



## ORIGINAL REPORT

## Trajectory of Systolic Blood Pressure in Children and Adolescents

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**PURPOSE:** Rapid height and weight changes during childhood contribute markedly to blood-pressure change during children's physical growth. This article evaluates the differences in systolic blood pressure (SBP) growth or changes between four gender-ethnic groups: African American males (AM), Caucasian males (CM), African American females (AF), and Caucasian females (CF).

**METHODS:** Subjects 6–9 years old at entry ( $n = 1302$ ) were followed for 12 years. The repeated-measure data of SBP were analyzed using the Gompertz growth model with random coefficients.

**RESULTS:** Mean SBP (mmHg) at age 6 years was lowest in African American girls ( $82.23 \pm 0.76$ ) and highest in Caucasian boys ( $102.83 \pm 0.5$ ). And for both ethnic groups, girls had lower levels at which SBP growth stopped. The peak growth ages (years) also differed by group:  $9.30 \pm 0.73$ ,  $9.91 \pm 0.28$ ,  $10.00 \pm 0.82$ , and  $10.60 \pm 0.22$  for African American girls, African American boys, Caucasian girls and Caucasian boys, respectively.

**CONCLUSION:** SBP growth differed among gender-ethnic groups with respect to mean SBP level at age 6, the level at which SBP growth stops and the mean age at which SBP growth rate was at its peak. *Ann Epidemiol* ■;■:■. © 2005 Elsevier Inc. All rights reserved.

**KEY WORDS:** Blood Pressure, Trajectory, Growth Curves, Children, Adolescents.

## INTRODUCTION

Blood pressure (BP) is an essential measure of the adequacy of circulation. It is continuously distributed in populations, and high levels contribute to the risks of many chronic diseases. Although the prevalence of high BP in the United States increases with age, this is not so for other populations, and therefore it is not a necessary concomitant of aging. Before adulthood, BP increase with age is viewed as a part of natural growth (1–5). From infancy throughout adolescence, rapid height and weight changes occur, and the rate of change contributes markedly to BP change during this period. Thus, BP levels in childhood and adolescence need to take account of the relative rank of the individual in growth and development (3, 5–9). In this article, the “growth” of BP refers to the changes in BP over time, and BP “growth curve” refers to its developmental trajectory.

Longitudinal studies of BP are scant in U.S. children. To our knowledge, longitudinal assessment of BP in the form of growth modeling in African American and Caucasian children has not been reported. This article describes the growth and growth velocity of systolic blood pressure (SBP) in four gender-ethnic groups of children: African American males (AM), Caucasian males (CM), African American females (AF), and Caucasian females (CF).

We focus on differential growth characteristics between the four groups with respect to starting SBP (mmHg) level, asymptote SBP (mmHg) level, and peak growth age (years) of SBP. Here, the starting level (SL) is the mean level of SBP at 6 years of age; asymptote level (AL) is the level at which SBP growth stops; and peak growth age (PGA) is the age at which SBP growth rate is the highest. These parameters are also illustrated.

## METHODS

## Study Design

The Minneapolis Children's Blood Pressure Study (MCBPS) is a community-based cohort study that began in 1978, and it is still ongoing. Data collected between 1978 and 1990 are utilized in the present analysis. Initially, over 99% of children in grades one through three enrolled in the Minneapolis Public School System gave their assent to participate in the study. Based on the SBP distribution and age, 1799 children

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## Selected Abbreviations and Acronyms

AF = African American females
AL = Asymptotic SBP level
AM = African American males
ANOVA = analysis of variance
BMI = body mass index
BP = blood pressure
CF = Caucasian female
CM = Caucasian male
ETHY = ethnicity
GEN = gender
MCBPS = Minneapolis children's blood pressure study
NLME = nonlinear mixed effects
NS = not significant
PGA = peak growth age
RZ = random zero
SBP = systolic blood pressure
SE = standard error
SES = socioeconomic status
SL = starting SBP level

were selected for longitudinal study. Only one child per family was eligible to participate. The detailed methodology of the MCBPS is described elsewhere (10, 11, 12).

## Sample Selection

Of the available sample participants ( $n = 1799$ ), 1540 children were either African American or Caucasian. Subjects who completed at least 5 timed measurements ( $n = 1302$ ) were included. The numbers of subjects were 247 AM, 443 CM, 220 AF, and 392 CF. There were no differences between those who completed  $\geq 5$  visits ( $n = 1302$ ) or  $< 5$  visits ( $n = 238$ ) except gender. Male

to female ratios were 110:128 and 690:612 in  $< 5$  and  $\geq 5$  visit groups respectively.

## Data Collection

A repeated measure data set included baseline measurements (1978) and semiannual and annual follow-up screenings from 1978 to 1990. Nineteen timed measurements were taken in 12 years (1978–1990). The subjects were 6–9 years old initially. Measurements including weight, height, and SBP were collected at 19 timed points. Demographic and other variables were obtained via questionnaires from the parents/guardians. Number and average age of subjects at each timed visit (12) are summarized in Table 1. There were no differences in the mean number of visits and average age at each visit between the four groups (12).

## Measurement and Quality Control

Multiple examination procedures were performed as part of the MCBPS protocol during the participants' visits. A random-zero (RZ) sphygmomanometer was used for measurements. The cuff bladder sizes were chosen to be wide enough to cover at least 120% of the diameter of the upper arm, and long enough to encircle over 90% of the upper arm. For the first nine screenings, supine BP was measured in the right arm with cuff size adjusted to arm circumference on all participants. For screenings 10 through 19, seated BP was measured in the same manner as the supine BP. The average of two successive readings of BP was recorded (10, 11). Strict quality control procedures were taken to reduce measurement errors (10, 11).

TABLE 1. Average age in years & [numbers] of subjects by visit and gender-ethnic groups

#	Time	All N = 1302	AM n = 247	CM n = 443	AF n = 220	CF n = 392
1	Spring 78	7.72[1302]	7.69[247]	7.72[443]	7.69[220]	7.76[392]
2	Fall 78	8.45[1039]	8.40[167]	8.45[385]	8.45[154]	8.47[333]
3	Spring 79	8.74[1173]	8.69[216]	8.74[411]	8.72[191]	8.77[355]
4	Fall 79	9.46[1207]	9.43[225]	9.47[416]	9.43[199]	9.48[367]
5	Spring 80	9.78[1242]	9.76[236]	9.78[419]	9.75[206]	9.81[381]
6	Fall 80	10.45[1202]	10.42[227]	10.46[407]	10.45[201]	10.47[367]
7	Spring 82	11.72[1082]	11.69[195]	11.73[382]	11.74[173]	11.72[332]
8	Fall 82	12.45[1040]	12.43[190]	12.45[365]	12.45[164]	12.46[321]
9	Spring 83	12.71[1033]	12.70[190]	12.71[362]	12.73[163]	12.71[318]
10	Fall 83	13.40[1013]	13.38[185]	13.41[363]	13.41[163]	13.40[302]
11	Spring 84	13.71[1012]	13.69[180]	13.71[362]	13.71[165]	13.71[305]
12	Fall 84	14.44[968]	14.43[177]	14.44[353]	14.44[154]	14.44[284]
13	Spring 85	14.70[981]	14.69[173]	14.70[353]	14.70[162]	14.70[293]
14	Fall 85	15.41[894]	15.40[157]	15.41[332]	15.40[142]	15.40[263]
15	Spring 86	15.70[930]	15.69[162]	15.70[343]	15.75[151]	15.68[274]
16	Spring 87	16.66[835]	16.61[137]	16.67[313]	16.68[129]	16.67[256]
17	Spring 88	17.47[626]	17.45[105]	17.51[242]	17.46[93]	17.44[186]
18	Spring 89	18.03[296]	18.13[53]	18.02[119]	17.99[42]	17.99[82]
19	Post High School	18.30[729]	18.35[118]	18.27[270]	18.24[117]	18.32[224]

AM = African American males; CM = Caucasian males;  
AF = African American females; CF = Caucasian females.

### Statistical Analyses

The Non-Linear Mixed Effects (NLME) (13) model was selected to describe the SBP growth trajectory at both population and individual levels for the following reasons:

1. Growth of SBP varied widely among children. Exploratory analyses revealed several non-linear patterns of BP growth, both between and within gender-ethnic groups and also between individuals with the same pattern. Thus, it was necessary to capture both individual and population average growth trajectories.
2. As in any longitudinal study, there were varying numbers of visits due to missed appointments among participants.
3. Also, the repeated measurements within the same individual were likely to be correlated (13, 14).

Statistically, we model the growth trajectory by assuming that an SBP measurement of the  $i^{\text{th}}$  individual at a given age is:

$$\text{SBP} = f(\text{age}, \text{covariates}, \text{coefficients}, \phi_i) + \varepsilon$$

where  $f$  is a mathematical function which incorporates the covariates gender, ethnicity, and change in body mass index (BMI) over time. Coefficients are the model parameters to be estimated,  $\phi_i$  is the random coefficients for the  $i^{\text{th}}$  individual, and  $\varepsilon$  is random error. The random coefficient  $\phi_i$  is used to capture deviation of the individual from the group average, allowing finer description of the individual growth trajectory.

We chose Gompertz non-linear function (15) as it has been used to describe SBP growth among other populations (16). Exploratory analyses revealed that various individual growth patterns observed in our data can be captured by a Gompertz growth function as well. The double-exponential Gompertz function (15) with four parameters,

$$f(\text{age}) = A + \exp(B)\exp(-\exp(C + D(\text{age} - 6)))$$

is used to describe the SBP growth in our analyses. All four parameters (A,B,C,D) have multifunctionality in determining the SBP growth trajectory. The values of the coefficients A, B, C, and D may vary with the covariates gender, ethnicity, and BMI status. In our final model,

$$A = a_0 + a_1 \text{ GEN} + a_2 \text{ ETHY} + a_3 \text{ BMI} + \alpha_i$$

$$B = b_0 + b_1 \text{ GEN} + b_2 \text{ ETHY} + \beta_i$$

$$C = c_0 + c_1 \text{ GEN} + c_2 \text{ ETHY} + \gamma_i$$

$$D = d_0$$

where  $\alpha_i$ ,  $\beta_i$ , and  $\gamma_i$  are the random coefficients quantifying interindividual variations. The equations for A, B, and C

represent how the covariates gender (GEN), ethnicity (ETHY), and BMI affect SBP growth by determining varying SBP growth levels among different gender-ethnic groups. Detailed model building and assessment were described elsewhere (17). Briefly, model building comprises three main steps: (1.) find an appropriate growth function that can capture the varying growth patterns observed in data. (2.) decide which population parameters need adjustment with random components, and (3.) determine what covariates affect which fixed-effect model parameters. Empirical methods were first used to determine the needs of random effects. The initial model included the maximum number of random components with which convergence was achieved in model fitting. Correlation among random components and residuals were checked to eliminate excessive random components when for example the correlation is extremely high. Likelihood ratio tests were formally conducted to assess the significance of a random component (18). Significance of covariates (e.g., gender and ethnicity) on model parameters was determined through likelihood ratio tests as well as the Akaike Information Criterion (AIC). Insignificant covariates were removed from the model. The near singular condition of the estimated covariance matrix of the model parameters can also indicate an overuse of the parameters. Finally, residuals were plotted for model diagnostics. Table 2 depicts the final model estimates.

BMI did not affect parameters other than A, hence BMI was excluded in B, C, and D. Covariates were not added to the parameter D because gender or ethnic differences in the curvature of the growth appear to be minimal and are of secondary importance compared with differences in the starting and asymptotic level of SBP. Upon fitting a SBP growth model, we estimated the starting SBP level (SL) and the asymptotic SBP level (AL), as well as the peak growth age (PGA). PGA is obtained as the point at which the second derivative of the Gompertz function with respect to age equals zero.

$$\text{SL (age = 6): } f(6) = [A + \exp(B)(\exp(-\exp(C)))]$$

$$\text{AL (age } \sim \infty): f(\infty) = [A + \exp(B)]$$

$$\text{PGA : } f''(\text{age}) = \exp(B - \exp(C + D(\text{age} - 6))) \cdot \exp(C + D(\text{age} - 6)) \cdot \exp(D^2 \cdot \text{age} \cdot (\exp(C + D(\text{age} - 6)) - 1)) = 0$$

Confidence limits for SL, AL and PGA were calculated using the “delta” or linear approximation method. Approximate 95% confidence limits based on normal approximation were then constructed to assess the significance differences between gender-ethnic groups.

**TABLE 2.** Final Model: SBP Growth as a function of age adjusting for BMI

Fixed effects	Fixed effects estimates	Standard error	Z ratio
A	102.82	0.66	155.17
A~GEN*	-17.97	5.76	-3.12
A~ETHY**	-3.47	0.85	-4.05
A~BMI	0.18	0.03	6.25
B	2.21	0.06	34.38
B~GEN*	0.81	0.26	3.14
B~ETHY**	0.21	0.06	3.46
C	1.98	0.21	9.53
C~GEN*	-0.26	0.32	-7.89
C~ETHY**	-0.30	0.13	-2.38
D	-0.43	0.04	-12.17

All fixed effects are statistically significant at 0.05 level.

A, B, C, D = Gompertz parameters [see text].

\*GEN coded as 0 = males & 1 = females.

\*\*ETHY coded as 0 = Caucasians & 1 = African Americans.

## RESULTS

There were no group differences in mean ages (Table 1) at all screenings (12). The results of the SBP growth model are summarized in Table 3. The starting SBP levels were significantly different among boys and girls as well as African Americans and Caucasians. At age 6, African American females ( $82.23 \pm 0.76$  mmHg) started at the lowest SBP level, followed by Caucasian females ( $84.93 \pm 0.75$  mmHg), African American males ( $99.40 \pm 0.76$  mmHg) and Caucasian males ( $102.83 \pm 0.50$  mmHg). The asymptotic level, the level at which SBP growth stopped, was significantly different between genders but not between two ethnic groups of males. Although African American females started at a slightly lower level than Caucasian females, and reached a slightly higher asymptote level ( $107.11 \pm 0.53$  mmHg) than Caucasian females ( $105.34 \pm 0.41$  mmHg) (Fig. 1), these differences were only marginally significant. Interestingly, females had lower starting and asymptote levels of SBP compared to males. Caucasian males exhibited both the highest starting and asymptote levels among all four groups. Figure 1 displays the

differential growth trajectories for the four gender-ethnic groups.

Figure 2 shows the growth velocity for the gender-ethnic groups. PGA corresponds to the age at which the rate reaches its peak. It was observed that African American subjects reached their PGA earlier than their Caucasian counterparts. African American females ( $9.3 \pm 0.73$  years) reached their peak earliest among all four gender-ethnic groups, followed by African American males ( $9.91 \pm 0.28$ ), Caucasian females ( $10.00 \pm 0.82$ ) and Caucasian males ( $10.60 \pm 0.22$ ), respectively. However, only the difference between African American and Caucasian males was significant. PGA generally varied more among females than among males.

In summary, although African Americans started at a slightly lower SBP than Caucasians, their asymptotic levels were comparable (or even higher in females) than those of Caucasians. The PGA was also earlier in African Americans than in Caucasians. Within ethnic groups, females had lower SBP at baseline and asymptotically, and also experienced their peak growth at an earlier age (as expected). Growth velocities were higher in females than in males; within gender groups, they were also higher in African Americans than in Caucasians.

## DISCUSSION

To our knowledge, this is the first study to describe SBP growth using growth modeling in African American and Caucasian children in the United States. Previous studies (19–27) often described tracking (tendency for a subject to maintain over time the same rank of distribution) of SBP rather than the developmental trajectory of SBP. Due to analytical differences, direct comparison to these studies cannot be made.

In contrast to reports in the literature that the racial difference of BP level under age 12 was not significant (5, 28), our study showed a significant difference between African Americans and Caucasians in starting SBP level

**TABLE 3.** Estimates of SBP growth, standard errors (S.E.) & 95% confidence limits (C.L.) —Minneapolis Children's Blood Pressure Study (MCBPS)

Group	N	Starting Level (mmHg)			Asymptote Level (mmHg)			Peak Growth Age (years)		
		Level	S.E.	C.L.	Level	S.E.	C.L.	Level	S.E.	C.L.
AM	247	99.40	0.76	97.91–100.89	110.60	0.54	109.54–111.66	9.91	0.28	9.36–10.46
CM	443	102.83	0.50	101.85–103.81	111.15	0.44	110.29–112.01	10.60	0.22	10.17–11.03
AF	220	82.23	0.76	80.75–83.71	107.11	0.53	106.07–108.15	9.30	0.73	7.87–10.73
CF	392	84.93	0.75	83.46–86.40	105.34	0.41	104.55–106.13	10.00	0.82	8.40–11.60

AM = African American males;

CM = Caucasian males;

AF = African American females;

CF = Caucasian females.

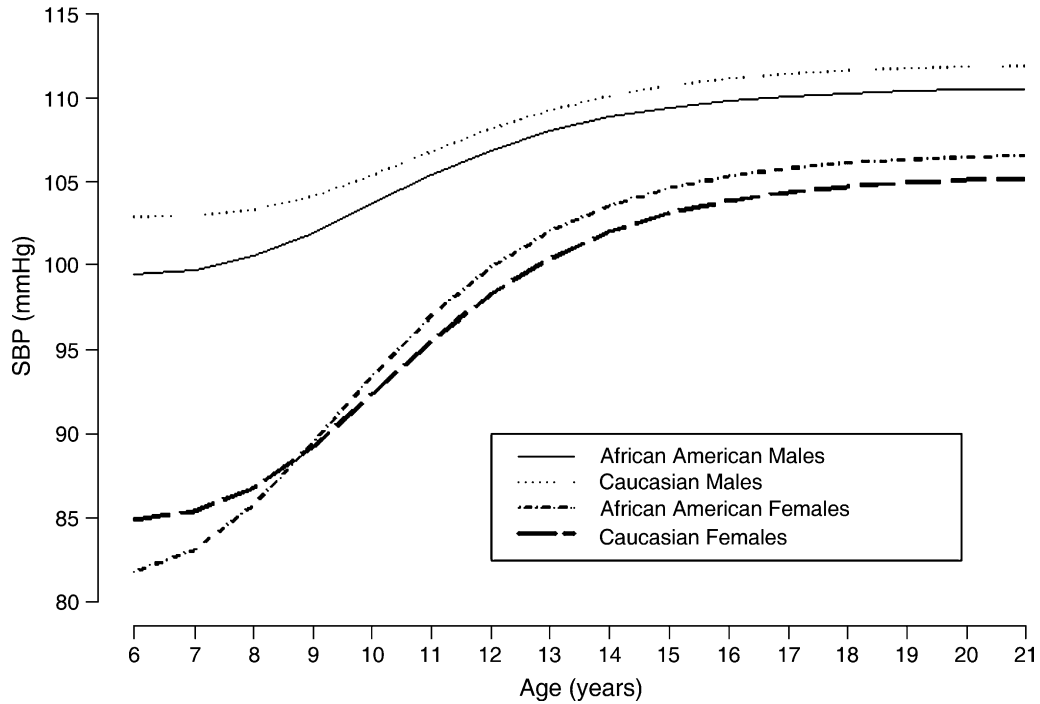


FIGURE 1. SBP growth - MCBPS (N=1302).

assessed at age 6 years. Growth differences in SBP among the four groups can also be explained in part by family history of high BP, SES, physical activity, and dietary intake levels (29, 30).

Two published studies that examined SBP longitudinally were in Japanese (16) and Hispanic populations (31).

However, the Hispanic children's study (31) did not fit an SBP growth model, but focused on the predictability from the baseline SBP to SBP at second time point. Akahoshi and colleagues (16) used a double exponential Gompertz function for analyses of BP growth. The Japanese subjects were 9 years old at entry and were followed for 9 years, with

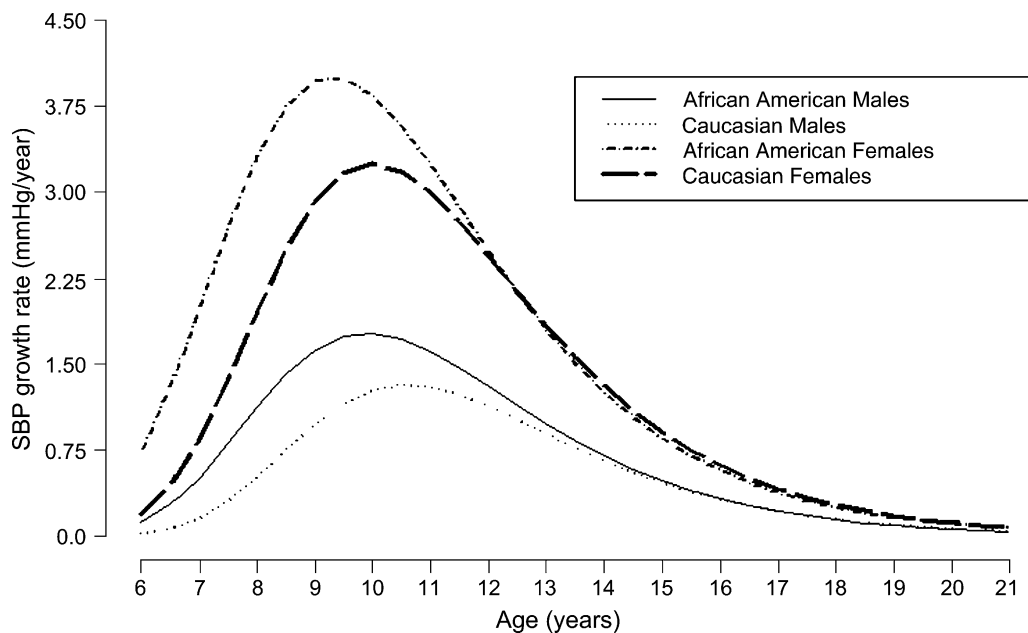


FIGURE 2. Growth rate of SBP - MCBPS (N=1302).

annual measurements of SBP ( $n = 418$ ). Methodological differences of BP measurement in the two studies are (a) use of standard mercury (16) versus RZ sphygmomanometer (current study) and (b) use of two (16) versus multiple (current study) cuff bladder sizes. These differences may have resulted in more precise BP measures in our study (5, 6, 32). Nonetheless, gender differences in the PGA of SBP in Japanese and Minneapolis children are similar, i.e., females reached their peak earlier than males. This finding satisfied two causal criteria: consistency and biological plausibility. In both studies, SBP did not increase linearly with age. In Japanese children (16), the age at maximum velocity of weight increase (VEL) was 12.30 and 13.46 years for females and males respectively and the age at maximum SBP velocity was 1–2 years later than the PGA of BMI (12). The contrast in findings between the two studies may result from the fact that Akahoshi and colleagues (16) did not take height into consideration. Although weight reflects the amount of adiposity, height is a true measure of physiologic maturation; hence, weight-height index or BMI may be a more appropriate covariate than weight alone.

Rosner and colleagues (33) reported ethnic differences in SBP based on eight large studies in the United States. When comparing the SBP levels at ages 6 and 17 of Rosner and colleagues (33) with our study, we found the trends were consistent: boys and Caucasians started at higher SBP levels than girls and African Americans at age 6. At age 17, African American girls exhibited higher SBP levels than their Caucasian counterparts.

Our study illustrates strengths in both design and analyses. Strengths in the design are the assessment of SBP measures with a robust method of measurement and prespecified quality control criteria (10, 11). Strength in analyses is attributed to the use of a NLME model, which accounts for variations in individuals and inferences can be made about individuals as well as subgroups within the population. The NLME model is a highly effective method of analyzing such repeated measurement data because it utilizes the strengths of conventional methods, namely, regression, time series, and repeated ANOVA, with random effects. Also, NLME methodology can naturally handle unbalanced observations among subjects. Hence, our approach provides a more accurate developmental trajectory of SBP compared to those studies that used traditional techniques. This study contributes the new information that SBP growth differs among the four gender-ethnic groups, even after adjusting for individual age and BMI changes that occur during developmental stages of childhood and adolescence.

In our study, attrition bias may occur if those who completed the study were different from those who withdrew. In a previous report (17), comparison of the baseline characteristics of those who completed and those

who missed the last screening revealed no significant differences. Also, a preliminary validation study that compared analyses ignoring or imputing the missing data yielded similar mean estimates (17).

Measurements of BP in children were taken with different postures for visits 1–9 (supine) and visits 10–19 (seated). It is known that significant differences in BP level occur between supine and seated positions (34, 35). Difference in BP due to change in posture was not expected to affect the validity of the results in our study because that change was uniform among all participants. A possible latent data shift due to postural change, however, would affect some characteristics of the growth curve of SBP (e.g., asymptote level). Our model was based on data smoothing over the latent BP shift and smoothing over this posture shift point will not change the overall shape of the SBP trajectory, which is the focus of this analysis. This smoothing appeared acceptable in view of the small BP shift relative to the large magnitude of data variation both within and among subjects.

The goal of our study was to describe the differences in SBP growth as age increases adjusting for BMI changes among four gender-ethnic groups. Due to the descriptive nature of this analysis, not all factors that may contribute to changes in BP were included. One of them is height. Although Voors and colleagues (36) and Gillum and colleagues (37) demonstrated that height is a stronger correlate of BP than age, Lauer and colleagues (38) showed that age may remain a factor independently of weight and height. Some studies stated that age was not a determinant of BP in adolescence, even though BP level increases with age (21, 39–43). Recently, BP nomograms were presented based on age, gender, and height, as they were important considerations for evaluating the normal limits of children's BP (44). When comparing age-only adjusted BP levels (7), with height-age-adjusted BP levels (36), the 90th and 95th percentiles for age and height for shorter children were lower than the same percentiles by age alone for both genders. While these studies (7, 44) provided clinically important BP tables, they were based on multiple-age cohorts, and not all cohorts had longitudinal measurements of BP.

Besides chronological age and height, developmental age (45, 46) may also contribute to BP levels in adolescents (47), although Londe and colleagues (48) reported there was no relation between sexual maturation and BP levels. Also, other factors that were not included in the current analysis (e.g., parental BP, socioeconomic status) may likely magnify ethnic differences rather than reduce them.

It has been documented that BMI and SBP are increasing among children and adolescents (49–51). Although BP increases during the normal growth period, those children with higher BP levels tend to track into higher BP levels in adulthood (10, 39, 41, 52–54). Increasing weight

consequently leads to rising BP especially SBP among children (49). Gender-ethnic differences in BP growth after body size adjustment may have implications for future management of BP-related cardiovascular risk.

Future research may use this data-analytic technique to achieve more comprehensive understanding of BP change in relation to other indices of physical development (skeletal age, sexual maturity). For example, future research may be able to answer the question, “Does the onset of menstruation lead to a spurt of BP increase?”

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