American Journal of Epidemiology

Vol. 167, No. 6
DOI: 10.1093/aje/kwm348
Advance Access publication January 29, 2008

Practice of Epidemiology

Determination of Blood Pressure Percentiles in Normal-Weight Children: Some Methodological Issues

B. Rosner[1], N. Cook[1], R. Portman[2], S. Daniels[3], and B. Falkner[4]

[1] Channing Laboratory, Brigham and Women's Hospital and Harvard Medical School, Boston, MA.
[2] University of Texas at Houston Health Science Center, University of Texas, Houston, TX.
[3] University of Colorado at Denver and Health Sciences Center, University of Colorado, Denver, CO.
[4] Department of Medicine, Jefferson Medical College, Thomas Jefferson University, Philadelphia, PA.

Received for publication February 7, 2007; accepted for publication November 5, 2007.

Blood pressure in children has consistently been related to adult blood pressure, with implications for long-term prevention of cardiovascular disease. The epidemic of obesity in children has resulted in corresponding increases in childhood blood pressure. In this paper, the authors develop norms for childhood blood pressure among normal-weight children (body mass index <85th percentile based on Centers for Disease Control and Prevention guidelines) as a function of age, sex, and height, using data from 49,967 children included in the database of the National High Blood Pressure Education Program Working Group on High Blood Pressure in Children and Adolescents (the Pediatric Task Force). The authors considered three types of models for pediatric blood pressure data, including polynomial regression, restricted cubic splines, and quantile regression, with the latter providing the best fit. The sex-specific norms presented here are a nonlinear function of both age and height and are generally slightly lower than previously developed norms based on Pediatric Task Force data including both normal-weight and overweight children.

blood pressure; child; models, statistical; pediatrics; regression analysis

Abbreviations: CDC, Centers for Disease Control and Prevention; CI, confidence interval; DBP, diastolic blood pressure; NHANES, National Health and Nutrition Examination Survey; OR, odds ratio; SBP, systolic blood pressure.

An important trend in pediatrics is incorporation of the measurement of blood pressure in the standard pediatric examination. Recent guidelines published in the Fourth Report on the Diagnosis, Evaluation, and Treatment of High Blood Pressure in Children and Adolescents (1) provide standards for accomplishing this goal. The report supplies tables of blood pressure percentiles based on the database created by the National High Blood Pressure Education Program Working Group on High Blood Pressure in Children and Adolescents (hereafter called the Pediatric Task Force), consisting of 63,227 children seen at 83,091 physician visits over the course of 11 studies. The estimated 50th, 90th, 95th, and 99th percentiles of blood pressure are given by sex, year of age (1–17 years), and height percentile (5th, 10th, 25th, 50th, 75th, 90th, and 95th) for both systolic blood pressure (SBP) and diastolic blood pressure (DBP) (Korotkoff 5).

A decision made in constructing these tables was that although weight or body mass index is an important predictor of blood pressure in both children and adults, percentiles should *not* be provided as a function of weight, so as to not encourage relatively high blood pressure to be considered normal just because a child is overweight or obese. However, overweight children were still included in the normative database. A resulting issue that arises is that norms for blood pressure will continue to increase as the level of obesity changes over time. For the current report, we modified the definition of the normative database to exclude

Correspondence to Dr. Bernard Rosner, Channing Laboratory, Brigham and Women's Hospital and Harvard Medical School, 181 Longwood Avenue, Boston, MA 02115 (e-mail: bernard.rosner@channing.harvard.edu).

TABLE 1. Demographic data on height/blood pressure distribution curves among normal-weight children included in the Pediatric Task Force database,* by study population†

Source population (reference no.(s))	Time period	Age (years)	Sex		Ethnic group							Children (visits) with systolic blood pressure data available	Children (visits) with diastolic blood pressure (Korotkoff 5) data available	Visits ≥85th percentile‡	
			Boys	Girls	Caucasian	African American	Hispanic	Asian	Native American	Other	Missing data			No.	%
NHANES§ II (4)	1976–1980	6–17	1,555	1,446	2,435	496	0	0	0	70	0	3,001 (3,001)¶	2,968 (2,968)	646	18
Pittsburgh, Pennsylvania (5)	1975–1982	1–5	141	130	166	104	0	0	0	0	1	271 (702)	0 (0)	191	21
Dallas, Texas (6, 7)	1976–1980	13–17	5,093	4,750	4,069	4,501	1,273	0	0	0	0	9,843 (17,830)	9,843 (17,824)	4,029	18
Bogalusa, Louisiana (8–10)	1973–1982	1–17	3,301	3,147	4,234	2,214	0	0	0	0	0	6,448 (13,190)	0 (0)	2,690	17
Houston, Texas (11)	1975–1978	3–17	1,182	1,094	609	516	1,050	22	0	0	79	2,276 (2,276)	0 (0)	555	20
South Carolina (12)	1982–1983	4–17	2,587	2,647	2,680	2,554	0	0	0	0	0	5,234 (5,234)	5,180 (5,180)	1,189	19
Iowa (13, 14)	1981	5–17	1,586	1,560	3,146	0	0	0	0	0	0	3,146 (3,146)	0 (0)	945	23
Providence, Rhode Island (15)	1985–1987	1–3	204	207	384	21	4	0	0	2	0	411 (723)	320 (442)	175	19
Minnesota (Sodium-Potassium Blood Pressure Trial in Children) (16)	1986–1987	9–17	7,645	6,934	8,626	2,462	362	1,424	407	1,298	0	14,579 (14,579)	14,401 (14,401)	4,823	25
NHANES III (17)	1988–1991	5–17	1,723	1,737	958	1,241	1,169	59	7	6	20	3,460 (3,460)	2,921 (2,921)	1,576	31
NHANES 1999–2000 (18)	1999–2000	8–17	634	664	320	362	571	0	0	45	0	1,298 (1,298)	1,281 (1,281)	806	38
Total															
No. or range		1–17	25,651	24,316	27,627	14,471	4,429	1,505	414	1,421	100	49,967 (65,439)	36,914 (45,017)	17,625	21
%			51	49	55	29	9	3	1	3	0				

* Fourth Report on the Diagnosis, Evaluation, and Treatment of High Blood Pressure in Children and Adolescents (1).
† Data presented are numbers unless otherwise specified.
‡ Visits excluded from the present analysis.
§ NHANES, National Health and Nutrition Examination Survey.
¶ Numbers in parentheses, number of physician visits.

TABLE 2. Results from polynomial regression models relating blood pressure to age and height *z* score among normal-weight* children in the Pediatric Task Force database

Parameter	Systolic blood pressure				Diastolic blood pressure (Korotkoff 5)			
	Boys		Girls		Boys		Girls	
	β†	*p* value‡	β	*p* value	β	*p* value	β	*p* value
Intercept	100.9		100.5		60.5		59.6	
Age − 10	1.78	<0.001	1.87	<0.001	0.72	<0.001	1.04	<0.001
$(\text{Age} - 10)^2$	0.15		0.041		−0.080		0.035	
$(\text{Age} - 10)^3$	0.002		−0.008		0.02		0.003	
$(\text{Age} - 10)^4$	−0.002		−0.0009		0.0002		−0.002	
Height *z* score								
*Z*ht	2.29	<0.001	1.75	<0.001	1.42	<0.001	1.39	<0.001
$Z\text{ht}^2$	−0.31		−0.06		−0.10		0.12	
$Z\text{ht}^3$	−0.03		−0.02		−0.02		−0.08	
$Z\text{ht}^4$	0.01		−0.002		0.01		−0.005	
Residual standard deviation	10.3		10.1		11.4		10.7	
ρ§	0.38		0.34		0.22		0.22	
No. of persons	25,651		24,316		18,925		17,989	
No. of physician visits	33,383		32,056		22,897		22,120	

* Body mass index <85th percentile by 1-year age-sex group (2) according to Centers for Disease Control and Prevention growth charts (3).

† Regression coefficient.

‡ *p* value from likelihood ratio test (4 df). Age: full model vs. reduced model with only *Z*ht terms; height: full model vs. reduced model with only age terms.

§ Intraclass correlation coefficient.

children who were either overweight (body mass index (weight (kg)/height (m)^2) >95th percentile) or at risk of becoming overweight (body mass index 85th–95th percentile) (2) on the basis of 2000 Centers for Disease Control and Prevention (CDC) growth charts (3), and we redefined blood pressure percentiles using this more restrictive database. The data used for the 2000 CDC growth charts were based on reference data sets from National Health Examination Survey II (1963–1965), National Health Examination Survey III (1966–1970), the Second National Health and Nutrition Examination Survey (NHANES II; 1976–1980), and the Third National Health and Nutrition Examination Survey (NHANES III; 1988–1994) and hence were roughly contemporary with the time period of the 11 studies used in the Pediatric Task Force report (1). We also explored several different analytic strategies for estimating blood pressure percentiles.

MATERIALS AND METHODS

In the Pediatric Task Force database (1), we had data available from 11 large pediatric blood pressure studies (4–18). Furthermore, the age distribution varied considerably in different studies and there were some differences in measurement techniques among studies, although all measurements were made with mercury manometers. In addition, although most studies provided cross-sectional data, other studies provided blood pressure data obtained at more than one age for a given child. Finally, the number of readings available per child varied by study. Some studies provided data from multiple readings taken at a single visit for a child, while other studies only provided data from one reading. For the sake of uniformity, we based all analyses on the first reading only. Even after accounting for age differences between studies, there were obvious study effects. We considered three different analytic approaches for relating blood pressure to age and height: polynomial regression, restricted cubic splines, and quantile regression.

Polynomial regression models

We first estimated the study effects by expressing blood pressure (BP) as a sex-specific fourth-degree polynomial function of age, height (ht) *z* score, and weight (wt) *z* score, as follows:

$$\text{BP}_{im} = \sum_{g=1}^{G} \delta_g \times S_g^{(i)} + \sum_{j=1}^{4} \beta_j(\text{age}_{im} - 10)^j + \sum_{k=1}^{4} \gamma_k(\text{Zht}_{im})^k + \sum_{l=1}^{4} \xi_l(\text{Zwt}_{im})^l + e_{im}, \quad (1)$$

where i = subject, m = visit, G = number of studies, $S_g^{(i)} = 1$ if subject i is in the gth study and 0 otherwise ($g = 1, \ldots, G$), age_{im} = age (years), and Zht_{im} and Zwt_{im} are height and weight z scores based on sex-specific CDC growth charts (3) for the ith child at the mth visit; $e_{im} \sim N(0, \sigma^2)$ and $\text{Corr}(e_{im_1}, e_{im_2}) = \rho$. The study effect estimates $\delta_1, \ldots, \delta_G$

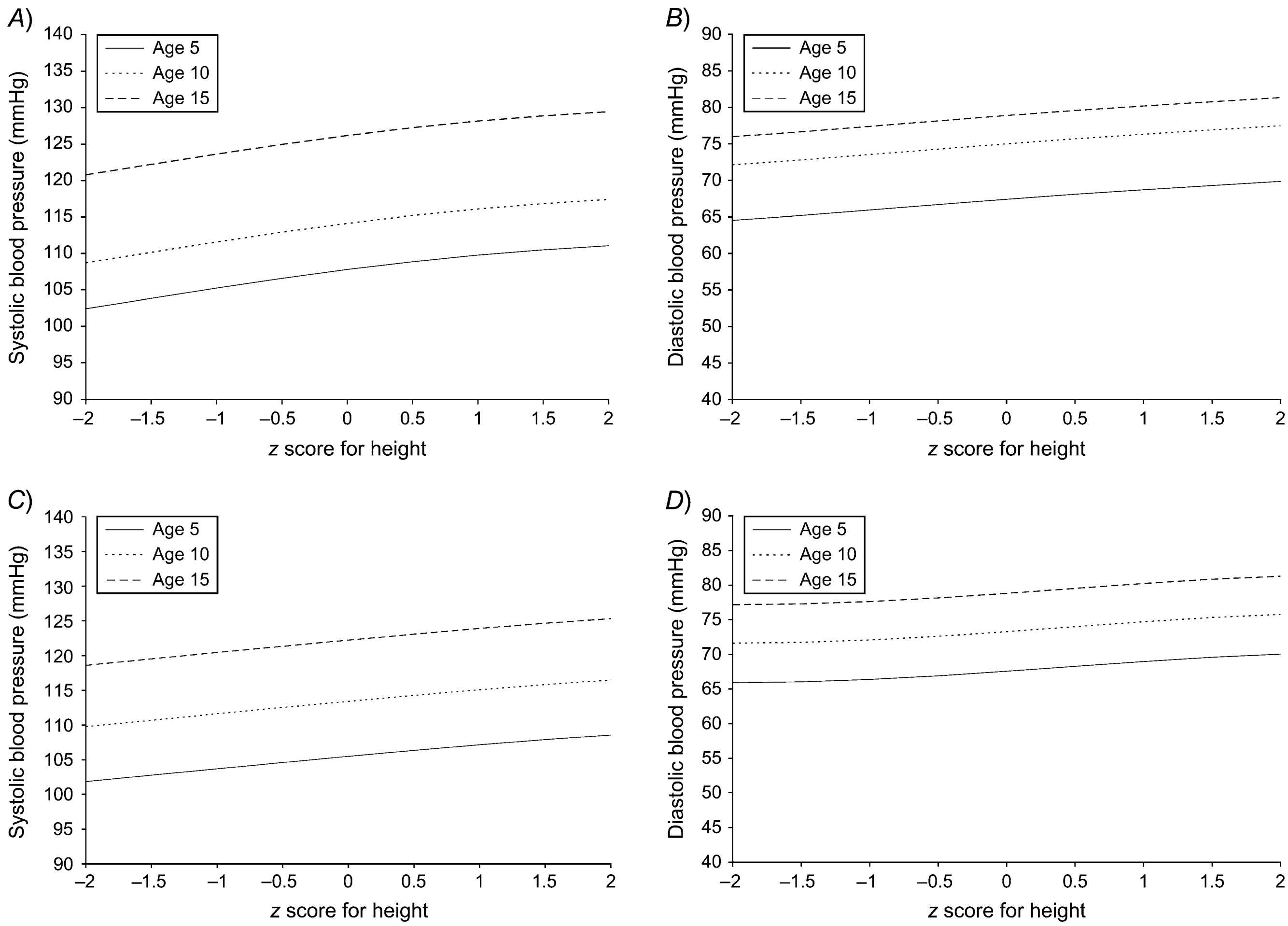

FIGURE 1. 90th percentile of blood pressure by percentile of height (height *z* score) among normal-weight children at ages 5, 10, and 15 years, obtained from polynomial regression models using Pediatric Task Force data. *A*) polynomial systolic blood pressure for boys; *B*) polynomial diastolic blood pressure for boys; *C*) polynomial systolic blood pressure for girls; *D*) polynomial diastolic blood pressure for girls.

were then used to estimate the blood pressure that would be obtained in a particular child if that child were from an average study by computing the adjusted blood pressure, given by

$$\mathrm{BP}^*_{im} = \mathrm{BP}_{im} - \left\{ \sum_{g=1}^{G} \delta_g S_g^{(i)} - \sum_{g=1}^{G} \delta_g / G \right\}. \qquad (2)$$

We then fitted a fourth-degree polynomial model to predict adjusted blood pressure as a function of age and height z score, as follows:

$$\mathrm{BP}^*_{im} = \alpha^* + \sum_{j=1}^{4} \beta_j^* (\mathrm{age}_{im} - 10)^j + \sum_{k=1}^{4} \gamma_k^* (\mathrm{Zht}_{im})^k + e^*_{im}, \qquad (3)$$

where $e^*_{im} \sim N(0, \sigma^{2*})$. The pth percentile of blood pressure for a child of age x and height z score Zht is then estimated by

$$\theta_p = \alpha^* + \sum_{j=1}^{4} \beta_j^* (x - 10)^j + \sum_{k=1}^{4} \gamma_k^* \mathrm{Zht}^k + Z_p \sigma^*,$$

where Z_p is the pth percentile of an $N(0, 1)$ distribution.

An advantage of equation 3 is that although the distribution of height varies greatly with age, the distribution of Zht does not, thus allowing one to estimate blood pressure percentiles as a function of age and height with a relatively simple polynomial model across a wide age range. However, a disadvantage of equation 3 is the assumption that the difference in average blood pressure between two children of the same age with height z scores of Z_1 and Z_2 is independent of age and is given by

$$\mathrm{BP}^*_{i_1m} - \mathrm{BP}^*_{i_2m} = \sum_{k=1}^{4} \gamma_k^* (Z_1^k - Z_2^k), \qquad (4)$$

which may or may not be true. To make the model more flexible, we could use ht_{im} instead of Zht_{im} in equation 3, but empirical evidence using this data set suggests that

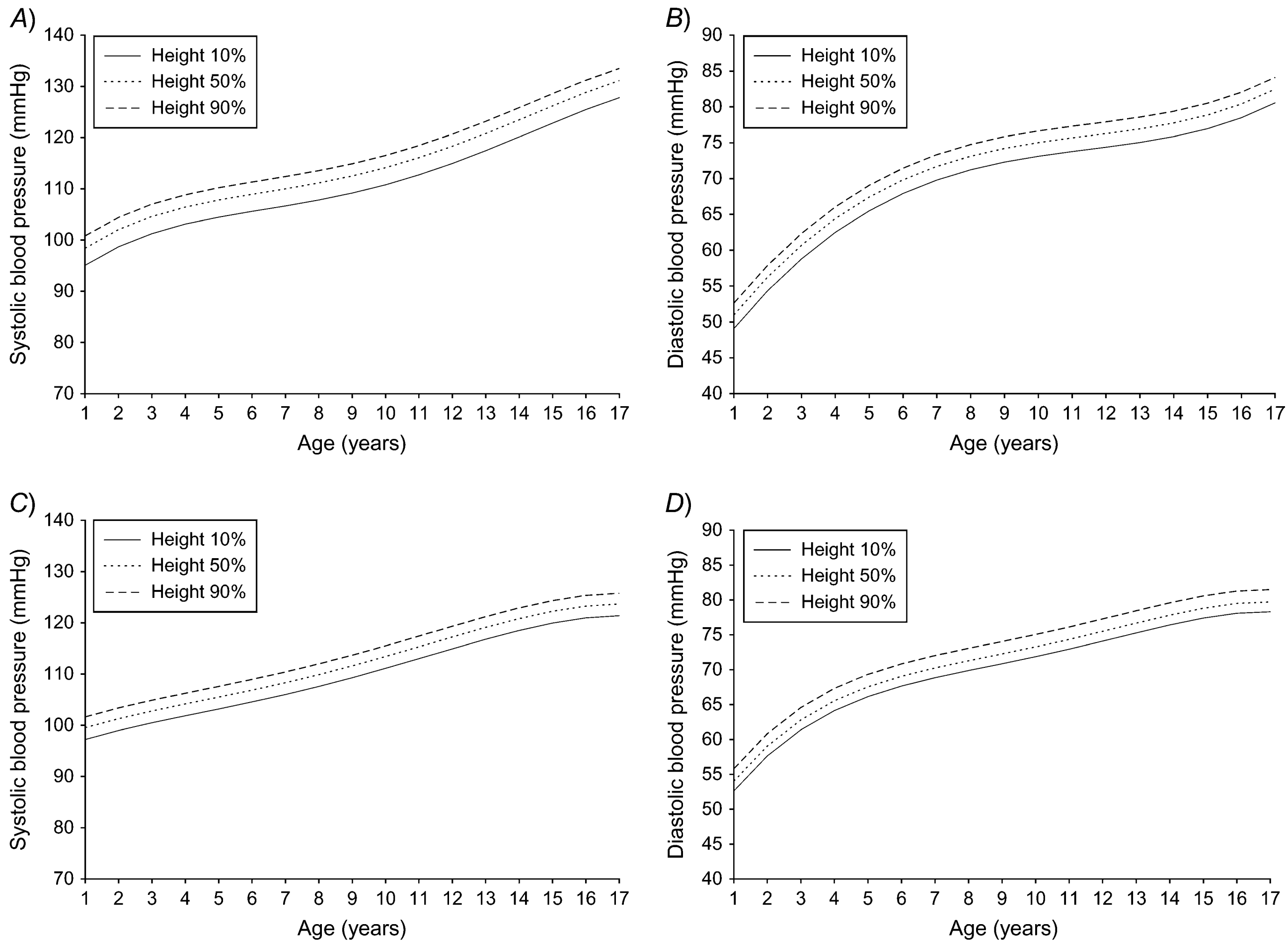

FIGURE 2. 90th percentile of blood pressure by age and percentile of height (10%, 50%, or 90%) among normal-weight children, obtained from polynomial regression models using Pediatric Task Force data. *A*) polynomial systolic blood pressure for boys, by age; *B*) polynomial diastolic blood pressure for boys, by age; *C*) polynomial systolic blood pressure for girls, by age; *D*) polynomial diastolic blood pressure for girls, by age.

the height coefficients may also depend on age if this parameterization is used.

Restricted cubic spline models

To build a more flexible model, we fitted a restricted cubic spline model (19). Under this model, each predictor variable is modeled using a restricted cubic spline representation with five knots which correspond to the 5th, 27.5th, 50th, 72.5th, and 95th percentiles, respectively, over the entire pediatric age range, as suggested by Harrell (20). To assess study effects, we first fitted a restricted cubic spline model of the form

$$\mathrm{BP}_{im} = \sum_{g=1}^{G} \alpha_g S_g^{(i)} + \sum_{j=1}^{4} \beta_j x_{im,j} + \sum_{k=1}^{4} \gamma_k h_{im,k} + \sum_{l=1}^{4} \delta_l w_{im,l} + e_{im}, \tag{5}$$

where

$$x_{im,1} = \mathrm{age}_{im}.$$

$$x_{im,j+1} = \left\{[(\mathrm{age}_{im} - t_j)_+^3] - [(\mathrm{age}_{im} - t_4)_+^3](t_5 - t_j)/(t_5 - t_4) + [(\mathrm{age}_{im} - t_5)_+^3](t_4 - t_j)/(t_5 - t_4)\right\}\Big/100,\quad j = 1, \ldots, 3.$$

$$h_{im,1} = \mathrm{ht}_{im.}$$

$$h_{im,k+1} = \left\{[(\mathrm{ht}_{im} - h_k)_+^3] - [(\mathrm{ht}_{im} - h_4)_+^3](h_5 - h_k)/(h_5 - h_4) + [(\mathrm{ht}_{im} - h_5)_+^3](h_4 - h_k)/(h_5 - h_4)\right\}\Big/100,\quad k = 1, \ldots, 3.$$

TABLE 3. Results from restricted cubic spline models relating blood pressure to age and height among normal-weight* children in the Pediatric Task Force database

Parameter	Systolic blood pressure				Diastolic blood pressure (Korotkoff 5)			
	Boys		Girls		Boys		Girls	
	β†	*p* value	β	*p* value	β	*p* value	β	*p* value
Intercept	47.0		63.0		−6.3		35.2	
Age spline terms								
x_1	−0.39	<0.001	−1.44	<0.001	1.97	<0.001	−0.65	<0.001
x_2	0.85		2.08		−2.62		0.47	
x_3	−5.65		−12.31		13.00		3.62	
x_4	19.38		26.86		−12.15		−21.52	
Height spline terms								
h_1	0.42	<0.001	0.35	<0.001	0.38	<0.001	0.23	<0.001
h_2	−0.01		−0.00		−0.00		−0.00	
h_3	0.04		0.01		−0.00		0.05	
h_4	−0.09		−0.08		0.04		−0.17	
Age × height spline terms‡								
z_1	0.00	0.19	−0.001	0.85	−0.07	<0.001	−0.04	0.097
z_2	0.07		−0.06		0.33		0.10	
z_3	−0.13		0.10		−0.54		−0.11	
z_4	0.07		−0.06		0.21		−0.01	
Residual standard deviation	10.3		10.1		11.3		10.7	
ρ§	0.38		0.35		0.23		0.22	
No. of persons	25,651		24,316		18,925		17,989	
No. of physician visits	33,383		32,056		22,897		22,120	

* Body mass index <85th percentile by 1-year age-sex group (2) according to Centers for Disease Control and Prevention growth charts (3).

† Regression coefficient.

‡ Males: (age − 10) × (height − 150); females: (age − 10) × (height − 147).

§ Intraclass correlation coefficient.

$$w_{im,1} = w_{im}.$$

$$w_{im,l+1} = \Big\{[(\mathrm{wt}_{im} - w_l)_+^3] - [(w_{im} - w_4)_+^3](w_5 - w_l)/(w_5 - w_4) + [(\mathrm{wt}_{im} - w_5)_+^3](w_4 - w_l)/(w_5 - w_4)\Big\}\Big/100,$$
$$l = 1, \ldots, 3.$$

$t_1, \ldots, t_5$ are the knots for age, $h_1, \ldots, h_5$ are the knots for height, and $w_1, \ldots, w_5$ are the knots for weight. We then computed study-adjusted blood pressures given by

$$\mathrm{BP}_{im}^* = \mathrm{BP}_{im} - \left\{\sum_{g=1}^{G} \alpha_g S_g^{(i)} - \sum_{g=1}^{G} \alpha_g / G\right\}$$

and estimated a restricted cubic spline model as a function of age, height, and age × height, given by

$$\mathrm{BP}_{im}^{**} = \sum_{j=1}^{4} \beta_j^{**} x_{im,j} + \sum_{k=1}^{4} \gamma_k^{**} h_{im,k} + \sum_{l=1}^{4} \delta_l^{**} z_{im,l} + e_{im}^{**}, \quad (6)$$

where $e_{im}^{**} \sim N(0, \sigma^{2**})$, $\mathrm{Corr}(e_{im,1}^{**}, e_{im,2}^{**}) = \rho$, $x_+ = x$ if $x > 0$ and $x_+ = 0$ if $x \le 0$, $x_{im,j}$ and $h_{im,k}$ are defined as above, $z_{im} = z_{im,1} = (\mathrm{age}_{im} - 10) \times (\mathrm{ht}_{im} - \bar{h})$, and $z_{im,k+1} = \{[(z_{im} - z_k)_+^3] - [(z_{im} - z_4)_+^3](z_5 - z_k)/(z_5 - z_4)] + [(z_{im} - z_5)_+^3]\,(z_4 - z_k)/(z_5 - z_4)\}/(100^2)$.

$z_1, \ldots, z_5$ are the knots for (age − 10)(ht − $\bar{h}$) and $\bar{h}$ = mean height over all children of a given gender. Restricted cubic splines (also referred to as natural splines) are constrained to be linear for values less than the first knot and greater than the last knot and may provide a better fit than unrestricted cubic splines, which sometimes behave poorly in the tails (19). These models are more flexible than simply adding interaction effects of age × *Z*ht to equation 3, since the shape of the function relating blood pressure to age and/or height is allowed to change over the range of each variable.

Quantile regression models

An assumption of the model shown in equation 6 is that the distribution of blood pressures is assumed to be normal, which implies that the effects of age and height are the same for all quantiles of blood pressure. To relax this assumption,

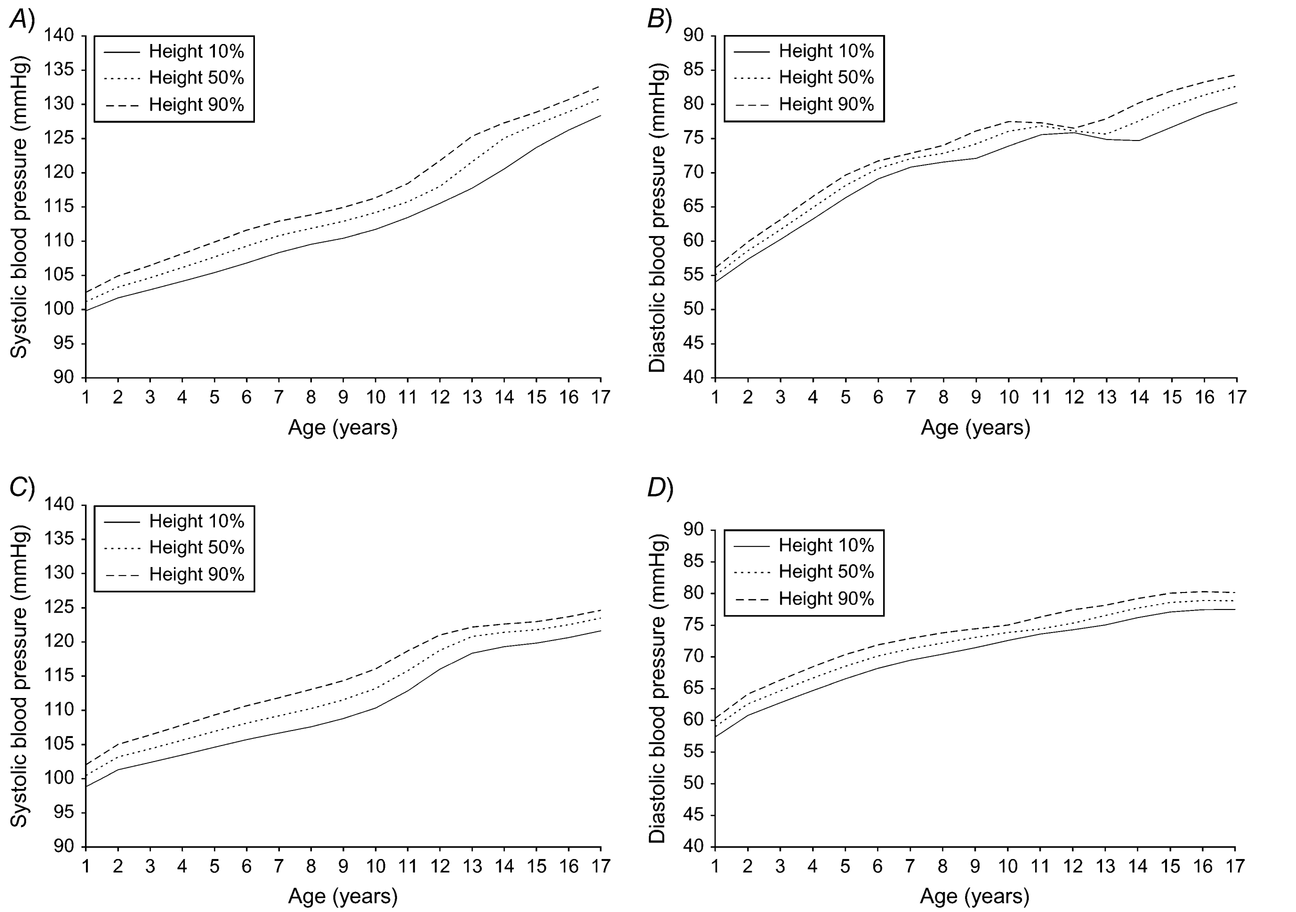

FIGURE 3. 90th percentile of blood pressure by age and percentile of height (10%, 50%, or 90%) among normal-weight children, obtained from restricted cubic spline models using Pediatric Task Force data. *A*) systolic blood pressure for boys (splines); *B*) diastolic blood pressure for boys (splines); *C*) systolic blood pressure for girls (splines); *D*) diastolic blood pressure for girls (splines).

we also considered quantile regression methods (21). To implement these methods, a separate regression is run for each quantile τ and the vector of parameters $\underset{\sim}{\beta}_\tau$ that minimize

$$\sum_{i=1}^{N} \rho_\tau(\mathrm{BP}_{im}^{**} - \underset{\sim}{Z}_i' \underset{\sim}{\beta}_\tau), \quad (7)$$

where $\rho_\tau(g) = g \times [\tau - I(g < 0)]$ and $I(a) = 1$ if a is true and 0 if a is false. The regression is estimated using PROC QUANTREG in SAS (SAS Institute, Inc., Cary, North Carolina). Thus, the assumption of normality of the residuals is not necessary for quantile regression.

We ran these regressions for each of $\tau = 0.01$, 0.05, 0.10, 0.25, 0.50, 0.75, 0.90, 0.95, and 0.99, where $\underset{\sim}{Z}_i = (S, \underset{\sim}{x}_{im}, \underset{\sim}{h}_{im}, \underset{\sim}{z}_{im})$ and $\underset{\sim}{S} = (S_1, \ldots, S_G)$, $\underset{\sim}{x}_{im} = (x_{im,1}, \ldots, x_{im,4})$, $\underset{\sim}{h}_{im} = (h_{im,1}, \ldots, h_{im,4})$, and $\underset{\sim}{z}_{im} = (z_{im,1}, \ldots, z_{im,4})$ are defined in equation 6. Thus, a separate set of regression coefficients $\underset{\sim}{\beta}_\tau$ is obtained for each τ. The quantile regression approach using separate restricted cubic splines for prediction for each quantile offers the most flexibility in terms of both specification of the regression function for a specific quantile and allowing for separate regression equations for different quantiles.

Assessing goodness of fit

To assess the goodness of fit of the polynomial regression approach shown in equation 3, the restricted cubic spline approach shown in equation 6, and the quantile regression approach shown in equation 7, we subdivided the data for each age according to sex-specific predicted blood pressure percentile, divided at 1 percent, 5 percent, 10 percent, 25 percent, 50 percent, 75 percent, 90 percent, 95 percent, and 99 percent, where the cutpoints were included in the upper segment. For each sex, we then compared the observed distribution of children in these blood pressure percentile groups with the expected distribution for each 1-year age group, combined the data into three age groups (1–5 years, 6–10 years, and 11–17 years) separately for boys and girls, and performed a chi-square goodness-of-fit test for each method within each of the six age-sex groups.

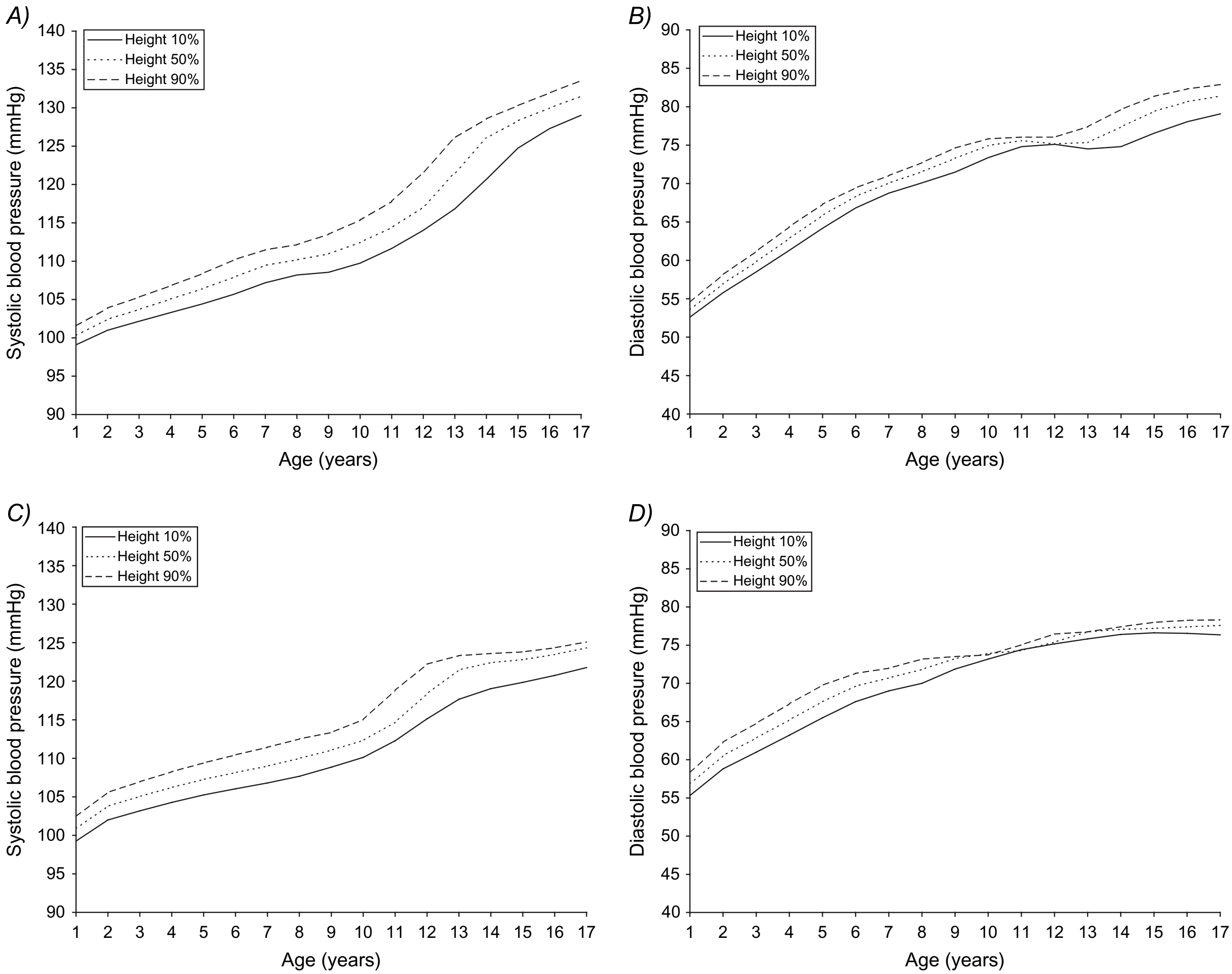

FIGURE 4. 90th percentile of blood pressure by age and percentile of height (10%, 50%, or 90%) among normal-weight children, obtained from quantile regression models using Pediatric Task Force data. *A*) systolic blood pressure for boys (quantile regression); *B*) diastolic blood pressure for boys (quantile regression); *C*) systolic blood pressure for girls (quantile regression); *D*) diastolic blood pressure for girls (quantile regression).

RESULTS

The Pediatric Task Force data were derived from 11 pediatric studies (4–18). Details on the design of these studies have been previously published (1). We included children from this database in this analysis only if their body mass index percentile was less than the 85th percentile for their 1-year age-sex group (2) based on the CDC growth charts (3). Demographic data for the study population are provided in table 1.

The age range was 1–17 years, with heterogeneous age distributions in different studies and a broad range of ethnicities over the 11 studies, which is similar to the entire Pediatric Task Force database. Approximately 21 percent of physician visits were excluded because the body mass index was ≥85th percentile, with the percentage excluded being notably higher in the later studies (NHANES III and NHANES 1999–2000).

Results from the polynomial regression models (equation 3) are presented separately for boys and girls in table 2. As expected, age and height z score were strong predictors of SBP and DBP for both boys and girls ($p < 0.001$). To allow better understanding of the relation of blood pressure to height, we display in figure 1 the predicted 90th percentile of blood pressure (prehypertensive level) by height z score for children aged 5, 10, and 15 years, separately for boys and girls. Prehypertensive blood pressure level appears to be an approximately linear function of height z score for a given age group. In addition, in figure 2 we plot the prehypertensive level by age for children at the 10th, 50th, and 90th height percentiles. The prehypertensive level shows a curvilinear increase with age, with the highest slope appearing in early childhood and adolescence and a more moderate rate of increase being evident in late childhood.

An advantage of this approach is that the blood pressures of children of different ages can be easily accommodated in a relatively simple polynomial model. The disadvantage is that based on equation 3, the mean difference in blood pressure for two children with height z scores of Zht and Zht_2 are the same for all ages. To test this assumption, we conducted additional analyses including interaction terms of (age − 10) × Zht, (age − 10) × Zht^2, (age − 10) × Zht^3, and (age − 10) × Zht^4 for all of the models in table 2. There were significant interaction effects for three of the four models (SBP in boys: for (age − 10) × Zht, $p = 0.025$; SBP in girls: for (age − 10) × Zht, $p = 0.002$; DBP in boys: for (age − 10) × Zht, $p = 0.051$, and for (age − 10) × Zht^2, $p = 0.034$).

To provide a more flexible model, we represented age, height, and age × height using restricted cubic splines, as given in equation 6. The resulting sex-specific models are presented in table 3. For illustration of the relations, plots of the prehypertensive level (≥90th percentile) of SBP and DBP by age are presented by percentile of height in figure 3. The differences in prehypertensive level between the 10th and 90th percentiles of height vary somewhat by age for SBP in females and are noticeably different by age for DBP in both boys and girls.

A limitation of the polynomial models shown in equation 3 and the spline models shown in equation 6 is that they assume that the distribution of blood pressures is normal with the same variance for all combinations of age and height. To relax this assumption, we fitted the quantile regression model in equation 7 separately by sex for the 1st, 5th, 10th, 25th, 50th, 75th, 90th, 95th, and 99th percentiles of blood pressure. The regression coefficients are given in Appendix tables 1–4. Plots of the quantile regression results for the 90th percentile of blood pressure by age and height percentile are given in figure 4.

In general, blood pressure increased with both age and height percentile, albeit in a nonlinear manner. For DBP, effects of height were smallest at the onset of puberty (ages 10–12 years) and largest for younger children and older adolescents. In addition, effects of height tended to be larger for boys than for girls. Table 4 shows the 90th percentile of blood pressure by height percentile in 1-year age-sex-specific groups. A complete table of the 1st, 5th, 10th, 25th, 50th, 75th, 90th, 95th, and 99th percentiles of blood pressure by height percentile in 1-year age-sex groups (Web table 1) is given on the *Journal*'s website (http://aje.oxfordjournals.org/) and at the following website: http://www.geocities.com/bernardrosner/Pediatrics.html.

Prehypertensive levels (≥90th percentile) for normal-weight adolescents (ages 13–17 years) ranged from 115 mmHg to 134 mmHg for SBP in boys, from 116 mmHg to 125 mmHg for SBP in girls, from 74 mmHg to 83 mmHg for DBP in boys, and from 75 mmHg to 78 mmHg for DBP in girls, which fits in well with the customary definition for hypertension of 140/90 mmHg for adults. Comparable levels for the Pediatric Task Force data (1) based on normal-weight and overweight children were: for SBP in boys, 118–135 mmHg; for SBP in girls, 118–127 mmHg; for DBP in boys, 75–84 mmHg; and for DBP in girls, 76–81 mmHg. These levels are slightly higher than those based on normal-weight children only. In addition, normative values vary widely by height among children of the same age (SBP in boys, 6–11 mmHg; SBP in girls, 5–7 mmHg; DBP in boys, 3–6 mmHg; and DBP in girls, 1–2 mmHg).

To assess goodness of fit, we compared the observed and expected percentages of children in different blood pressure percentile groups by age (1–5, 6–10, and 11–17 years) and sex for both SBP and DBP for both the spline and quantile regression models. Web table 2, which is posted on the *Journal*'s website (http://aje.oxfordjournals.org/), displays the observed number and percentage of children falling into each percentile category, along with the percentage expected. For each age group, the goodness of fit of the quantile regression model (Q) is generally excellent, with no significant difference between observed and expected counts. Conversely, the restricted cubic spline models (S) consistently showed a poor goodness of fit. The assumption of normality was inappropriate for both SBP, which was generally positively skewed, and DBP, which was generally negatively skewed.

In the preceding analyses in this paper, we considered SBP and DBP separately. However, the determination of prehypertension is based on both SBP and DBP and is defined as blood pressure at or above the 90th percentile for either SBP or DBP. In table 5, we present the numbers and percentages of children who were at or above the 90th percentile for SBP and DBP separately and in combination, as well as the percentage of prehypertensive children. These data were calculated for both the normal-weight Pediatric Task Force children (body mass index <85th percentile) included in this report and the overweight Pediatric Task Force children (body mass index ≥85th percentile) who were excluded from this report.

Among normal-weight children, 10 percent of children had SBP ≥90th percentile, 10 percent of children had DBP ≥90th percentile, 3 percent had both SBP and DBP ≥90th percentile, and 18 percent were prehypertensive (either SBP or DBP ≥90th percentile), on the basis of a single visit. The prevalence of prehypertension was significantly higher for overweight children (odds ratio (OR) = 2.3, 95 percent confidence interval (CI): 2.2, 2.4) than for normal-weight children, as was the prevalence of elevated SBP (OR = 2.8, 95 percent CI: 2.6, 2.9), elevated DBP (OR = 1.9, 95 percent CI: 1.8, 2.0), and elevation of both SBP and DBP (OR = 3.2, 95 percent CI: 3.0, 3.5).

DISCUSSION

The development of norms for pediatric blood pressure is challenging because of the nonlinear relation between blood pressure levels and both age and height. Several functional forms were considered in this analysis. We determined that the use of the quantile regression model offered the most flexibility and the best fit of the models considered. The methods presented in this paper are somewhat different from the penalized likelihood LMS (lambda-mu-sigma) methods of Cole and Green (22, 23) that are used to estimate height

TABLE 4. 90th percentile of systolic and diastolic blood pressure by age, sex, and percentile of height among normal-weight* children in the Pediatric Task Force database†

Age (years)	Height percentile													
	Boys							Girls						
	5%	10%	25%	50%	75%	90%	95%	5%	10%	25%	50%	75%	90%	95%
1														
SBP‡ (mmHg)	98	99	99	100	100	101	101	98	99	99	100	101	102	102
DBP‡ (mmHg)	52	52	53	53	54	54	54	54	55	56	56	57	58	58
Height (cm)	77	78	80	82	85	87	88	75	77	79	81	83	85	86
2														
SBP (mmHg)	100	100	101	102	103	103	104	101	101	102	103	104	105	106
DBP (mmHg)	55	55	56	56	57	58	58	58	58	59	60	61	62	62
Height (cm)	86	87	90	92	95	97	99	85	86	89	91	94	96	97
3														
SBP (mmHg)	101	102	102	103	104	105	105	102	103	104	104	105	106	107
DBP (mmHg)	58	58	59	59	60	61	61	60	61	61	62	63	64	65
Height (cm)	92	94	96	99	102	104	106	91	92	95	98	100	103	105
4														
SBP (mmHg)	102	103	104	105	105	106	107	103	104	105	106	107	108	108
DBP (mmHg)	60	61	62	62	63	64	64	62	63	64	65	66	67	67
Height (cm)	99	100	103	106	109	112	113	97	99	101	104	108	110	112
5														
SBP (mmHg)	103	104	105	106	107	108	108	104	105	106	107	108	109	110
DBP (mmHg)	63	64	65	65	66	67	67	64	65	66	67	68	69	70
Height (cm)	104	106	109	112	116	119	120	104	105	108	111	115	118	120
6														
SBP (mmHg)	105	105	106	107	109	110	110	105	106	107	108	109	110	111
DBP (mmHg)	66	66	67	68	68	69	69	67	67	68	69	70	71	71
Height (cm)	110	112	115	119	122	126	127	110	112	115	118	122	126	128
7														
SBP (mmHg)	106	107	108	109	110	111	111	106	106	107	109	110	111	112
DBP (mmHg)	68	68	69	70	70	71	71	68	68	69	70	71	72	72
Height (cm)	116	118	121	125	129	132	134	116	118	121	125	129	132	135
8														
SBP (mmHg)	107	108	109	110	111	112	112	107	107	108	110	111	112	113
DBP (mmHg)	69	70	70	71	72	72	73	69	70	71	72	72	73	73
Height (cm)	121	123	127	131	135	139	141	121	123	127	131	135	139	141
9														
SBP (mmHg)	107	108	109	110	112	113	114	108	108	109	111	112	113	114
DBP (mmHg)	70	71	72	73	74	74	74	71	71	72	73	73	73	73
Height (cm)	126	128	132	136	141	145	147	125	128	131	136	140	144	147

Table continues

and weight quantiles for pediatric growth data. However, Wei et al. (24) performed a study comparing quantile regression methods for fitting pediatric growth data and the LMS methods; the results indicated very similar estimated quantiles using these two approaches. An advantage of the quantile regression approach is that it is relatively easy to incorporate covariates into the analysis of growth data. In the setting in this paper, this involves estimating blood pressure quantiles as a nonlinear function of both age and height. Quantile regression has also been used to accurately assess the effects of early-life risk factors on adult body size, where adult body size is characterized by body mass index at 20 and 40 years of age (25). In general, quantile regression would be expected to be a useful analytic tool with which to study adult body mass index, which is almost always nonnormally distributed.

TABLE 4. Continued

Age (years)	Height percentile													
	Boys							Girls						
	5%	10%	25%	50%	75%	90%	95%	5%	10%	25%	50%	75%	90%	95%
10														
SBP (mmHg)	108	109	111	112	113	115	116	109	110	111	112	113	115	116
DBP (mmHg)	72	73	74	74	75	75	76	72	73	73	73	73	73	73
Height (cm)	130	133	137	141	146	150	153	130	132	136	141	146	150	153
11														
SBP (mmHg)	110	111	112	114	116	117	118	111	112	113	114	116	118	120
DBP (mmHg)	74	74	75	75	75	76	76	74	74	74	74	74	75	75
Height (cm)	135	137	142	146	151	156	159	136	138	143	148	153	157	160
12														
SBP (mmHg)	113	114	115	117	119	121	122	114	115	116	118	120	122	122
DBP (mmHg)	75	75	75	75	75	76	76	75	75	75	75	76	76	76
Height (cm)	140	143	148	153	158	163	166	143	146	150	155	160	164	166
13														
SBP (mmHg)	115	116	118	121	124	126	126	116	117	119	121	122	123	123
DBP (mmHg)	74	74	74	75	76	77	77	75	75	75	76	76	76	76
Height (cm)	147	150	155	160	166	171	173	148	151	155	159	164	168	170
14														
SBP (mmHg)	119	120	123	126	127	128	129	118	118	120	122	123	123	123
DBP (mmHg)	74	74	75	77	78	79	80	76	76	76	76	77	77	77
Height (cm)	154	157	162	167	173	177	180	151	153	157	161	166	170	172
15														
SBP (mmHg)	123	124	126	128	129	130	130	118	119	121	122	123	123	124
DBP (mmHg)	75	76	78	79	80	81	81	76	76	76	77	77	78	78
Height (cm)	159	162	167	172	177	182	184	152	154	158	162	167	171	173
16														
SBP (mmHg)	126	127	128	129	131	131	132	119	120	122	123	124	124	124
DBP (mmHg)	77	78	79	80	81	82	82	76	76	76	77	78	78	78
Height (cm)	162	165	170	175	180	184	186	152	154	158	163	167	171	173
17														
SBP (mmHg)	128	129	130	131	132	133	134	120	121	123	124	124	125	125
DBP (mmHg)	78	79	80	81	82	82	83	76	76	77	77	78	78	78
Height (cm)	164	166	171	176	181	185	187	152	155	159	163	167	171	174

* Body mass index <85th percentile by 1-year age-sex group (2) according to Centers for Disease Control and Prevention growth charts (3).

† A complete table of the 1st, 5th, 10th, 25th, 50th, 75th, 90th, 95th, and 99th percentiles of blood pressure by height percentile in 1-year age-sex groups (Web table 1) is given on the *Journal*'s website (http://aje.oxfordjournals.org/) and at the following website: http://www.geocities.com/bernardrosner/Pediatrics.html.

‡ SBP, systolic blood pressure; DBP, diastolic blood pressure.

Another issue is that although weight is a major determinant of blood pressure in both children and adults, it is important to not raise the norm for blood pressure in an overweight child. Hence, we restricted the normative population to include normal-weight children only. Thus, the prehypertensive and hypertensive levels in this report are slightly lower than those previously published (1), which included both normal-weight and overweight children. The one exception to this rule occurs for the youngest children (ages 1–2 years), for whom the levels in this report are higher for the shortest children because of the relaxation of the criterion that the difference in mean blood pressure by z score of height is the same for all age groups.

In addition, although all studies used mercury manometers in the measurement of blood pressure, there were obvious study effects. We chose to base the norms on children from an ‘‘average’’ study. Whether these norms are also appropriate for oscillometric blood pressure readings remains an open question which can best be addressed by studies including both oscillimetric and mercury readings

TABLE 5. Odds ratio for being at or above the 90th percentile of systolic and/or diastolic blood pressure among normal-weight and overweight children in the Pediatric Task Force database

	Normal-weight children* (n = 45,017)‡		Overweight children† (n = 12,941)		Odds ratio	95% confidence interval
	No.	%	No.	%		
≥90th percentile for SBP§	4,608	10	3,118	24	2.8	2.6, 2.9
≥90th percentile for DBP§	4,551	10	2,235	17	1.9	1.8, 2.0
≥90th percentile for both SBP and DBP	1,134	3	996	8	3.2	3.0, 3.5
Prehypertensive¶	8,025	18	4,357	34	2.3	2.2, 2.4

* Body mass index <85th percentile by 1-year age-sex group (2) according to Centers for Disease Control and Prevention growth charts (3).

† Body mass index ≥85th percentile.

‡ Number of children for whom data on both SBP and DBP were available.

§ SBP, systolic blood pressure; DBP, diastolic blood pressure.

¶ ≥90th percentile for either SBP or DBP.

taken in the same children. Another issue is that blood pressure varies considerably in children, and it is not uncommon to find children who are prehypertensive (≥90th percentile) or hypertensive (≥95th percentile) at one physician visit and normotensive at a second visit. The present guidelines require confirmation of a prehypertensive or hypertensive level of blood pressure on three separate occasions (1). Whether this approach is the most efficient method of identifying prehypertensive and hypertensive children remains an open question.

ACKNOWLEDGMENTS

This work was supported by National Institutes of Health grant HL40619.

The authors acknowledge Marion McPhee for programming assistance and Shelly Magno and Lisa Ottaviani for administrative assistance.

Conflict of interest: none declared.

REFERENCES

1. National High Blood Pressure Education Program Working Group on High Blood Pressure in Children and Adolescents. The fourth report on the diagnosis, evaluation, and treatment of high blood pressure in children and adolescents. Pediatrics 2004;114(suppl):555–76.
2. Ogden CL, Flegal KM, Carroll MD, et al. Prevalence and trends in overweight among U.S. children and adolescents, 1999–2000. JAMA 2002;288:1728–32.
3. National Center for Health Statistics, Centers for Disease Control and Prevention. 2000 CDC growth charts: United States. Hyattsville, MD: National Center for Health Statistics, 2000. (www.cdc.gov/growthcharts).
4. National Center for Health Statistics, Centers for Disease Control and Prevention. National Health and Nutrition Examination Survey data. NHANES II. Hyattsville, MD: National Center for Health Statistics, 1980.
5. Schachter J, Kuller LH, Perfetti C. Blood pressure during the first five years of life: relation to ethnic group (black or white) and to parental hypertension. Am J Epidemiol 1984; 119:541–53.
6. Fixler DE, Laird WP. Validity of mass blood pressure screening in children. Pediatrics 1983;72:459–63.
7. Barón AE, Freyer B, Fixler DE. Longitudinal blood pressure in blacks, whites and Mexican Americans during adolescence and early adulthood. Am J Epidemiol 1986;123: 809–17.
8. Voors AW, Foster TA, Frerichs RR, et al. Studies of blood pressure in children, ages 5–14 years in a total biracial community: The Bogalusa Heart Study. Circulation 1976;54: 319–27.
9. Berenson GS, McMahan CA, Voors AW, et al. Cardiovascular risk factors in children: the early natural history of atherosclerosis and essential hypertension. New York, NY: Oxford University Press, 1980.
10. Berenson GS. Causation of cardiovascular risk factors in children. Perspectives on cardiovascular risk in early life. New York, NY: Raven Press, 1986.
11. Gutgesell M, Terrell G, Labarthe D. Pediatric blood pressure: ethnic comparison in a primary care center. Hypertension 1981;3:39–49.
12. Lackland DT, Riopel DA, Shepard DM, et al. Blood pressure and anthropometric measurement results of the South Carolina Dental Health and Pediatric Blood Pressure Study. Columbia, SC: South Carolina Department of Health and Environmental Control, 1985.
13. Clarke WR, Schrott HG, Leaverton PE, et al. Tracking of blood lipids and blood pressures in school-age children: The Muscatine Study. Circulation 1978;58:626–34.
14. Lauer RM, Clarke WR, Beaglehole R. Level, trend, and variability of blood pressure during childhood: The Muscatine Study. Circulation 1984;69:242–9.
15. McGarvey ST, Zinner SH, Willett WC, et al. Maternal prenatal dietary potassium, calcium, magnesium and infant blood pressure. Hypertension 1991;17:218–24.
16. Gomez O, Prineas RJ, Sinaiko AR. The Sodium-Potassium Blood Pressure Trial in Children. Control Clin Trials 1991;12:408–23.
17. National Center for Health Statistics, Centers for Disease Control and Prevention. National Health and Nutrition Examination Survey data. NHANES III. Hyattsville, MD: National Center for Health Statistics, 1991.

18. National Center for Health Statistics, Centers for Disease Control and Prevention. National Health and Nutrition Examination Survey data. NHANES 1999–2000. Hyattsville, MD: National Center for Health Statistics, 2000.
19. Stone CJ, Koo CY. Additive splines in statistics. In: Proceedings of the Statistical Computing Section of the American Statistical Association. Alexandria, VA: American Statistical Association, 1985:45–8.
20. Harrell FJ. Regression modeling strategies. New York, NY: Springer Publishing Company, 2001.
21. Koenker R. Quantile regression. San Diego, CA: Elsevier, 2001.
22. Cole TJ, Green PJ. Smoothing reference centile curves: the LMS method and penalized likelihood. Stat Med 1992;11:1305–19.
23. Cole TJ. The LMS method for constructing normalized growth standards. Eur J Clin Nutr 1990;44:45–60.
24. Wei Y, Pere A, Koenker R, et al. Quantile regression methods for reference growth charts. Stat Med 2006;25:1369–82.
25. Terry MB, Wei Y, Esserman D. Maternal, birth, and early-life influences on adult body size in women. Am J Epidemiol 2007;166:5–13.

APPENDIX TABLE 1. Regression coefficients for systolic blood pressure in boys, obtained from quantile regression models using Pediatric Task Force data (33,383 physician visits)

Variable	Quantile								
	0.01	0.05	0.1	0.25	0.5	0.75	0.9	0.95	0.99
Intercept	−15.2	7.5	−3.8	30.8	49.3	45.8	71.1	102.7	99.6
Age									
x_1	0.16	−0.00	0.26	−0.04	−0.05	0.28	−0.59	−1.23	−2.85
x_2	0.79	0.41	0.59	0.35	0.56	0.32	0.95	0.86	3.07
x_3	−16.24	−5.84	−10.58	−3.51	−5.01	−3.01	−3.23	3.25	−6.50
x_4	64.96	25.15	40.4	16.99	21.31	12.58	5.83	−15.79	−4.98
Height									
h_1	0.70	0.59	0.68	0.47	0.37	0.43	0.33	0.16	0.35
h_2	−0.02	−0.01	−0.01	−0.01	−0.00	−0.01	−0.00	0.01	−0.00
h_3	0.08	0.05	0.06	0.04	0.04	0.04	0.02	−0.01	0.05
h_4	−0.15	−0.09	−0.11	−0.10	−0.12	−0.11	−0.07	−0.05	−0.13
Age × height									
z_1	0.01	0.00	0.03	−0.01	0.01	0.01	−0.02	−0.03	−0.04
z_2	0.10	0.09	0.13	0.10	0.03	0.10	0.15	0.07	−0.04
z_3	−0.16	−0.16	−0.24	−0.17	−0.06	−0.19	−0.27	−0.14	0.07
z_4	0.06	0.07	0.14	0.07	0.03	0.11	0.16	0.10	−0.03

APPENDIX TABLE 2. Regression coefficients for systolic blood pressure in girls, obtained from quantile regression models using Pediatric Task Force data (32,056 physician visits)

Variable	Quantile								
	0.01	0.05	0.1	0.25	0.5	0.75	0.9	0.95	0.99
Intercept	−7.5	30.9	22.7	44.8	63.7	66.1	92.4	117.6	135.7
Age									
x_1	−1.23	−1.13	−0.87	−0.92	−1.21	−1.19	−1.85	−2.10	−1.85
x_2	1.26	1.59	1.48	1.55	1.96	1.79	2.55	2.70	2.06
x_3	−6.88	−11.74	−11.82	−10.78	−12.51	−9.53	−13.64	−11.26	−8.05
x_4	20.47	34.59	34.23	27.84	28.01	16.34	26.23	13.42	16.92
Height									
h_1	0.71	0.46	0.54	0.41	0.33	0.36	0.25	0.10	−0.01
h_2	−0.01	−0.00	−0.01	−0.00	−0.00	−0.00	−0.00	0.01	0.01
h_3	−0.07	−0.03	0.02	0.01	0.02	0.02	0.05	0.01	−0.09
h_4	0.36	0.11	−0.06	−0.09	−0.16	−0.13	−0.31	−0.18	0.17
Age × height									
z_1	−0.00	−0.02	0.00	−0.01	−0.00	−0.01	−0.02	−0.03	−0.03
z_2	0.53	0.69	0.32	0.15	−0.17	−0.19	−0.18	−0.48	0.34
z_3	−0.69	−1.00	−0.47	−0.2	0.26	0.30	0.27	0.72	−0.59
z_4	0.14	0.39	0.18	0.05	−0.13	−0.16	−0.10	−0.30	0.42

APPENDIX TABLE 3. Regression coefficients for diastolic blood pressure (Korotkoff 5) in boys, obtained from quantile regression models using Pediatric Task Force data (22,897 physician visits)

Variable	Quantile								
	0.01	0.05	0.1	0.25	0.5	0.75	0.9	0.95	0.99
Intercept	−13.6	−17.0	−42.5	−25.4	−0.8	14.4	13.7	10.9	−2.7
Age									
x_1	−1.13	2.25	3.16	2.72	1.69	1.40	1.79	1.71	3.81
x_2	−1.71	−3.79	−3.82	−3.25	−2.43	−1.94	−2.09	−1.54	−2.31
x_3	28.86	23.13	16.96	13.53	12.06	11.15	11.89	6.08	3.52
x_4	−81.17	−35.18	−12.00	−4.04	−8.67	−15.71	−20.30	−5.59	8.02
Height									
h_1	0.41	0.29	0.47	0.42	0.36	0.31	0.34	0.39	0.40
h_2	0.00	0.00	−0.01	−0.01	−0.00	−0.00	−0.01	−0.01	−0.01
h_3	−0.03	−0.05	−0.02	0.00	−0.00	0.01	0.02	0.05	0.02
h_4	0.05	0.14	0.11	0.04	0.03	−0.00	−0.03	−0.06	0.06
Age × height									
z_1	−0.01	−0.06	−0.03	−0.05	−0.09	−0.07	−0.05	−0.03	0.06
z_2	−0.12	0.4	0.36	0.37	0.37	0.22	0.19	0.15	0.04
z_3	0.30	−0.66	−0.59	−0.63	−0.63	−0.33	−0.30	−0.23	−0.05
z_4	−0.27	0.26	0.22	0.28	0.28	0.08	0.10	0.06	−0.02

APPENDIX TABLE 4. Regression coefficients for diastolic blood pressure (Korotkoff 5) in girls, obtained from quantile regression models using Pediatric Task Force data (22,120 physician visits)

Variable	Quantile								
	0.01	0.05	0.1	0.25	0.5	0.75	0.9	0.95	0.99
Intercept	36.3	15.9	9.1	21.7	43.4	42.4	31.5	42.9	106.9
Age									
x_1	−0.45	−0.35	0.14	−0.26	−1.48	−0.25	−0.19	−0.21	−0.86
x_2	−0.23	−0.65	−1.08	−0.23	1.48	0.36	0.85	1.27	1.94
x_3	28.85	19.54	16.10	6.69	−2.83	1.58	−5.00	−7.75	−5.95
x_4	−129.83	−72.08	−48.10	−20.92	−7.69	−13.36	5.54	8.43	−7.02
Height									
h_1	−0.02	0.23	0.27	0.26	0.22	0.20	0.33	0.26	−0.13
h_2	0.00	−0.00	−0.00	−0.00	−0.00	−0.00	−0.01	−0.01	0.00
h_3	0.05	0.10	0.04	0.03	0.07	0.04	0.08	0.07	0.06
h_4	−0.27	−0.51	−0.17	−0.15	−0.27	−0.10	−0.23	−0.18	−0.28
Age × height									
z_1	−0.06	0.01	−0.03	−0.02	−0.03	−0.02	−0.00	0.01	−0.12
z_2	−0.30	−1.35	0.58	0.03	−0.35	0.18	−0.37	−0.44	0.59
z_3	0.63	2.08	−0.85	0.01	0.55	−0.25	0.59	0.68	−0.76
z_4	−0.55	−1.00	0.34	−0.08	−0.27	0.09	−0.32	−0.32	0.14