Blood Pressure Changes During Adolescence and Subsequent Adult Blood Pressure Level

BARBARA WOYNAROWSKA, DEBABRATA MUKHERJEE, ALEX F. ROCHE, AND ROGER M. SIERVOGEL

SUMMARY Serial data were analyzed for blood pressure recorded between the ages of 9 to 18 years for 278 children and for a subset of this group whose blood pressure was measured at the age of 30 ± 5.0 years (n = 93). Blood pressures were measured by auscultation over the antecubital fossa with the participant seated. Systolic blood pressure was recorded when the first sound was heard, and diastolic blood pressure was recorded when all sounds disappeared (fifth phase). A linear regression model was fitted to the data for each individual, and adjustments were made for regression toward the mean using maximum likelihood procedures. There were no significant correlations between the estimated initial values of blood pressure and the rate of change from 9 to 18 years of age. The associations between the levels of blood pressure at 9 years of age and at 30 years of age were significant for systolic blood pressure only in male subjects and were not significant for diastolic blood pressure in either sex. The correlations between the rate of blood pressure change from 9 to 18 years of age and blood pressure levels at 30 years of age were nonsignificant. When the initial values and the rate of change in blood pressure from 9 to 18 years of age were taken into account simultaneously, they accounted for approximately 20% of the variation in systolic blood pressure levels at 30 years of age. This finding indicates that children with higher blood pressure levels at about 9 years of age and with rapid increases in blood pressure during pubescence may have an increased risk of becoming hypertensive. The sib-sib correlations for the estimated blood pressure levels at 9 years of age were significant and generally similar to those previously reported from cross-sectional studies. The correlations between the rates of blood pressure change from 9 to 18 years of age for sibling pairs were nonsignificant. (Hypertension 7: 695-701, 1985)

KEY WORDS blood pressure • longitudinal study • children • adults • familial aggregation

There is considerable practical and theoretical interest in the extent to which there is tracking of blood pressure (BP). Tracking is defined as the maintenance, over time, of relative rank for a variable and thus an ability to predict subsequent observations based on earlier values. Many have reported that tracking of BP occurs in children and adolescents,1-6 but others have found a lack of tracking, especially during pubescence.7-12

Little is known about the relationship between BP level and the rate of change in BP during childhood and adolescence. Hofman and Valkenburg13 reported that the initial level of BP was negatively associated with subsequent change in systolic (SBP) and diastolic (DBP) blood pressure, even after adjusting for regression toward the mean. The relationship between the rate of change in BP during adolescence and the level of BP in adulthood is unknown. The aims of the present study were to investigate the relationship between BP before pubescence (9 yr of age) and the change in BP from 9 to 18 years of age and the associations between these values and adult BP levels. An additional aim was to estimate the strength of the associations between siblings for BP at 9 years of age and for the change in BP from 9 to 18 years of age.

Material and Methods

The data were obtained from a subset of 146 male and 132 female participants in the Fels Longitudinal Study. The participants were white, were generally of

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middle socioeconomic status, and lived in southwestern Ohio when they were enrolled. The participants were examined semiannually near their birthdays and half-birthdays. For inclusion in these analyses at least 12 of the possible 19 serial measurements of BP were required for each individual between the ages of 9 and 18 years; the median number of measurements per individual was 15. These children were all prepubertal at the age of 9 years (Tanner, stage 1), except for a few girls who had early stages of breast and pubic hair development. All of the children in this study were already familiar with the procedures for the measurement of BP, because of their previous semiannual visits. A subset of the sample (49 males and 44 female subjects) had measurements of BP levels within the age range 30 ± 5 years. The study group included 203 siblings in 73 nuclear families with two or more offspring per family.

The BP values were obtained by auscultation during routine scheduled examinations. Prior to 1973, about 95% of these BP values were measured by one of four research physicians who were long-term senior members of the Fels Research Institute staff. Since 1973, blood pressures have been measured by research technologists who received extensive special training. These pressures were measured on the left arm with the participant sitting quietly and relaxed. A wall model mercury sphygmomanometer (W.A. Baum Co., Copiague, NY, USA) was used with a cuff chosen such that the width was about two-thirds the length of the upper arm. The SBP was recorded when the first sound was heard in the antecubital fossa, and the DBP was recorded when there was a total disappearance of sounds (fifth phase). Diastolic pressures at the fifth phase were analyzed rather than those at the fourth phase because prior to 1973 most fourth phase diastolic pressures were not measured. Since 1973, both fourth and fifth phase diastolic pressures have been measured. Prior to 1976, BP values were measured once at each examination. Since that time, BP has been measured three times at each examination, and the means of the second and third of these measurements were used in the analyses.

Since 1976, replicability of BP measurement has been monitored. In one such study, 100 participants were chosen at random for the analysis of intraobserver errors of measurement. The SBP and DBP were recorded by one observer with two subsequent replicates at the same examination. The mean absolute difference between the first and second measurements, the standard deviation of this difference, the technical error of measurement, the coefficient of variation, and the coefficient of reliability are presented in Table 1. The technical error of measurement is the square root of the sum of squares of differences within an observer. This figure is comparable to the mean and SD of the absolute differences. The coefficient of variation is the ratio of the technical error of measurement to the overall mean. This is somewhat different from the usual coefficient of variation, which relates to the distribution of a variable. Finally, an estimate of the coefficient of reliability of the interclass correlation (i.e., an estimate of the sameness of two replicated measurements) is provided. These analyses showed that the measurements of SBP tended to be more reliable than those of DBP, but both sets of measurements had rather small technical errors, some of which would have been due to short-term physiological fluctuations.

The statistical analysis included fitting a linear model to the serial data for each individual using the following formula: \( y_{ij} = \beta_0 + \beta_1 t_i + e_{ij} \), where \( y_{ij} \) is the observed SBP or DBP for \( i \)th individual on the \( j \)th occasion, \( \beta_0 \) is the intercept at 9 years, \( \beta_1 \) is the slope, \( t_i \) is the \( j \)th time point for the \( i \)th individual, \( e_{ij} \) is the random error, and \( P_i \) is the number of available data points for the \( i \)th individual. Thus, for each individual, \( \hat{\beta}_1 \) is the estimated initial value, \( \hat{\beta}_1 \) is the rate of change, and \( t_i \) is estimated. The simple adjustment might drastically change the magnitude and the direction of the slope. A detailed comparison between the least squares estimates of \( \hat{y} \) and its estimation by the maximum likelihood method is given by Wu and colleagues, who demonstrated that the latter provides more consistent solutions.

Correlations were calculated between the estimates of the initial values (\( \hat{\beta}_0 \) at 9 years and the slopes (rate of change from 9 to 18 years of age; \( \hat{\beta}_1 \)) with adult BP. In addition, familial correlations for the estimated parameters and their z-transformations were calculated using the Statistical Analysis System. Since multiple sib pairings may be constructed in sibships with more than two children, the total number of sibships, rather

<table>
<thead>
<tr>
<th>Variable</th>
<th>SBP</th>
<th>DBP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean ± SD of 1st measurement (mm Hg)</td>
<td>102 ± 11</td>
<td>59 ± 10</td>
</tr>
<tr>
<td>Mean ± SD of 2nd measurement (mm Hg)</td>
<td>102 ± 11</td>
<td>59 ± 10</td>
</tr>
<tr>
<td>Overall mean ± SD (mm Hg)</td>
<td>102 ± 11</td>
<td>59 ± 10</td>
</tr>
<tr>
<td>Mean ± SD of absolute intra-observer differences (mm Hg)</td>
<td>4 ± 4</td>
<td>5 ± 4</td>
</tr>
<tr>
<td>Technical error of measurement (( \delta_z ; mm Hg ))</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Coefficient of variation (%)</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Coefficient of reliability (( \omega^2 ))</td>
<td>85</td>
<td>78</td>
</tr>
</tbody>
</table>


than the total number of pairs, was used as the sample size for the various sibling correlations. This underestimates the true sample size; consequently, the asymptotic standard errors are inflated.

**Results**

The mean SBP and DBP by age and sex are given in Table 2. There were significant sex differences only for SBP at 14.5 through 30 years of age and for DBP at 30 years of age with larger means for the male subjects than for the female subjects. In each sex, the means for SBP increased with age in a rather regular fashion without evidence of a pubescent spurt. The increase in the means for SBP from 18 to 30 years of age was markedly greater for male subjects (5 mm Hg) than for female subjects (1 mm Hg). The standard deviations for SBP did not tend to increase with age until 13.0 years of age in male subjects and 10.0 years of age in female subjects. After these ages, the increases were small and irregular in each sex. The means for DBP at 14.5 through 30 years of age were slightly larger from 15.0 years of age in male subjects and 10.0 years of age in female subjects. After these ages, the increases were markedly greater for male subjects (5 mm Hg) than for female subjects (1 mm Hg). The standard deviations for DBP did not tend to increase with age until 13.0 years of age in male subjects they were slightly larger from 15.0 to 17.0 years of age than at other ages.

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The distributions of the estimated individual initial values ($\beta_0$) of SBP at 9 years of age were unimodal in each sex (Figure 1). The distribution was skewed slightly to the right in the boys but was not significantly different from normal in the girls. The distribution of the estimated rate of change ($\beta_1$) in SBP from 9 to 18 years of age was close to symmetrical in the male subjects but was slightly skewed to the left in the female subjects. The means for the regression parameters ($\beta_0$ and $\beta_1$) for SBP differed significantly from zero ($p < 0.0001$). There were significant sex differences for the estimated initial values for SBP with a larger mean value for the female subjects than for the male subjects ($p < 0.05$) and for the estimated rate of change ($p < 0.001$). The estimated mean rate of change in SBP, as estimated from individual linear regressions of SBP on age, was 2.4 mm Hg/yr (SD ± 1.1 mm Hg) in the male subjects and 1.3 mm Hg/yr (SD ± 1.4 mm Hg) in the female subjects.

The distributions of the estimated initial values and rates of change for DBP were normal in each sex (see Figure 1), and there was no significant sex difference in either of these values. The estimated mean rates of change for DBP were 0.8 mm Hg/yr in each sex (SD ± 1.1 mm Hg/yr for male subjects and ± 1.0 mm Hg/yr for female subjects). Examples of the fit of the function to the observed data for randomly selected individuals are presented in Figure 2. These graphs illustrate some of the fluctuations in the recorded BP that reflect the sums of measurement errors and physiological variations.

The regression coefficients ($\gamma_1$ and $\gamma_2$) of the rates of change in BP from 9 to 18 years of age on the estimated initial values, and their standard errors, were calculated using both linear regression and maximum likelihood methods (Table 3). Each of these methods showed a negative relationship between BP level at about 9 years of age and the change in BP from 9 to 18 years of age. The linear regression coefficients were negative and significantly different from zero in the male subjects and in the female subjects ($p < 0.0001$). The $R^2$ values indicate that, in the male subjects, 26% of the variance of the SBP change and 15% of the variance of the DBP change could be accounted for by the initial values. The corresponding percentages of the variance explained for the female subjects were 33% and 41% respectively. The adjusted coefficients for the rates of change in SBP and in DBP using the maximum likelihood method were negative for each sex, but they were nearer zero than the values before adjustment (see Table 3).

The estimated initial BP at 9 years of age and the rate of change from 9 to 18 years of age for each individual were regressed against observed BP at 30 ± 5 years of age (Table 4). Using the partial $F$-test criterion, the regression coefficients for both initial value and rate of change were significant at the 0.01 level. Eighteen percent of the variance in adult SBP for men and 21% of the variance for women were accounted for by this model. The corresponding estimated values for DBP accounted for relatively little of the variance in DBP at
**Figure 1.** The distributions of the estimated initial values ($\beta_0$) and the rates of change ($\beta_1$) in systolic and diastolic blood pressure from 9 to 18 years of age in male and female subjects.

<table>
<thead>
<tr>
<th>Method used</th>
<th>Boys</th>
<th>Girls</th>
<th>Boys</th>
<th>Girls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression $R^2$</td>
<td>0.26</td>
<td>0.33</td>
<td>0.15</td>
<td>0.41</td>
</tr>
<tr>
<td>Linear regression coefficient ($\beta_1$ $\pm$ SE)</td>
<td>$-0.08 \pm 0.01$</td>
<td>$-0.10 \pm 0.01$</td>
<td>$-0.08 \pm 0.02$</td>
<td>$-0.10 \pm 0.01$</td>
</tr>
<tr>
<td>Variance of initial value (mm Hg²)</td>
<td>50</td>
<td>65</td>
<td>28</td>
<td>42</td>
</tr>
<tr>
<td>Avg mean square error from linear regression of BP on age (mm Hg²)</td>
<td>46</td>
<td>42</td>
<td>49</td>
<td>45</td>
</tr>
<tr>
<td>Maximum likelihood Adjustment coefficient ($\lambda$)</td>
<td>0.93</td>
<td>0.64</td>
<td>1.73</td>
<td>1.07</td>
</tr>
<tr>
<td>Adjusted regression coefficient ($\gamma$ $\pm$ SE)</td>
<td>$-0.06 \pm 0.01$</td>
<td>$-0.09 \pm 0.01$</td>
<td>$-0.04 \pm 0.03$</td>
<td>$-0.09 \pm 0.01$</td>
</tr>
</tbody>
</table>
RATES OF BLOOD PRESSURE CHANGE DURING CHILDHOOD/Woynarowska et al.

**Figure 2.** The observed data and linear regression lines for systolic and diastolic blood pressures in two randomly selected subjects.

![Graphs showing systolic and diastolic blood pressures over age](image)

**Table 4.** Regression Coefficients of Estimated Initial Values (9 yr of age) and Rates of Change in Blood Pressure (BP) from 9 to 18 Years of Age on Adult (30 ± 5 yr of age) Levels of Systolic and Diastolic Blood Pressure

<table>
<thead>
<tr>
<th>Sex</th>
<th>Systolic BP</th>
<th>Diastolic BP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial value (mm Hg)*</td>
<td>Rate of change (mm Hg/yr)*</td>
<td>R²</td>
</tr>
<tr>
<td>Males</td>
<td>0.62†</td>
<td>0.20</td>
</tr>
<tr>
<td>Females</td>
<td>0.60†</td>
<td>0.19</td>
</tr>
</tbody>
</table>

**Table 5.** Sib-sib Correlations for Estimated Initial Blood Pressure at 9 Years of Age and Rates of Change in Blood Pressure (mm Hg/yr) from 9 to 18 Years of Age (n = 203 pairs)

<table>
<thead>
<tr>
<th>Blood pressure</th>
<th>Initial value</th>
<th>Rate of change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>z</td>
</tr>
<tr>
<td>Systolic</td>
<td>0.33*</td>
<td>0.36</td>
</tr>
<tr>
<td>Diastolic</td>
<td>0.23*</td>
<td>0.24</td>
</tr>
</tbody>
</table>

*Coefficients ± SE.
†p < 0.01 and ‡p < 0.05.

30 years of age in either sex, and the regression coefficients were not statistically significant (except for the initial value in male subjects).

Sib-sib correlations were calculated for the initial values and for the rates of change in BP that were estimated by linear regression (Table 5). All the correlations were positive. They were significant for all sib-sib pairings of estimated SBP and DBP at 9 years of age (p < 0.01) but not for rates of change from 9 to 18 years of age. Also, there were significant correlations for the initial values in subtypes of sib-sib pairings (p < 0.01) except for brother-brother pairings of SBP and sister-sister pairings of DBP. The subtype correlations for rate of change of BP were nonsignificant except for SBP in brother-brother pairs and for DBP in sister-sister pairs.

**Discussion**

The mean BP values for the participants in the present study were lower than the U.S. reference means and were generally between the 5th and 10th percentiles of the reference data recommended by the Task Force on Blood Pressure Control in Children. Similar differences from the national reference values have been reported from a large survey of U.S. children. These differences may be attributed to actual differ-
ences in BP among groups or to biases caused by methodological differences. In the present study, lower values would be expected because of the habituation associated with serial measurements. The average rate of increase in BP as measured by the mean rate of change in BP from 9 to 18 years of age was generally in agreement with that reported for Dutch children.13

Fluctuations were present in the serial BP measurements. Several sources of such fluctuations have been reported: real or biological intraindividual variations, some of which may be associated with growth and maturation,7-9,20 effects of environmental factors such as season, diurnal variations, and responses to environmental temperature21,22 and measurement errors.7,8,22-25 Most of the data analyzed in the present study were obtained by single sets of BP measurements at each examination. There were no significant differences between the means of the first and second sets of BP measurements in a randomly selected group of participants. This finding is in agreement with some previous reports,7,26 but larger differences have been reported in older children.27 It was considered justifiable to pool data from examinations when only one set of BP measurements was recorded with the means for multiple sets recorded at other examinations because the differences were not significant in the present data.

In the present study, the technical errors of measurement, for data recorded since 1976, were 4 mm Hg and 5 mm Hg for SBP and DBP respectively; these values were comparable to the mean absolute differences between the first and second sets of measurements. The coefficient of variability was twice as large for DBP as it was for SBP. This finding may be related to the larger interclass correlations for SBP than for DBP. These fluctuations were present in the serial BP measurements that reflect the sums of measurement errors and biological intraindividual variations. These fluctuations support conclusions regarding the difficulty of predicting future BP from single casual measurements in children and adolescents.23,27,28 These fluctuations also may be responsible for the variations among reports concerning the possible tracking of BP during childhood.1-12

In the present data, there were significant negative associations between the initial BP values at 9 years of age and the rates of change from 9 to 18 years of age in each sex, when an unadjusted linear regression method was used. After adjustment for regression toward the mean by the maximum likelihood method, the regression coefficients of rate of change on initial values were still negative but were closer to zero. This finding is in agreement with the report of Hofman and Valkenburg,13 who found nonsignificant correlations between the initial BP value and the rate of BP change for Dutch children aged 5 to 19 years. Reports concerning such relationships in adults are discordant. Some have reported positive correlations between the initial BP level and the rate of BP change from analyses by the maximum likelihood method,15,29 but others have reported negative correlations.13 The present findings and those of Hofman and Valkenburg13 suggest that the more consistent lack of a significant relationship in children than in adults may be due to the greater intraindividual variability of BP measurements in children than in adults. This variability may be associated with interindividual differences among children in maturity at an age and in rates of growth in stature, and weight and in indices of body composition, such as the body mass index (weight/height²). These factors are being analyzed in relation to BP using data from the children included in the present study (unpublished observations, 1985).

In the present study, the initial SBP values were significantly correlated with those at 30 years of age in male subjects only. Significant associations (r from +0.19 to +0.52) between SBP and DBP levels in childhood with those in young adulthood have been reported in earlier studies.3-5,6 Correlations between the rates of change in BP during puberty and the levels at 30 years of age were nonsignificant in the present study for each sex. When the initial values and the rates of change were taken into account simultaneously there were significant positive correlations with SBP in adulthood for each sex. About 20% of the variance of SBP at 30 years of age can be accounted for by the estimated BP at 9 years of age and the rate of change in BP from 9 to 18 years of age, which provides further evidence for tracking. These findings show that children with high SBP at about 9 years of age and a rapid rate of increase in BP during pubescence and adolescence tend to have elevated BP in adulthood.

Previous studies of familial correlations for BP have used cross-sectional data. In the present longitudinal study, the sib-sib correlations for the estimated SBP and DBP at 9 years of age were positive and significant even using conservative standard errors. These correlations were generally similar to those reported from other studies.30-31 On the other hand, there was no strong evidence for sibling resemblance for the rate of change in BP from 9 to 18 years of age. By themselves, the sibling correlations provide little information about the genetic involvement in these traits, since this familial resemblance may result from shared genes or shared environments or both. Almost all sib-sib correlations for the rate of BP change within subtypes of sibships were nonsignificant. In agreement with earlier reports,20,30,32,33 the pattern of intrafamilial correlations did not suggest sex effects.

In conclusion, the correlations between BP levels before pubescence and the rates of change in BP from 9 to 18 years of age were near zero, particularly after correcting for regression to the mean. The inability to predict future values of BP from single casual measurements supports the need for serial BP measurements, perhaps at annual intervals, as a part of preventive health care. Serial data may be difficult to interpret because of short-term fluctuations, but benefits could be expected if the methods are carefully standardized. Childhood serial data (e.g., the estimated BP at 9 yr of age and the rate of change from 9 to 18 yr of age) accounted for 20% of the variation in SBP at 30 years of age in the present study, which indicates the need
for serial data so that the rate of change can be established. Children with higher BP levels at about 9 years of age and with large increases in BP from 9 to 18 years of age may have an increased risk of becoming hypertensive.

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B Woynarowska, D Mukherjee, A F Roche and R M Siervogel

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