Trajectory of Body Mass Index from Ages 2 to 7 Years and Age at Peak Height Velocity in Boys and Girls

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Objective To examine the associations between body mass index (BMI) at 2-4 years and 5-7 years and age at peak height velocity (APHV), an objective measure of pubertal timing, among boys and girls from predominantly racial minorities in the US that have been historically underrepresented in this research topic.

Study design This study included 1296 mother–child dyads from the Boston Birth Cohort, a predominantly Black and low-income cohort enrolled at birth and followed prospectively during 1998-2018. The exposure was overweight or obesity, based on Centers for Disease Control and Prevention reference standards. The outcome was APHV, derived using a mixed effects growth curve model. Multiple regression was used to estimate the overweight or obesity–APHV association and control for confounders.

Results Obesity at 2-4 years was associated with earlier APHV in boys (*B* in years, −0.19; 95% CI, −0.35 to −0.03) and girls (*B*, −0.22; 95% CI, −0.37 to −0.07). Obesity at 5-7 years was associated with earlier APHV in boys (*B*, −0.18; 95% CI, −0.32 to −0.03), whereas overweight and obesity at 5-7 years were both associated with earlier APHV in girls (overweight: *B*, −0.24; 95% CI, −0.40 to −0.08; obesity: *B*, −0.27; 95% CI, −0.40 to −0.13). With BMI trajectory, boys with persistent overweight or obesity and girls with overweight or obesity at 5-7 years, irrespective of overweight or obesity status at 2-4 years, had earlier APHV.

Conclusions This prospective birth cohort study found that overweight or obesity during 2-7 years was associated with earlier pubertal onset in both boys and girls. The BMI trajectory analyses further suggest that reversal of overweight or obesity may halt the progression toward early puberty. *(J Pediatr 2021;230:221-9)*.

Early puberty has implications for a range of cardiometabolic health outcomes,[1-3] including obesity, heart disease,[4] stroke, diabetes,[5] and the metabolic syndrome[6-10]; psychosocial and behavioral outcomes[11-13] including substance use,[14-17] depression, anxiety, and eating disorders; breast and possibly endometrial, cervical, and testicular cancer[18,19]; and increased all-cause mortality. These associations are hypothesized to relate to a combination of increased body mass index (BMI), cardiovascular risk factors, adverse metabolic imprinting, and programming effects of birth weight.[20-23]

There has been a global secular trend toward earlier pubertal onset[24-29] tracking with the childhood obesity epidemic, leading to the hypothesis that the 2 may be related.[30] Many studies have investigated this hypothesis in girls, but the evidence has been scarce and conflicting in boys, with mostly cross-sectional or retrospective cohort studies that have shown different results.[31-39] Prospective cohort studies showed an inverse relationship between pubertal onset and prepubertal BMI[40-43] but did not adjust for important potential confounders such as maternal obesity and maternal age at menarche.

Among the challenges involved in studying pubertal onset in boys is the lack of an objective, standardized, and easily obtainable measure. Although girls have age at menarche to mark puberty, boys require more burdensome measures, such as testicular volume measurement or longitudinal Tanner staging. Age at peak height velocity (APHV), which reflects the timing of the pubertal growth spurt and correlates with the development of secondary sexual characteristics, has been increasingly used.[44,45]

APHV	Age at peak height velocity
BBC	Boston Birth Cohort
BMC	Boston Medical Center
BMI	Body mass index

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Using a well-established prospective birth cohort, the Boston Birth Cohort (BBC), we sought to examine the relationships between overweight and obesity at 2-4 years and 5-7 years, BMI trajectories between these periods, and APHV in both boys and girls. We used age- and sex-specific BMI percentiles and z-scores, which are widely used surrogates for body fat mass and remain relatively stable throughout the pubertal transition.[46-48] We hypothesized that overweight and obesity during the 2 age intervals would be associated with earlier APHV.

Methods

The BBC is a cohort of predominantly Black, low-income mother–child dyads receiving care at Boston Medical Center (BMC). The BBC has been described previously.[49-51] To summarize, mothers delivering singleton live births were approached within 1-3 days postpartum and invited to enroll. Exclusion criteria included in-vitro fertilization, multiple-gestation pregnancies, major birth defects, and deliveries induced by maternal trauma. The postnatal follow-up included enrolled children who continued to receive pediatric care at BMC from birth up to 21 years of age. Written consent was obtained from all mothers and from some children depending on their age. Maternal demographic characteristics and medical histories were obtained during a standardized questionnaire interview, and birth and child health outcomes were obtained by reviewing electronic medical records. All data were deidentified and accessible only to authorized investigators. The BMC and Johns Hopkins School of Public Health institutional review boards approved the study protocol.

A total of 8509 mother–child dyads was recruited among 10 252 mothers asked to enroll between 1998 and 2006 (**Figure 1**; available at www.jpeds.com). Of these, 3163 children continued to receive care at BMC, 3039 had BMI measurements from well-child visits, and 1296 had at least 1 recorded height measurement at or greater than 9 years. Compared with the 8509 dyads originally enrolled, the 1296 mothers included in this study are more likely to be Black, overweight or obese before pregnancy, and, among mothers of boys only, have pre-existing or gestational diabetes (**Table I**; available at www.jpeds.com).

Child weight and height were measured during pediatric clinic visits. BMI percentiles were calculated using reference standards from the Centers for Disease Control and Prevention.[52] Overweight was defined as BMI ≥85th and <95th percentile for age and sex, obese as BMI ≥95th percentile, and overweight or obesity as BMI ≥85th percentile. Exposures were BMI category at 2-4 years, at 5-7 years, and BMI trajectories, which were categorized into 4 groups: (1) persistently not overweight or obese: not overweight or obese at 2-4 years and 5-7 years; (2) not overweight or obese to overweight or obese: not overweight or obese at 2-4 years and overweight or obese at 5-7 years; (3) overweight or obese to not overweight or obese: overweight or obese at 2-4 years and not overweight or obese at 5-7 years; (4) persistently overweight or obese: overweight or obese at 2-4 years and 5-7 years.

APHV was calculated using the SuperImposition by Translation And Rotation mixed effects growth curve model, a well-validated, flexible model that uses subject-specific random effects to fit individual growth curves to a mean curve and provides unbiased estimates of APHV (sitar package in R).[53,54]

We identified covariates that have been associated with childhood obesity and/or with earlier puberty. Of these, the BBC included data on maternal race (dichotomized as Black vs non-Black due to greater rates of early puberty and obesity among Black children),[55-57] maternal education (high school or below vs college or greater, as an indicator of socioeconomic position[58]), marital status (married vs unmarried, as an indicator of household structure[59,60]), maternal age at menarche[61] (divided into terciles), prepregnancy BMI[62,63] (not overweight or obese [BMI <25 kg/m^2] vs overweight or obesity [BMI ≥25 kg/m^2]), pre-existing or gestational diabetes,[64] smoking during pregnancy,[65] preterm birth, and low birth weight. Household income was not included because of the large amount of missing data (>30%).

Missing maternal characteristics and children's BMI measurements were imputed using multiple imputation by chained equations with predictive mean matching via *mice* package in R (R Foundation),[66] using methods described previously.[51] Missing BMI measurements were imputed for the last year of each developmental window. For example, a child missing a BMI measurement between 5-7 years would have BMI imputed at 7 years. In total, 105 (15.8%) boys and 88 girls (13.9%) were missing a BMI measurement between 2-4 years, and 104 boys (15.7%) and 85 (13.4%) girls were missing a BMI measurement between 5-7 years. Other variables that required imputation were maternal education (1.1% missing data among boys; 1.6% among girls), prepregnancy BMI (5.0% among boys; 5.2% among girls), age at menarche (2.4% among boys and girls), and smoking during pregnancy (0.8% among boys; 1.4% among girls).

Characteristics of the 4 BMI trajectory groups were compared using χ^2 tests for categorical variables and ANOVA for continuous variables. Crude and adjusted linear regression were performed to examine the following: associations between BMI categories at 2-4 years, BMI categories at 5-7 years, and APHV, comparing overweight, obese, and overweight or obese to a reference of normal BMI; linear trends between BMI z-scores at 2-4 years, 5-7 years, and APHV; and associations between BMI trajectories and APHV. Interactions between BMI categories at 2-4 years and 5-7 years also were examined using a cross-product term.

Final adjusted models included the following covariates: maternal race, maternal education level, maternal marital status, maternal age at menarche, prepregnancy BMI, maternal diabetes, smoking status during pregnancy, and child's preterm birth and low birth weight status. Stratified analyses were performed by each stratum of the covariates, and sensitivity analyses were performed using the imputed

dataset after removing children with only 1 height measurement, as well as using the unimputed dataset. R software, version 3.5.3 (R Foundation for Statistical Computing) and SAS (SAS Institute), version 9.4, were used for all analyses. A significance level of 2-sided $P < .05$ was used.

Results

In total, 1296 mother–child dyads (663 boys and 633 girls) were included, of which 853 (63.8%) were Black. Mean APHV was 12.2 years in boys and 10.2 years in girls ($P < .001$), and 12.3 years in Black boys and 10.2 years in Black girls (**Figure 2**; available at www.jpeds.com). Distributions of BMI trajectory groups were 345 (50.0%) boys and 328 (51.8%) girls in the persistently not overweight or obese group, 77 (11.6%) boys and 75 (11.9%) girls in the not overweight or obese to the overweight or obese group, 66 (10.0%) boys and 57 (9.0%) girls in the overweight or obese to not overweight or obese group, and 175 (26.4%) boys and 173 (27.3%) girls in the persistently overweight or obese group (**Table II**). Obesity prevalence increased from 19.0% at 2-4 years to 25.0% at 5-7 years in boys, and from 18.0% to 24.6% in girls.

Table II presents univariate comparisons of the characteristics of the BMI trajectory groups by sex. Compared with counterparts with normal BMIs, boys with

Table II. Characteristics of 1296 mother–child pairs by sex and BMI trajectory group (imputed data)

Variables/BMI trajectory groups	Total	Non-overweight or obese to non-overweight or obese	Non-overweight or obese to overweight or obese	Overweight or obese to non-overweight or obese	Overweight or obese to overweight or obese	*P* value
Boys						
n (%)	663	345 (50.0)	77 (11.6)	66 (10.0)	175 (26.4)	
Maternal characteristics						
Age, y, mean ± SD	28.7 ± 6.7	28.0 ± 6.8	31.1 ± 6.5	28.5 ± 6.2	29.0 ± 6.7	.003
Race, n (%)						.286
Black	442 (66.5)	223 (64.6)	47 (61.0)	46 (69.7)	125 (71.4)	
Non-Black	223 (33.5)	122 (35.4)	30 (39.0)	20 (30.3)	50 (28.6)	
Education level, n (%)						.627
High school or less	446 (67.1)	235 (68.1)	54 (70.1)	40 (60.6)	117 (66.9)	
Some college or greater	219 (32.9)	110 (31.9)	23 (29.9)	26 (39.4)	58 (33.1)	
Marital status, n (%)						.375
Married	226 (34.0)	117 (33.9)	30 (39.0)	22 (33.3)	72 (41.1)	
Not married	439 (66.0)	228 (66.1)	47 (61.0)	44 (66.7)	103 (58.9)	
Prepregnancy BMI category, n (%)						<.001
Normal (BMI <25)	309 (37.5)	180 (52.2)	31 (40.3)	36 (54.6)	60 (34.3)	
Overweight or obese (BMI ≥25)	356 (53.5)	165 (47.8)	46 (59.7)	30 (45.5)	115 (65.7)	
Age at menarche, y, mean ± SD	13.0 ± 2.0	12.9 ± 2.0	13.2 ± 1.7	13.1 ± 2.0	13.1 ± 2.3	.769
Diabetes, n (%)	89 (13.4)	38 (11.0)	8 (10.4)	6 (9.1)	37 (21.1)	.006
Smoked during pregnancy, n (%)	118 (17.7)	58 (16.8)	19 (24.7)	11 (16.7)	30 (17.1)	.419
Child characteristics						
Low birth weight (<2500 g), n (%)	163 (24.6)	93 (27.0)	23 (29.9)	16 (24.2)	31 (17.7)	.083
Preterm birth, n (%)	180 (27.1)	91 (26.4)	32 (41.6)	24 (36.4)	33 (18.9)	<.001
Age at peak height velocity, y, mean ± SD	12.2 ± 0.8	12.3 ± 0.8	12.2 ± 0.9	12.3 ± 0.6	12.1 ± 0.9	.036
Girls						
n (%)	633	328 (51.8)	75 (11.9)	57 (9.0)	173 (27.3)	
Maternal characteristics						
Age, y, mean ± SD	28.4 ± 6.9	27.8 ± 7.0	29.1 ± 6.9	28.9 ± 7.1	29.1 ± 6.5	.161
Race, n (%)						.208
Black	411 (64.9)	204 (62.2)	54 (72.0)	34 (59.7)	119 (68.8)	
Non-Black	222 (35.1)	124 (37.8)	21 (28.0)	23 (40.3)	154 (31.2)	
Education level, n (%)						.506
High school or less	433 (68.4)	217 (66.2)	55 (73.3)	42 (73.)	118 (68.2)	
Some college or greater	200 (31.6)	111 (33.8)	20 (26.7)	15 (26.3)	55 (31.8)	
Marital status, n (%)						.254
Married	203 (32.1)	103 (31.4)	25 (33.3)	22 (38.6)	69 (39.9)	
Not married	430 (67.9)	225 (68.6)	50 (66.7)	35 (61.4)	104 (60.1)	
Prepregnancy BMI category, n (%)						<.001
Normal (BMI <25)	293 (46.3)	183 (55.8)	34 (45.3)	25 (43.9)	52 (30.1)	
Overweight or obese (BMI ≥25)	340 (53.7)	145 (44.2)	41 (54.7)	32 (56.1)	121 (69.9)	
Age at menarche, y, mean ± SD	12.9 ± 2.1	13.0 ± 2.1	12.9 ± 2.0	13.2 ± 2.0	12.7 ± 2.0	.366
Diabetes, n (%)	62 (9.8)	24 (7.3)	5 (6.7)	6 (10.5)	27 (15.6)	.021
Smoked during pregnancy, n (%)	107 (16.9)	56 (17.1)	18 (24.0)	12 (21.1)	23 (13.3)	.181
Child characteristics						
Low birth weight (<2500 g), n (%)	190 (30.0)	120 (36.6)	19 (25.3)	12 (21.1)	40 (23.1)	.004
Preterm birth, n (%)	174 (27.5)	100 (30.5)	16 (21.3)	16 (28.1)	42 (24.3)	.283
Age at peak height velocity, y, mean ± SD	10.2 ± 0.7	10.3 ± 0.7	10.0 ± 0.7	10.2 ± 0.7	10.1 ± 0.7	<.001

overweight or obesity at 5-7 years were more likely to be born to mothers with prepregnancy BMI ≥25 (65.7% among persistently overweight or obese and 59.7% among not overweight or obese to overweight or obese, compared with 47.8% among persistently not overweight or obese and 45.5% among overweight or obese to not overweight or obese, $P < .001$) and diabetes (21.1% and 11.0% vs 10.4% and 9.1%, respectively, $P = .006$). Boys who were persistently with overweight or obesity were least likely to be born preterm (18.9% compared with 26.4% among persistently not overweight or obese, 41.6% among not overweight or obese to overweight or obese, and 36.4% among overweight or obese to not overweight or obese groups, $P < .001$). Girls with persistent overweight or obesity were more likely to have mothers with prepregnancy BMI ≥25 (69.9 %, $P < .001$) and diabetes (15.6%, $P = .021$) compared with girls in other BMI trajectory groups.

As shown in Table III, obesity at 2-4 years was associated with significantly earlier APHV in boys (adjusted *B*, −0.19 year; 95% CI, −0.35 to −0.03) and girls (*B*, −0.22; 95% CI, −0.37 to –0.07) after adjusting for pertinent covariates. Overweight at 2-4 years was also associated with earlier APHV, but this was not statistically significant with either sex. Tests for linear trend showed an inverse relationship between BMI z-score at 2-4 years and APHV that was significant in girls ($P < .001$) but not in boys ($P = .161$) (Table III and Table IV [available at www.jpeds.com]).

Obesity at 5-7 years was associated with significantly earlier APHV in boys (adjusted *B*, −0.18 year; 95% CI, −0.32 to −0.03), and both overweight (*B*, −0.24 year; 95% CI, −0.40 to −0.08) and obesity (*B*, −0.27 year; 95% CI, −0.40 to −0.13) at 5-7 years were associated with significantly earlier APHV in girls. Tests for linear trend found an inverse relationship between APHV and BMI z scores at 5-7 years in both boys ($P = .041$) and girls ($P < .001$).

Figure 3 depicts how APHV varied with BMI trajectory, which was confirmed in regression models. Compared with boys who were persistently not overweight or obese from 2-4 years to 5-7 years, boys who were persistently overweight or obese had significantly earlier APHV (*B*, −0.21 year; 95% CI, −0.36 to −0.07). Girls, in contrast, had earlier APHV regardless of whether they were persistently overweight or obese (*B*, −0.23 year; 95% CI, −0.36 to −0.10), or had normal BMIs at 2-4 years and became overweight or obese at 5-7 years (*B*, −0.35 year; 95% CI, −0.52 to −0.18) (Table III).

Table III. Associations between APHV and BMI category at 2-4 years, BMI category at 5-7 years, and BMI trajectories from 2-4 years to 5-7 years (imputed data)

BMI category in ages 2-4 y		Male (N = 663)			Female (N = 633)		
Ages 2-4	**Ages 5-7**	**n**	**Crude**	**Adjusted**	**n**	**Crude**	**Adjusted**
<85th		422	Ref	Ref	403	Ref	Ref
85th-94th		115	−0.06 (−0.22, 0.11)	−0.07 (−0.23, 0.09)	116	−0.06 (−0.21, 0.08)	−0.07 (−0.21, 0.08)
≥95th		126	−0.19 (−0.35, −0.04)*	−0.19 (−0.35, −0.03)*	114	−0.22 (−0.37, −0.07)†	−0.22 (−0.37, −0.07)†
P for trend‡			.099	.161		<.001	<.001
<85th		422	Ref	Ref	403	Ref	Ref
≥85th		241	−0.13 (−0.25, 0.00)*	−0.13 (−0.26, −0.01)*	230	−0.13 (−0.24, −0.02)*	−0.13 (−0.25, −0.01)*
BMI category in ages 5-7 y							
Ages 2-4	**Ages 5-7**						
	<85th	411	Ref	Ref	385	Ref	Ref
	85th-94th	86	−0.12 (−0.31, 0.06)	−0.15 (−0.33, 0.03)	92	−0.24 (−0.40, −0.08)†	−0.24 (−0.40, −0.08)†
	≥95th	166	−0.19 (−0.33, −0.04)*	−0.18 (−0.32, −0.03)*	156	−0.28 (−0.41, −0.15)§	−0.27 (−0.40, −0.13)§
	P for trend‡		.034	.041		<.001	<.001
	<85th	411	Ref	Ref	385	Ref	Ref
	≥85th	252	−0.17 (−0.29, −0.04)†	−0.17 (−0.29, −0.04)†	248	−0.26 (−0.37, −0.15)§	−0.25 (−0.36, −0.14)§
BMI trajectories							
Ages 2-4	**Ages 5-7**						
<85th	<85th	345	Ref	Ref	328	Ref	Ref
<85th	≥85th	77	−0.07 (−0.26, 0.13)	−0.07 (−0.27, 0.12)	75	−0.36 (−0.54, −0.19)§	−0.35 (−0.52, −0.18)§
≥85th	<85th	66	0.02 (−0.18, 0.23)	0.01 (−0.20, 0.22)	57	−0.09 (−0.29, 0.10)	−0.11 (−0.31, 0.08)
≥85th	≥85th	175	−0.20 (−0.35, −0.06)†	−0.21 (−0.36, −0.07)†	173	−0.23 (−0.36, −0.10)§	−0.23 (−0.36, −0.10)§
P for interaction¶			.286	.338		.109	.091

Associations presented as β (95% CI). Adjusted βs are adjusted for maternal race/ethnicity, maternal education level, maternal marital status, smoking during pregnancy, maternal prepregnancy BMI category, maternal age at menarche, maternal diabetes, low birth weight status, and preterm birth status.

*$P < .05$.

†$P < .01$.

‡*P* values for trend are based on linear regression models using BMI z scores as a continuous variable.

§$P < .001$.

¶*P* values for interaction are based on models including an interaction term between BMI category at 2-4 years and BMI category at 5-7 years.

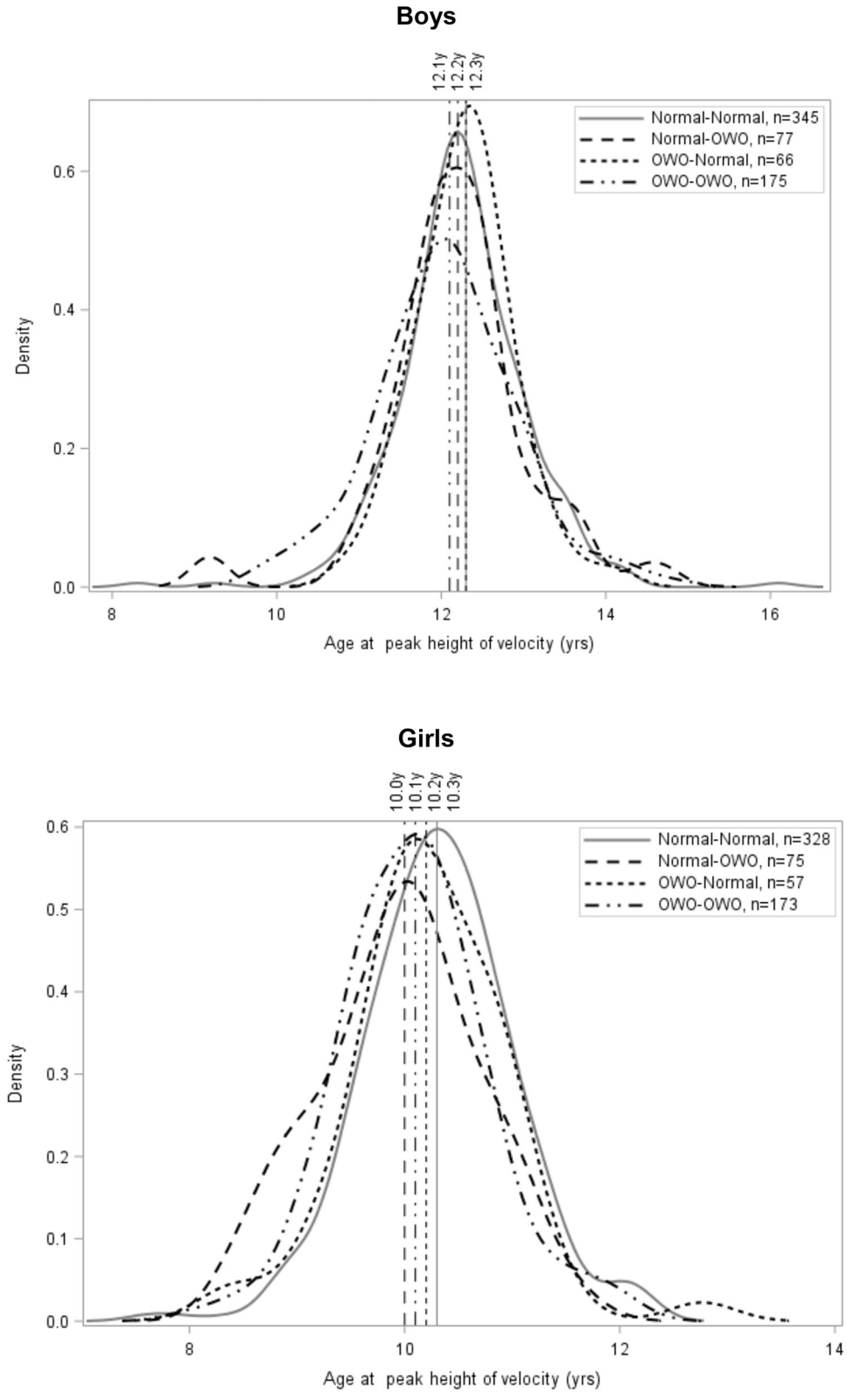
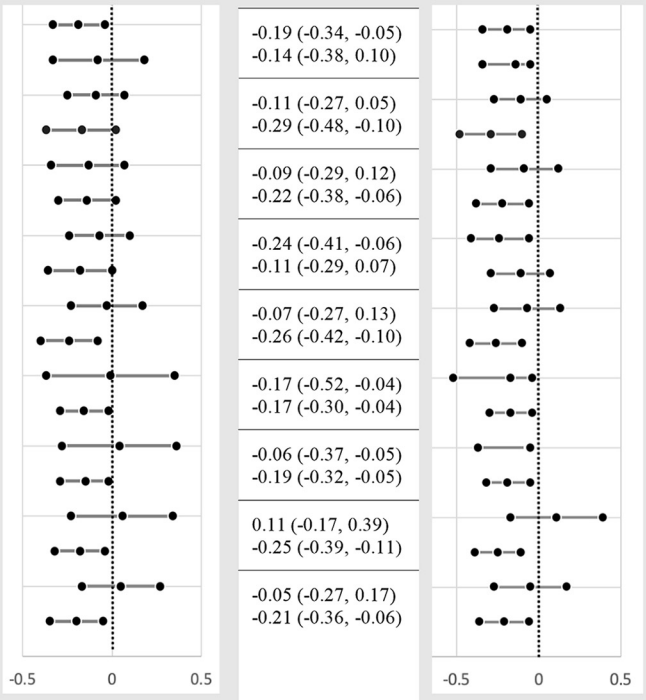


Figure 3. Distribution of APHV by BMI trajectory among boys and girls.

Boys

Category	Subgroup	N	OWO at 2-4y	OWO at 5-7y
Maternal Race	Black	442	-0.19 (-0.33, -0.04)	-0.19 (-0.34, -0.05)
	Non-Black	223	-0.08 (-0.33, 0.18)	-0.14 (-0.38, 0.10)
Maternal Education	HS or below	446	-0.09 (-0.25, 0.07)	-0.11 (-0.27, 0.05)
	College/above	219	-0.17 (-0.37, 0.02)	-0.29 (-0.48, -0.10)
Maternal Marital Status	Married	216	-0.13 (-0.34, 0.07)	-0.09 (-0.29, 0.12)
	Not married	439	-0.14 (-0.30, 0.02)	-0.22 (-0.38, -0.06)
Prepregnancy BMI Category	Normal (<25)	309	-0.07 (-0.24, 0.10)	-0.24 (-0.41, -0.06)
	OWO (≥25)	356	-0.18 (-0.36, 0.00)	-0.11 (-0.29, 0.07)
Maternal age at menarche	Below median	332	-0.03 (-0.23, 0.17)	-0.07 (-0.27, 0.13)
	Above median	331	-0.24 (-0.40, -0.08)	-0.26 (-0.42, -0.10)
Maternal Diabetes	Yes	89	-0.01 (-0.37, 0.35)	-0.17 (-0.52, -0.04)
	No	574	-0.16 (-0.29, -0.02)	-0.17 (-0.30, -0.04)
Smoked in pregnancy	Yes	118	0.04 (-0.28, 0.36)	-0.06 (-0.37, -0.05)
	No	545	-0.15 (-0.29, -0.02)	-0.19 (-0.32, -0.05)
Low birth weight	Yes	163	0.06 (-0.23, 0.34)	0.11 (-0.17, 0.39)
	No	500	-0.18 (-0.32, -0.04)	-0.25 (-0.39, -0.11)
Preterm birth	Yes	180	0.05 (-0.17, 0.27)	-0.05 (-0.27, 0.17)
	No	483	-0.20 (-0.35, -0.05)	-0.21 (-0.36, -0.06)



Girls

Category	Subgroup	N	OWO at 2-4y	OWO at 5-7y
Maternal Race	Black	411	-0.11 (-0.25, 0.03)	-0.26 (-0.40, -0.12)
	Non-Black	222	-0.18 (-0.38, 0.03)	-0.24 (-0.44, -0.04)
Maternal Education	HS or below	433	-0.11 (-0.25 0.04)	-0.22 (-0.36, -0.07)
	College/ above	200	-0.19 (-0.39, 0.00)	-0.34 (-0.53, -0.16)
Maternal Marital Status	Married	203	-0.18 (-0.38, 0.02)	-0.27 (-0.46, -0.07)
	Not married	430	-0.12 (-0.26, 0.02)	-0.25 (-0.39, -0.11)
Prepregnancy BMI Category	Normal (<25)	293	-0.21 (-0.39, -0.03)	-0.34 (-0.52, -0.17)
	OWO (≥25)	340	-0.08 (-0.23, 0.07)	-0.19 (-0.34, -0.04)
Maternal age at menarche	Below median	317	-0.14 (-0.31, 0.03)	-0.24 (-0.40, -0.07)
	Above median	316	-0.13 (-0.29, 0.03)	-0.25 (-0.40, -0.10)
Maternal Diabetes	Yes	62	-0.23 (-0.59, 0.13)	-0.13 (-0.49, 0.23)
	No	571	-0.12 (-0.24, 0.00)	-0.26 (-0.38, -0.14)
Smoked in pregnancy	Yes	107	-0.01 (-0.31, 0.30)	-0.03 (-0.40, -0.15)
	No	526	-0.16 (-0.28, -0.03)	-0.27 (-0.40, -0.15)
Low birth weight	Yes	190	-0.29 (-0.50, -0.07)	-0.25 (-0.46, -0.04)
	No	443	-0.08 (-0.22, 0.05)	-0.25 (-0.38, -0.12)
Preterm birth	Yes	174	-0.22 (-0.43, -0.01)	-0.20 (-0.41, 0.01)
	No	459	-0.10 (-0.24, 0.04)	-0.26 (-0.39, -0.12)

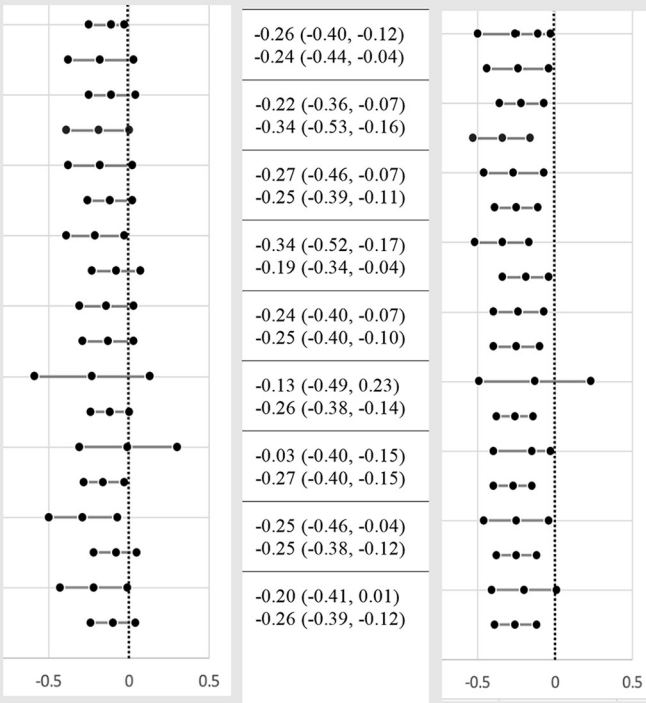


Figure 4. Subgroup analysis of associations between APHV and overweight or obesity at 2-4 years and 5-7 years. Associations are presented as βs (95% CI) and adjusted for all other covariates except for the stratified variable. *HS*, high school.

Sensitivity analysis of the associations between BMI categories and APHV, and between BMI trajectories and APHV, found similar results after removing children with only 1 height measurement (**Table V**; available at www.jpeds.com) and using the unimputed dataset (**Table VI**; available at www.jpeds.com). Overweight or obesity at 2-4 years and at 5-7 years were both associated with earlier APHV in boys and girls, persistent overweight or obesity was associated with earlier APHV in boys, and girls who were overweight or obese at 5-7 years had earlier APHV regardless of BMI at 2-4 years.

Subgroup analyses revealed negative point estimates across most strata, indicating an inverse relationship between overweight or obesity during the 2 periods and APHV (**Figure 4**). The only positive point estimates were for boys born with low birth weight, born preterm, or born to mothers who smoked during pregnancy, and none of these relationships were statistically significant. Interestingly, the associations between overweight or obesity and APHV were more often statistically significant among children with mothers without diabetes (compared with children with mothers with diabetes), Black children (compared with non-Black children), children whose mothers did not have overweight or obesity (compared with children whose mothers had overweight or obesity), and children who were not born preterm (compared with children who were born preterm).

Discussion

This prospective birth cohort study of predominantly Black mothers and children found significant associations between overweight and obesity at 2-4 years and 5-7 years with earlier APHV in both boys and girls. These associations persisted after we controlled for a variety of potential confounders and across strata of pertinent covariates. A dose–response relationship was observed, with greater BMI z-scores associated with earlier APHV. Importantly, associations between APHV and BMI trajectories from 2-4 years to 5-7 years revealed that children with a normal BMI at 5-7 years, regardless of their BMI at 2-4 years, did not experience earlier APHV. The inverse was also true among girls with overweight or obesity at 5-7 years who experienced earlier APHV regardless of their BMI at 2-4 years. This suggests that the period of time immediately before puberty may be most important in triggering early puberty, and that "removing" this obesity exposure period has potential to halt the trend toward earlier puberty. This points to the possibility that interventions promoting a normal weight early in and across childhood may alter a child's pubertal development and subsequent health outcomes.

Although previous studies have investigated these relationships, this study is unique in that we controlled for multiple confounders and due to the prospective, longitudinal design of the cohort, we were able to establish temporality. This study revealed a dose–response relationship by demonstrating the specificity of the exposure–effect relationship in that children in the overweight or obese to not overweight or obese group, who had the obesity exposure "removed," did not experience early APHV unlike their peers who became or remained overweight or obese.

In addition, this study focuses on a predominantly Black, low-income, and urban prospective cohort in the US that includes both boys and girls. Studying the factors that contribute to earlier APHV in this population—which can inform interventions—is important from an equity and policy perspective because children who are racialized as Black, on average, experience more accelerated pubertal development compared with children who are racialized as White. Further, children racialized as Black bear a disproportionate burden of obesity- and cardiometabolic-related health risks and adverse outcomes, which may have lifelong and even multigenerational impacts. Although the mechanisms underlying these observed differences are not fully understood, research suggests various impacts of structural racism including early life adversity such as stress and material hardship, compromise in the intrauterine environment manifesting as a smaller birth size, rapid growth during infancy, and a lack of access to nutritious foods and spaces for physical activity.[55-57]

Moving away from the social construct of race and the repercussions of this construct, the biological mechanisms linking childhood obesity to early APHV implicate multiple factors that work together to activate the hypothalamic–pituitary–gonadal axis. Notably, leptin, a hormone secreted by adipose tissue, may play a permissive role in pubertal development due to its ability to activate gonadotropin-releasing hormone pulsatility, trigger luteinizing hormone and follicle-stimulating hormone release from the anterior pituitary, and stimulate enzymes needed to synthesize adrenal androgens.[67,68] Adipose tissue also produces aromatase, which converts androgens to estrogen and promotes puberty in girls (its role in boys remains uncertain). In addition, early weight gain is associated with insulin resistance, which is in turn associated with increased adrenal androgen secretion and compensatory increase in insulin, which results in reduced levels of sex hormone binding globulin, increasing free-sex steroid levels to exert biological effects.[69,70]

Another mechanism linking childhood obesity to early APHV is found in the early life origins of disease hypothesis, which postulates that common exposures in utero and during early childhood influence development and health outcomes. As such, the same exposures can promote both childhood obesity and early puberty. One example is smoking during pregnancy, which is associated with an increased risk of childhood obesity[71] as well as with early puberty. The early life origins hypothesis suggests that an interaction between maternal metabolic genes and smoking occurs to contribute to childhood obesity, and that in utero exposure to this endocrine disrupter may alter hormone functioning to trigger earlier pubertal development.[72] Another possibility is that epigenetic mechanisms may act to simultaneously increase the risks of childhood obesity and of early APHV.

The prospective and longitudinal nature of this study facilitated the study of specific developmental windows and BMI trajectories. The availability of demographic, clinical, and behavioral data allowed us to draw on more comprehensive models such as the life course model to explain how health disparities may originate from compounding and cumulative effects of exposures during critical stages of development. Because of the richness of the dataset, we were able to control for many confounders and move closer to conditional exchangeability between the exposure groups. Finally, we used a measure of puberty that is standardized, objective, and well-supported by previous studies.

One limitation of this study is that BMI does not differentiate between lean mass and fat mass and may have lower sensitivity than specificity in detecting excess adiposity.[73] Another limitation is that many other confounders were not included, such as nutrition, endocrine disrupting chemicals, genetic variants, and epigenetic changes. The influences of these factors on the obesity-puberty associations remain to be examined.

Our results have potential implications for preventive health efforts targeting critical developmental stages, and for addressing health inequities by focusing on racial minority populations that face the impacts of structural disadvantage and are often underrepresented in policy and research. ■

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Data Statement

Data sharing statement available at www.jpeds.com.

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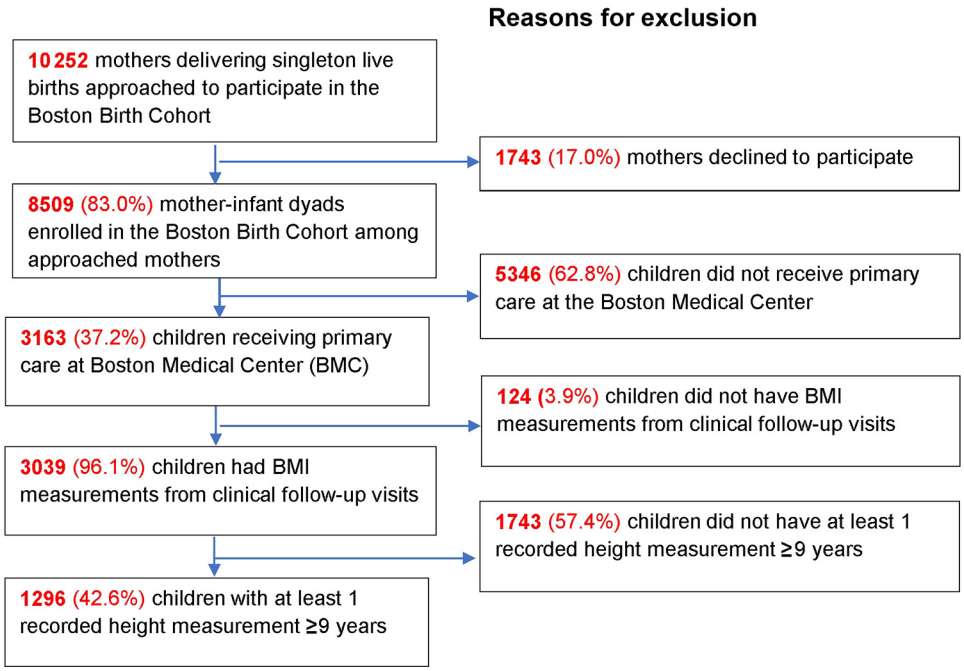

Figure 1. Flowchart of study inclusion and exclusion. Percentages are calculated using the number in the immediately previous step as the "total".

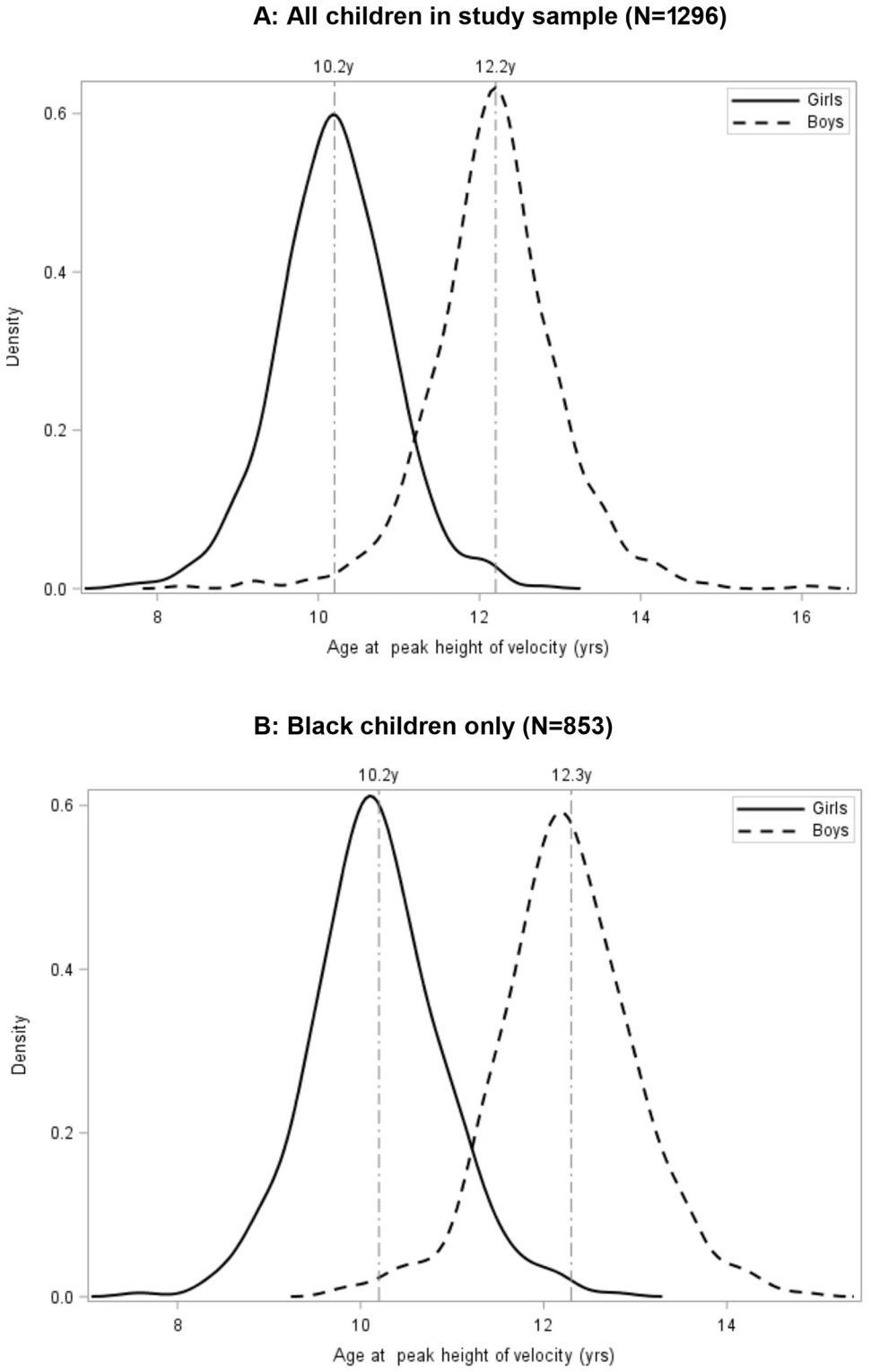

Figure 2. Distribution of APHV by sex. **A,** All children in study sample (N = 1296); and **B,** Black children only (N = 853).

Table I. Comparison of characteristics between total BBC sample and sample included in this study (unimputed data)

Variables	Total BBC sample	Included in this study	*P* value
Boys			
n	4237	663	
Maternal characteristics			
Age, y, mean ± SD	28.2 ± 6.4	28.7 ± 6.7	.072
Race, n (%)			<.001
Black	1997 (47.1)	441 (66.5)	
Non-Black	2240 (52.9)	222 (33.5)	
Education level, n (%)*			.135
High school or less	2680 (64.2)	441 (67.2)	
Some college or greater	1493 (35.8)	215 (32.8)	
Marital status, n (%)†			.253
Married	1609 (38.8)	239 (36.4)	
Not married	2541 (61.2)	417 (63.4)	
Prepregnancy BMI, kg/m^2, mean ± SD‡	26.0 ± 6.2	26.6 ± 6.3	.013
Prepregnancy overweight or obesity, n (%)‡	1876 (47.5)	337 (53.5)	.005
Age at menarche, y, mean ± SD§	12.9 ± 1.9	13.0 ± 2.1	.136
Diabetes, n (%)¶	456 (10.8)	89 (13.4)	.044
Smoked during pregnancy, n (%)**	780 (18.6)	116 (17.6)	.568
Child characteristics			
Birth weight, g, mean ± SD††	3028 ± 771	2992 ± 818	.291
Low birth weight, n (%)††	1002 (23.7)	163 (24.6)	.601
Preterm birth, n (%)	1173 (27.7)	180 (27.2)	.774
Gestational age, wk, mean ± SD	37.9 ± 3.1	37.8 ± 3.4	.227
Girls			
n	4272	633	
Maternal characteristics			
Age, y, mean ± SD	28.2 ± 6.5	28.4 ± 6.9	.376
Race, n (%)			<.001
Black	2034 (47.6)	411 (64.9)	
Non-Black	2238 (52.4)	222 (35.1)	
Education level, n (%)‡‡			.213
High school or less	2743 (65.7)	425 (68.2)	
Some college or greater	1433 (34.3)	198 (31.8)	
Marital status, n (%)§§			.390
Married	1511 (36.1)	214 (34.3)	
Not married	2679 (63.9)	410 (65.7)	
Prepregnancy BMI, kg/m^2, mean ± SD¶¶	26.0 ± 6.2	26.6 ± 6.3	.013
Overweight or obesity, n (%)¶¶	1887 (47.4)	325 (54.2)	.002
Age at menarche, y, mean ± SD***	12.9 ± 1.9	12.9 ± 2.1	.602
Diabetes, n (%)†††	427 (10.0)	62 (9.8)	.868
Smoked during pregnancy, n (%)‡‡‡	856 (20.2)	106 (17.0)	.060
Child characteristics			
Birth weight, g, mean ± SD	2887 ± 762	2836 ± 795	.120
Low birth weight, n (%)	1219 (28.5)	191 (30.2)	.395
Preterm birth, n (%)	1143 (26.8)	174 (27.5)	.698
Gestational age, wk, mean ± SD	37.9 ± 3.2	37.7 ± 3.5	.101

Data on baseline characteristics was complete with the exception of following variables labeled with footnotes.
*Maternal education level: N = 4173 (missing 64) for total sample, N = 656 (missing 7) for included sample.
†Maternal marital status: N = 4150 (missing 87) for total sample, N = 656 (missing 7) for included sample.
‡Pre-pregnancy BMI and overweight or obesity: N = 3947 (missing 290) for total sample, N = 630 (missing 33) for included sample.
§Age at menarche: N = 3335 (missing 902) for total sample, N = 647 (missing 16) for included sample.
¶Maternal diabetes: N = 4233 (missing 4) for total sample, N = 663 (missing 0) for included sample.
**Smoked during pregnancy: N = 4203 (missing 34) for total sample, N = 658 (missing 5) for included sample.
††Birth weight and low birth weight: N = 4236 (missing 1) for total sample, N = 663 (missing 0) for included sample.
‡‡Maternal education level: N = 4263 (missing 96) for total sample, N = 623 (missing 10) for included sample.
§§Maternal marital status: N = 4190 (missing 82) for total sample, N = 654 (missing 9) for included sample.
¶¶Prepregnancy BMI and overweight or obesity: N = 3983 (missing 289) for total sample, N = 600 (missing 33) for included sample.
***Age at menarche: N = 3412 (missing 860) for total sample, N = 617 (missing 16) for included sample.
†††Maternal diabetes: N = 4267 (missing 5) for total sample, N = 633 (missing 0) for included sample.
‡‡‡Smoked during pregnancy: N = 4238 (missing 34) for total sample, N = 624 (missing 9) for included sample.

Table IV. Associations between BMI z scores at ages 2-4 years and 5-7 years and APHV (imputed data)

	Crude				Adjusted			
	β	se	*P* value	R^2	β	se	*P* value	Partial R^2
Boys								
2-4 y	−0.04	0.02	.099	0.003	−0.03	0.02	.161	0.002
5-7 y	−0.05	0.02	.034	0.005	−0.05	0.03	.041	0.005
Girls								
2-4 y	−0.08	0.02	<.001	0.02	−0.09	0.03	<.001	0.021
5-7 y	−0.12	0.02	<.001	0.04	−0.12	0.02	<.001	0.039

Adjusted βs are adjusted for maternal race/ethnicity, maternal education level, maternal marital status, smoking during pregnancy, maternal prepregnancy BMI category, maternal age at menarche, maternal diabetes, low birth weight status, and preterm birth status.

Table V. Associations between APHV and BMI category at 2-4 years, BMI category at 5-7 years, and BMI trajectories from 2-4 years to 5-7 years after removing children with only 1 BMI measurement (n = 1258) (imputed data)

BMI percentiles		Male (N = 637)		Female (N = 621)	
Ages 2-4 y	Ages 5-7 y	Crude	Adjusted	Crude	Adjusted
<85th		Ref	Ref	Ref	Ref
85th-94th		−0.06 (−0.23, 0.11)	−0.07 (−0.24, 0.09)	−0.06 (−0.21, 0.09)	−0.07 (−0.21, 0.08)
≥95th		−0.20 (−0.36, −0.04)*	−0.20 (−0.36, −0.03)*	−0.22 (−0.37, −0.07)†	−0.22 (−0.37, −0.07)†
	P for trend‡	.077	.134	<.001	<.001
<85th		Ref	Ref	Ref	Ref
≥85th		−0.13 (−0.26, 0.00)*	−0.14 (−0.27, −0.01)*	−0.13 (−0.25, −0.01)*	−0.13 (−0.25, −0.01)*
Ages 2-4 y	**Ages 5-7 y**				
	<85th	Ref	Ref	Ref	Ref
	85th-94th	−0.13 (−0.32, 0.05)	−0.16 (−0.34, 0.03)	−0.25 (−0.41, −0.08)†	−0.24 (−0.40, −0.08)†
	≥95th	−0.20 (−0.34, −0.05)†	−0.19 (−0.34, −0.04)*	−0.28 (−0.41, −0.15)§	−0.27 (−0.40, −0.14)§
P for trend‡		.028	.034	<.001	<.001
	<85th	Ref	Ref	Ref	Ref
	≥85th	−0.18 (−0.30, −0.05)†	−0.18 (−0.31, −0.05)†	−0.26 (−0.38, −0.15)§	−0.25 (−0.37, −0.14)§
BMI trajectories					
Ages 2-4 y	**Ages 5-7 y**				
<85th	<85th	Ref	Ref	Ref	Ref
<85th	≥85th	−0.07 (−0.27, 0.13)	−0.08 (−0.28, 0.12)	−0.37 (−0.54, −-0.19)§	−0.35 (−0.53, −0.18)§
≥85th	<85th	0.04 (−0.18, 0.25)	0.02 (−0.19, 0.24)	−0.08 (−0.28, 0.12)	−0.10 (−0.31, 0.10)
≥85th	≥85th	−0.21 (−0.36, −0.07)†	−0.22 (−0.37, −0.07)†	−0.24 (−0.37, −0.11)§	−0.23 (−0.36, −0.10)§
P for interaction¶		.286	.338	.109	.091

Associations presented as β (95% CI). Adjusted βs are adjusted for maternal race/ethnicity, maternal education level, maternal marital status, smoking during pregnancy, maternal prepregnancy BMI category, maternal age at menarche, maternal diabetes, low birth weight status, and preterm birth status.

*$P < .05$.

†$P < .01$.

‡*P* values for trend are based on linear regression models using BMI z scores as a continuous variable.

§$P < .001$.

¶*P* values for interaction are based on models including an interaction term between BMI category at 2-4 years and BMI category at 5-7 years.

Table VI. Sensitivity analysis of associations between BMI categories and APHV and BMI trajectories and APHV (unimputed data)

BMI percentiles		Crude	Adjusted	Crude	Adjusted
Ages 2-4	**Ages 5-7**	**Male (N = 558)**		**Female (N = 545)**	
<85th		Ref	Ref	Ref	Ref
85th-94th		−0.06 (−0.24, 0.12)	−0.07 (−0.27, 0.12)	−0.06 (−0.22, 0.10)	−0.04 (−0.21, 0.13)
≥95th		−0.22 (−0.39, −0.05)*	−0.22 (−0.39, −0.04)*	−0.22 (−0.37, −0.06)†	−0.21 (−0.38, −0.04)*
	P for trend‡	.075	.114	<.001	<.001
<85th		Ref	Ref	Ref	Ref
≥85th		−0.15 (−0.29, −0.01)*	−0.15 (−0.30, −0.01)*	−0.14 (−0.27, −0.02)*	−0.12 (−0.26, 0.01)
Ages 2-4	**Ages 5-7**	**Male (N = 559)**		**Female (N = 548)**	
	<85th	Ref	Ref	Ref	Ref
	85th-94th	−0.17 (−0.36, 0.02)	−0.23 (−0.43, −0.03)*	−0.28 (−0.45, −0.12)†	−0.30 (−0.48, −0.12)†
	≥95th	−0.23 (−0.38, −0.08)†	−0.22 (−0.38, −0.06)†	−0.32 (−0.46, −0.18)§	−0.32 (−0.47, −0.17)§
P for trend‡		.018	.046	<.001	<.001
	<85th	Ref	Ref	Ref	Ref
	≥85th	−0.21 (−0.34, −0.07)†	−0.22 (−0.36, −0.08)†	−0.31 (−0.43, −0.19)§	−0.31 (−0.44, −0.18)§
BMI trajectories					
Ages 2-4	**Ages 5-7**	**Male (N = 520)**		**Female (N = 514)**	
<85th	<85th	Ref	Ref	Ref	Ref
<85th	≥85th	−0.09 (−0.34, 0.15)	−0.15 (−0.40, 0.10)	−0.41 (−0.61, −0.22)§	−0.45 (−0.66, −0.24)§
≥85th	<85th	0.05 (−0.23, 0.34)	0.03 (−0.26, 0.32)	−0.12 (−0.37, 0.12)	−0.17 (−0.42, 0.08)
≥85th	≥85th	−0.23 (−0.39, −0.07)†	−0.23 (−0.40, −0.07)†	−0.29 (−0.43, −0.16)§	−0.29 (−0.45, −0.14)§
P for interaction¶		.329	.571	.134	.056

Associations presented as β (95% CI). Adjusted βs are adjusted for maternal race/ethnicity, maternal education level, maternal marital status, smoking during pregnancy, maternal pre-pregnancy BMI category, maternal age at menarche, maternal diabetes, low birth weight status, and preterm birth status.

*$P < .05$.

†$P < .01$.

‡*P* values for trend are based on linear regression models using BMI z scores as a continuous variable.

§$P < .001$.

¶*P* values for interaction are based on models including an interaction term between BMI category at 2-4 years and BMI category at 5-7 years.