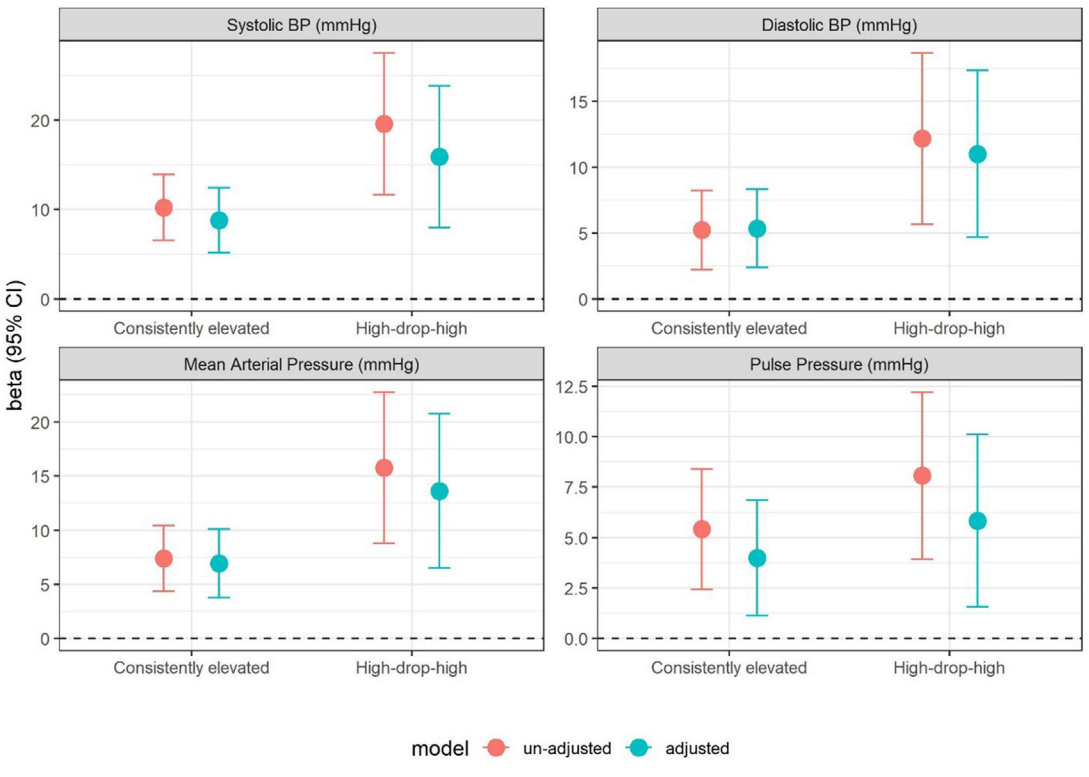
Statistics/Model	"Consistently Low" (n = 303)	"Consistently Elevated" (n = 51)	"High-Drop-High" (n = 30)
Person-months at risk	13,686	2,166	1,248
Hypertension cases in 5 y postpartum	21	15	14
Incidence rate, per 1,000 person-month	1.53	6.93	11.22
HR (95% CI)			
Unadjusted	Reference	4.37 (2.08-9.18)	5.12 (2.04-12.83)
Adjusted for confounders[a]	Reference	4.91 (2.01-11.98)	5.44 (1.89-15.69)
Adjusted for confounders[a] + HDP	Reference	3.42 (1.30-9.02)	2.15 (0.61-7.54)
Adjusted for confounders[a], removing HDP	Reference	6.21 (0.93-41.40)	-[b]

[a]Included maternal age, recruitment site and time of pregnancy recruitment, ethnicity by country of birth, education, household income, prepregnancy BMI, total gestational weight gain, parity, and newborn sex. [b]Model did not converge due to low number of cases.
HDP = hypertensive disorder of pregnancy.

experienced a greater decrease in DBP over the postpartum period compared to "consistently low" group. (Supplemental Figure 3, Supplemental Table 5).

In sensitivity analyses, excluding participants with stage 1 or higher hypertension before 20 gestational weeks did not meaningfully change the number, shape, nor membership of the 3 distinct SBP

FIGURE 1 Adjusted Beta Coefficients (95% CI) for Longitudinal Blood Pressure Measures From 24 to 60 Months Postpartum Among 359 Participants Followed Up in the MADRES Cohort



All models used the "consistently low" trajectory group as the reference and adjusted for maternal age, recruitment site and time of pregnancy recruitment, ethnicity by nativity, education, household income, prepregnancy BMI, total weight gain, parity, and newborn sex.
BMI = body mass index; BP = blood pressure.

trajectory groups (Supplemental Figure 4). Results from subsequent association analyses on these stage 1 or higher hypertension-free trajectory groups with 5-year postpartum hypertension and BP were similar to the main results. Adjusting for additional pregnancies after the index pregnancy did not impact the effect estimation (Supplemental Table 6).

DISCUSSION

In a predominately low-income Hispanic pregnancy cohort, we identified 3 distinct gestational SBP trajectories, 2 of which were prospectively associated with higher risk of hypertension up to 5 years postpartum. While most of the population had a "consistently low" SBP trajectory during pregnancy with a low risk of postpartum hypertension, a substantial proportion (12.4%) of the population had a "consistently elevated" SBP trajectory. This group's BP levels remained below diagnostic cutoffs of hypertension (<130/80 mm Hg) across pregnancy. However, this group had four-fold higher risk of postpartum hypertension compared to the "consistently low" group and this association was neither driven by gestational hypertension or preeclampsia (GH/PE). A unique characteristic of the "consistently elevated" group is the absence of the typical midpregnancy BP dip. We also identified a small proportion (7.4%) of the population who had a "high-drop-high" SBP trajectory that was dominated by GH/PE cases, with a five-fold increased risk of postpartum hypertension.

Our identification of 3 distinct SBP trajectories is novel and further advances the field by showing a prospective association of trajectory groups with increased risk of hypertension in 5 years postpartum. Our BP trajectories were generally consistent with previous findings. For instance, using the same statistical approach as ours, Gunderson et al[18] identified 6 SBP trajectories between 0 and 20 gestational weeks that had differential initial BP values at the beginning of pregnancy and differential BP trends over pregnancy. Because they did not include BP measures after 20 gestational weeks, a "high-drop-high" group was not seen.[18] However, the group that had the highest initial BP and a decreasing trend over 20 gestational weeks, similar to our "high-drop-high" group in the first half of pregnancy, had the highest risk of pre-eclampsia.[18] Like our "consistently elevated" group, the second highest risk group was characterized by a subclinically elevated initial BP and a flattened trend over pregnancy.[18] In another study of health registration data from 29,000 pregnant women, 4 trajectory groups were identified: stably high, stably low, moderate BP with a decreasing trend, and a moderate BP with an increasing trend, where the risk of HDPs was the highest in the stably high group, followed by the moderate increasing group.[8] Indeed, because BP normally decreases in the first half pregnancy, the nadir of BP levels and rate of change before or after reaching the nadir have both been previously associated with increased risk of HDP.[5,9,19-21]

To the best of our knowledge, we are the first to prospectively link distinct gestational BP trajectories with long-term cardiovascular health outcomes. Our identification of a subclinically elevated gestational BP trajectory that is strongly related to postpartum hypertension is a novel finding with clinical relevance. Although previous studies have examined BP trajectories during pregnancy, none were able to relate to postpartum risk, possibly due to the lack of long-term follow-up after delivery.[8,9,18,19] One retrospective analysis of gestational BP trajectory found comparable between those who developed hypertension at 1 year postpartum and those who did not, but the sample size was small (n = 129).[22] On the other hand, previous studies on the long-term risk of hypertension or CVD primarily focused on available pregnancy outcomes (eg, HDP) retrospectively, and thus have overlooked the valuable information contained in patterns of BP measures during prenatal visits. Our findings, especially the "consistently elevated" trajectory group, strongly suggest that BP trajectories, characterized by both subclinically elevated BP levels and the absence of the typical midpregnancy BP dip, can provide additional insight into cardiovascular health adaptation during pregnancy and long-term impacts after pregnancy. Importantly, adjusting for or removing diagnosed cases of GH/PE did not meaningfully affect the association of this "consistently elevated" trajectory group with postpartum hypertension. Because this group's BP did not meet diagnosis of stage 1 or higher hypertension before 20 gestational weeks, nor diagnosis of GH/PE after 20 gestational weeks, they are likely to remain neglected in perinatal practices, although they are at risk of long-term postpartum hypertension. As the American College of Obstetricians and Gynecologists has dubbed the 12 weeks postpartum as the "fourth trimester,"[23] developing screening guidelines to review and identify patterns from richer prenatal BP measures shortly after pregnancy could potentially early identify women at higher risk of hypertension in later life. Such a fourth trimester screening could be particularly helpful and practical to identify those in the "consistently elevated" trajectory group, that is, gestational SBP remains stably elevated within a subclinical range

(120-130 mm Hg).[23] We also found that the "high-drop-high" trajectory group may experience unique cardiovascular adaptations postpartum, characterized by declining DBP postpartum. Such patterns could indicate underlying physiological mechanisms distinct from other trajectory groups, which warrant further investigation.

The mechanisms underlying the association of SBP trajectories with long-term risk of hypertension remain unclear. During pregnancy, hemodynamic changes, such as increased stroke volume and heart rate, could directly induce vascular and left ventricular remodeling, which may not fully resolve after delivery and thus increase the long-term risk of postpartum hypertension.[24,25] These drastic changes in cardiovascular system may explain our findings on the "high-drop-high" group's association with postpartum hypertension, which was not significant after adjusting for HDP. However, the "consistently elevated" group's association with postpartum hypertension was independent of HDPs, suggesting this group's long-term risk may be driven by a combination of subclinical BP elevation and a maladaptation of BP across pregnancy, as indicated by the absence of a midpregnancy dip. Notably, this group had existing suboptimal cardiometabolic health, indicated by higher prevalence of obesity and risk of gestational diabetes than the other trajectory groups. While current BP guidelines have been lowered to diagnose hypertension in the general population, these lower cutoff values have not been applied in pregnant individuals,[26] which may partially explain the existence of the "consistently elevated" group and their subclinical BP elevation that falls into the "prehypertension" range for nonpregnant population. Previous trials of treating mild hypertension in early pregnancy improved pregnancy and birth outcomes[27,28] and further studies are warranted to test the effectiveness and safety of adopting more stringent hypertension diagnosis guidelines in pregnancy.

Our study is strengthened by the application of a novel approach to identify prenatal BP trajectories and a comprehensive, prospective postpartum follow-up. Although our sample size for postpartum follow-up visits is somewhat limited, the characteristics of those who participated in follow-up vs those who did not were comparable. Because most of the missingness for postpartum information was due to interruptions during the COVID-19 pandemic, we anticipate more participants to be followed in future follow-up visits. Second, gestational BP measures were abstracted from medical records, and thus may be prone to variability and measurement error. However, no significant differences in average prenatal BP were observed among participating clinics. Therefore, measurement errors are likely to be random and drive the association to the null. Third, our study population is predominantly low-income and Hispanic, thus limiting the findings' generalizability. Fourth, while our findings contribute to the understanding of BP dynamics during pregnancy and their long-term implications, assessing the incremental predictive value of BP trajectories within existing prediction models was beyond the scope of this study. Future research should explore whether incorporating BP trajectory groups into predictive frameworks that include first-trimester BP, prepregnancy BMI, and HDPs can enhance the accuracy and clinical utility of hypertension risk predictions postpartum. Such efforts could facilitate more targeted monitoring and intervention strategies for at-risk populations. In future research, a joint modeling framework may be especially valuable for studies that aim to capture the dynamic relationship between postpartum BP changes and the timing of hypertension onset.[29]

CONCLUSIONS

We identified 3 distinct SBP trajectories during pregnancy among a low-income Hispanic population. Longer-term risk of hypertension over 5 postpartum years significantly increased in a group with consistently elevated SBP over pregnancy. Identifying this at risk, but potentially unrecognized group, could improve women's long-term cardiovascular health.

ACKNOWLEDGMENTS The authors would like to thank all MADRES participants, the study staff, and our community clinic partners for their many contributions to this work.

FUNDING SUPPORT AND AUTHOR DISCLOSURES

This work was supported by NIH grants P50MD015705, P50ES026086, UH3OD023287, P30ES007048, R01ES027409, and EPA grant 83615801-0. The content of this paper is solely the responsibility of the authors and does not necessarily represent the official views of these funding organizations. The funding organizations had no roles in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication. The authors have reported that they have no relationships relevant to the contents of this paper to disclose.

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PERSPECTIVES

COMPETENCY IN MEDICAL KNOWLEDGE: In a predominately low-income Hispanic pregnancy cohort, we identified 3 distinct gestational systolic BP trajectories. Compared to the majority with a consistently low BP trajectory, people with a unique trajectory, characterized by consistent subclinically elevated systolic BP, had fourfold increased risk of hypertension over the first 5 years postpartum. The association of the consistently elevated BP trajectory and postpartum hypertension risk was independent of pre-eclampsia and gestational hypertension.

TRANSLATIONAL OUTLOOK: Identifying individuals with a pattern of consistently elevated systolic BP within the subclinical range during pregnancy may identify individuals at risk of developing hypertension.

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KEY WORDS blood pressure, gestation, latent, postpartum, trajectory, women's health

APPENDIX For supplemental tables and figures, please see the online version of this paper.