Innovative Blood Pressure Measurements Yield Information Not Reflected by Sitting Measurements
LYNN B. JORDE AND ROGER R. WILLIAMS

SUMMARY A study of 873 healthy adults and children from Utah kindreds was performed to identify redundant and unique information contained in multiple diverse blood pressure determinations. Systolic blood pressure, fourth-phase and fifth-phase diastolic blood pressures, and simultaneous heart rates were measured in subjects sitting, standing, supine, and tilting, during half-maximal handgrip exercise, and just before blood drawing. A correlation matrix of 57 blood pressure and pulse variables in 618 healthy adults was analyzed. Factor analysis of the correlation matrix showed that all systolic blood pressures loaded as a single factor, accounting for 44% of the total variance of the observed variables. All heart rates also loaded together as a single factor. Diastolic blood pressures showed much more heterogeneity of information distributed among five separate factors. The same basic factors were found in young adults (age, 18-35 years) and older adults (age, 36+ years). Children under 12 years of age showed very different factor patterns, and youths 12 to 17 years of age showed patterns intermediate between those of adults and children. In light of recent clinical trials, better definitions are being sought for hypertension. Information from blood pressures other than sitting determinations may improve the definition of hypertension or better predict which patients have the highest risk of hypertension and its cardiovascular complications.

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KEY WORDS • diastolic blood pressure • correlation • factor analysis • systolic blood pressure • blood pressure determinants

In many studies of blood pressure, measurements are made only on subjects resting in a sitting position, although blood pressure values are known to vary considerably, depending on levels and types of activity. In addition, different subjects can respond quite differently to the same variation in activity. For example, diastolic blood pressure rises on standing in some persons but drops in others. Such differences may well reflect basic physiological mechanisms that vary in subgroups of the population. Variation in these mechanisms among healthy subjects could be due to differences in genetic constitution or to environmental factors such as salt intake or obesity. Analysis of multiple blood pressure measurements under a variety of circumstances may thus provide clues to the heterogeneous components that underlie blood pressure variation.

The present study analyzed a battery of 15 blood pressure and pulse measurements. Multivariate statistical techniques were used to investigate patterns of correlation among the measurements. The study sample was divided into four age groups to determine if these correlation patterns changed with age.

The blood pressure factors obtained in this study were tested for associations with 35 predictive variables (e.g., body size, obesity, sodium excretion, biochemical variables) in a subsequent study. The correlation patterns of independent blood pressure factors with predictive variables should yield further insight into the physiological mechanisms and population heterogeneity of blood pressure variation.

Subjects and Methods
Data are reported on 618 healthy adults (age ≥ 18 years) and 255 healthy children (age < 18 years) who are members of large Utah kindreds. While many of these persons are from hypertension-prone kindreds, none of them were receiving medication for hypertension at the time of evaluation. These samples were stratified into four age groups for analysis: 1 to 11 years, 12 to 17 years, 18 to 35 years, and older than 35 years. The study protocol described herein was ap-
proved by the Institutional Review Board of the University of Utah School of Medicine.

All subjects attended clinic on weekdays from 0800 to 1200 in a fasting state, having consumed their last meal on the previous evening. They had been instructed to avoid smoking cigarettes before coming to clinic and during the clinic examination.

Fifteen determinations of systolic blood pressure, fourth-phase and fifth-phase diastolic blood pressure, and simultaneous heart rate measurements were obtained during six controlled clinic situations: just before blood drawing; after several minutes of rest in supine position; 30 and 60 seconds after being raised to 50 degrees on a tilt table; 2 minutes after resumption of supine position from tilt; sitting (6 measurements); standing (2 measurements); and after 1½ minutes of half-maximal isometric handgrip exercise. After each blood pressure measurement was obtained, a resting period of 2 or more minutes was allowed so that the subject could begin each test in approximately equivalent circumstances. The subject’s pulse was recorded before provocative maneuvers such as standing or isometric handgrip exercise. The resting period after each test was maintained until the subject’s heart rate returned to the baseline value before beginning the next test.

It was not possible to have all subjects pass through the sequence of tests in the same order. To test the effect of the order of examinations on blood pressure determinations, 10 subjects underwent each of the tests repetitively on 4 consecutive days. On Days 1 and 3, the tests were performed beginning with the least stressful and progressing to more stressful maneuvers (the first test was supine blood pressure, and the last was isometric handgrip pressure). On Days 2 and 4, stressful and nonstressful tests were administered alternately (e.g., handgrip pressure followed by supine pressure followed by standing pressure). Analysis of these data demonstrated that both systolic and diastolic blood pressures were entirely equivalent in the two sequences. As in the protocol used for all subjects, rest periods were given to allow the heart rate to return to baseline value before proceeding to the next test.

In earlier stages of sampling, more tilt measurements were taken (up to 6 minutes), but these were discontinued after finding nearly perfect correlation of later tilt readings with the 30-second and 1-minute measurements. Two blood pressure measurements were also taken during blood drawing in earlier stages. These were terminated after finding nearly perfect correlations with the measurements taken just before blood drawing.

Most blood pressure determinations were obtained using Sphygmometrics Infrasonde SR-II automated devices (no longer available) calibrated daily with a mercury manometer. Two of the six sitting measurements were obtained using the Hawksley Random Zero Sphygmomanometer (Gelman Instrument, Ann Arbor, MI, USA) operated by screeners trained according to guidelines from the Hypertension Detection and Follow-up Program. Using double-lumen stethoscopes, screeners were trained to obtain blood pressure measurements that would agree within plus or minus 2 mm Hg when simultaneous determinations were made on the same subject. Audiograms were administered to all screeners to verify auditory acuity. Cuff sizes used included large adult cuff, regular adult cuff, and pediatric cuff. Cuff use followed standard clinical guidelines, and cuff type was recorded for each subject. Blood pressure recording disks obtained from the SR-II automated device traced the actual Korotkoff sounds. The deflation rate of the blood pressure cuff was controlled to maintain a difference of no more than 2 mm Hg between each recorded Korotkoff sound. All disks were labeled and collected during clinic and read after the subjects had left. Systolic pressure was defined as the first deflection of Korotkoff sounds. Fourth-phase diastolic pressure was defined as the first Korotkoff sound showing marked decrease with continued decreasing amplitude of the recorded sound waves. Fifth-phase diastolic blood pressure was recorded as the cessation of any Korotkoff sounds. All blood pressure disks were read by two screeners who periodically both read the same set of disks to confirm the reproducibility of their interpretations.

Simultaneous heart rates were derived from electronic rate meters sensing the Korotkoff signals from the automated SR-II sphygmomanometers. A Jamar adjustable hand dynamometer (Asimow Engineering, Los Angeles, CA, USA) with quantitative strength indicator was used to determine maximal strength and to maintain and monitor half-maximal handgrip exercise with the subject’s left hand for 2 minutes while blood pressure was measured from the right arm.

Since the subjects were members of large kindreds, it was possible to evaluate the family history of hypertension for most subjects. A numerical index of family history was computed for 536 adults using the method of Williams et al.²

Product-moment correlations were computed between all pairs of variables. Since 57 variables were measured, the matrix of correlation values required reduction. This was done by using a standard factor analytic approach⁶ with varimax rotation. The SPSS statistical package⁷ was used to perform these operations. Factor analysis (and principal components analysis, a closely related technique) has been employed widely in the biological sciences as a means of reducing large correlation matrices to smaller sets of easily interpretable factors.⁸,⁹ The analysis yields one or more uncorrelated factors that account for the maximum possible variance of the observed variables. Each factor consists of a set of numerical loadings, one for each variable in the analysis. These loadings are correlation coefficients that express the relationship between each variable and the factor. A loading of zero would indicate no relationship between the variable and the factor, while a loading of 1.0 or −1.0 would indicate that the factor explains all of the variance of the variable. The number of factors retained for inspection is determined by the percent of total variance of the observed variables accounted for by each factor.
Typically, only those factors accounting for more variance than any single variable are retained. Since distributions of blood pressure measurements are typically somewhat skewed, they violate the normality assumptions desirable for factor analysis. Such skewness usually is not severe, however, and factor analysis is robust with regard to this assumption. Since more complex statistical tests requiring normality were not used, the measurements were not transformed.

Because the subjects were members of large kindreds, the assumption of independence of measurements was violated. Thus, statistical significance levels of the correlation measurements could be somewhat misleading. In this study, however, we were interested mainly in the patterns of correlation as they are reflected in the results of factor analysis.

### Results

The reproducibility of the measurements was analyzed for nine subjects (age, 7-49 years) who underwent the entire battery (except blood drawing) on 4 consecutive days. The coefficient of variation was 7% or less for systolic determinations in each of these settings and 8% or less for all diastolic measurements. This variation includes individual day-to-day variation and all measurement errors (apparently minimized quite well by the controlled protocol).

The usual effect of each measurement situation on blood pressure is indicated by the means and standard deviations listed in Table 1. Some of the correlations between different blood pressure measurements are summarized by the abbreviated correlation matrix in Table 2. Correlations between diastolic measurements were consistently lower than correlations between systolic measurements.

### Table 1. Means and Standard Deviations of Blood Pressure and Pulse Measurements

<table>
<thead>
<tr>
<th>Measurement variable</th>
<th>Age group (yr)</th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1-11 (n = 127)</td>
<td>12-17 (n = 128)</td>
<td>18-35 (n = 375)</td>
<td>36+ (n = 243)</td>
<td></td>
</tr>
<tr>
<td>Systolic BP</td>
<td>91.3 ± 11.0</td>
<td>101.3 ± 9.6</td>
<td>106.6 ± 10.4</td>
<td>117.0 ± 16.0</td>
<td></td>
</tr>
<tr>
<td>4th-phase DBP</td>
<td>55.9 ± 12.4</td>
<td>65.5 ± 9.2</td>
<td>72.8 ± 10.1</td>
<td>79.8 ± 11.6</td>
<td></td>
</tr>
<tr>
<td>5th-phase DBP</td>
<td>49.1 ± 12.6</td>
<td>58.9 ± 9.5</td>
<td>66.8 ± 9.4</td>
<td>73.6 ± 10.7</td>
<td></td>
</tr>
<tr>
<td>HR*</td>
<td>87.2 ± 12.1</td>
<td>77.0 ± 12.6</td>
<td>70.8 ± 10.7</td>
<td>70.3 ± 10.8</td>
<td></td>
</tr>
<tr>
<td>Systolic BP</td>
<td>89.1 ± 11.8</td>
<td>102.4 ± 10.3</td>
<td>107.8 ± 11.5</td>
<td>114.9 ± 16.6</td>
<td></td>
</tr>
<tr>
<td>4th-phase DBP</td>
<td>52.5 ± 12.3</td>
<td>62.2 ± 10.1</td>
<td>68.7 ± 10.0</td>
<td>74.5 ± 11.3</td>
<td></td>
</tr>
<tr>
<td>5th-phase DBP</td>
<td>45.9 ± 12.3</td>
<td>54.4 ± 10.7</td>
<td>63.0 ± 10.2</td>
<td>70.0 ± 11.3</td>
<td></td>
</tr>
<tr>
<td>Sitting automated</td>
<td>93.2 ± 12.8</td>
<td>108.1 ± 12.2</td>
<td>111.4 ± 12.6</td>
<td>119.1 ± 18.1</td>
<td></td>
</tr>
<tr>
<td>Systolic BP</td>
<td>61.0 ± 13.1</td>
<td>72.7 ± 12.3</td>
<td>76.9 ± 10.3</td>
<td>81.5 ± 11.7</td>
<td></td>
</tr>
<tr>
<td>4th-phase DBP</td>
<td>64.0 ± 13.5</td>
<td>65.1 ± 13.6</td>
<td>70.6 ± 11.6</td>
<td>75.0 ± 14.5</td>
<td></td>
</tr>
<tr>
<td>5th-phase DBP</td>
<td>103.8 ± 14.1</td>
<td>95.0 ± 14.1</td>
<td>87.1 ± 13.1</td>
<td>82.4 ± 13.2</td>
<td></td>
</tr>
<tr>
<td>Standing</td>
<td>92.1 ± 12.9</td>
<td>108.4 ± 11.8</td>
<td>113.4 ± 11.9</td>
<td>122.1 ± 16.3</td>
<td></td>
</tr>
<tr>
<td>Systolic BP</td>
<td>53.7 ± 10.6</td>
<td>60.5 ± 9.1</td>
<td>64.6 ± 9.3</td>
<td>71.1 ± 9.4</td>
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</tr>
<tr>
<td>4th-phase DBP</td>
<td>45.6 ± 11.1</td>
<td>50.8 ± 10.0</td>
<td>57.2 ± 11.1</td>
<td>63.7 ± 10.8</td>
<td></td>
</tr>
<tr>
<td>5th-phase DBP</td>
<td>79.2 ± 13.3</td>
<td>65.7 ± 12.3</td>
<td>62.5 ± 11.2</td>
<td>62.8 ± 11.4</td>
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<tr>
<td>Supine</td>
<td>96.6 ± 13.2</td>
<td>109.1 ± 11.8</td>
<td>113.9 ± 12.7</td>
<td>119.3 ± 16.7</td>
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</tr>
<tr>
<td>Systolic BP</td>
<td>63.7 ± 10.9</td>
<td>70.2 ± 9.7</td>
<td>76.5 ± 10.0</td>
<td>82.2 ± 9.9</td>
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<tr>
<td>4th-phase DBP</td>
<td>55.9 ± 12.6</td>
<td>60.9 ± 11.9</td>
<td>69.1 ± 11.0</td>
<td>75.4 ± 12.1</td>
<td></td>
</tr>
<tr>
<td>5th-phase DBP</td>
<td>97.2 ± 13.2</td>
<td>86.9 ± 14.8</td>
<td>80.5 ± 14.1</td>
<td>76.0 ± 12.9</td>
<td></td>
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<tr>
<td>Tilt</td>
<td>98.9 ± 15.6</td>
<td>123.9 ± 17.2</td>
<td>130.1 ± 19.6</td>
<td>144.0 ± 24.7</td>
<td></td>
</tr>
<tr>
<td>Systolic BP</td>
<td>63.5 ± 16.6</td>
<td>83.9 ± 14.0</td>
<td>89.9 ± 16.2</td>
<td>96.2 ± 16.3</td>
<td></td>
</tr>
<tr>
<td>4th-phase DBP</td>
<td>57.1 ± 17.3</td>
<td>77.2 ± 14.0</td>
<td>84.4 ± 16.5</td>
<td>90.9 ± 16.0</td>
<td></td>
</tr>
<tr>
<td>5th-phase DBP</td>
<td>108.6 ± 15.5</td>
<td>101.6 ± 14.5</td>
<td>92.6 ± 15.5</td>
<td>91.9 ± 15.2</td>
<td></td>
</tr>
<tr>
<td>Grip</td>
<td>99.7 ± 11.2</td>
<td>113.0 ± 13.9</td>
<td>115.1 ± 13.8</td>
<td>123.3 ± 17.0</td>
<td></td>
</tr>
<tr>
<td>Systolic BP</td>
<td>59.9 ± 9.4</td>
<td>67.5 ± 9.2</td>
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<td>77.9 ± 11.7</td>
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</tbody>
</table>

Values are means ± SD. Pulse measurements are the second measurement in all instances except blood draw. BP = blood pressure; DBP = diastolic blood pressure; HR = heart rate.

*This heart rate value applies to both automated and random zero sitting measurements.
...variables. The percentage of variance sub-
sumed in each factor is also given. In total, these nine
factors accounted for 81.2% of the variance of the 57
variables.

All of the systolic blood pressure measurements had
high loadings (>0.67) on the first factor, which ac-
counted for 44.5% of the total variance. The diastolic
blood pressure measurements had much lower load-
ings (0.30–0.40) on the first factor. This result reflects
the fact that the moderate correlations between dia-
static and systolic measurements were lower than the
correlations among systolic measurements them-
selves. Since the factors were uncorrelated, the re-
main ing factors represent correlations obtained after
controlling for the effects of this first factor.

The fourth-phase and fifth-phase diastolic measure-
ments in each setting were always very highly correlat-
ed (>0.90), so they always loaded on the same fac-
tors. Hereafter, they will be referred to together.

The second factor consisted of all of the supine and
tilt diastolic measurements, while the third factor had
high loadings for all of the sitting diastolic measure-
ments. Most of the pulse measurements had high load-
ings on the fourth factor. Factors 5, 6, and 7 contained
separate and distinct high loadings for diastolic blood
pressure during isometric handgrip, while standing,
and before blood drawing, respectively. The final two
factors, which account for very little additional vari-
ance, had high loadings for pulse measurements during
handgrip exercise and blood drawing.

Factor analysis was also performed separately on
young adults (age, 18–35 years) and older adults (age
>35 years). The results for each group were nearly
identical.

Since the systolic measurements all loaded on one
factor while the diastolic measurements separated into
five different factors, one should typically observe
greater intrindividual variation in diastolic blood
pressure than in systolic blood pressure when these are
measured in different environments. To verify this as-
sumption with direct measurements, average sitting
blood pressure (2 automated measurements) was sub-
tracted from average standing blood pressure (2 auto-
mated measurements). Table 4 shows the distribution
of these differences. It is consistent with the factor
analysis results that 41% of the diastolic measurements
showed differences greater than 10 mm Hg in the
standing versus sitting positions, while only 29% of
the systolic measurements showed differences of this
magnitude. For most persons, standing pressure was
higher than sitting pressure, but the reverse was true
Factor 1, which accounted for 40.5% of the total variance of the correlation matrix, had high loadings for all of the supine and tilt blood pressure measurements (both systolic and diastolic). All of the systolic measurements loaded highly on Factor 2, although the supine and tilt systolic measurements had comparatively low loadings (0.50–0.55). Factor 3 consisted of some resting diastolic measurements and all of the handgrip blood pressure measurements (systolic and diastolic). Most of the pulse measurements loaded on Factor 4, and most of the sitting diastolic measurements loaded on Factor 5. Factor 6 consisted of all standing blood pressure measurements (diastolic and systolic), Factor 7 contained the blood draw diastolic measurements, and Factor 8 contained the supine and tilt pulse measurements.

The nine factors for the 128 youths aged 12 to 17 years are shown in Table 6. This pattern was much more similar to that of the adult sample. All of the systolic measurements loaded highly on the first factor, and nearly all of the pulses loaded on the second factor. Tilt diastolic pressures loaded on the third factor, and the sitting diastolic pressures split into Factors 4 and 7. Factor 5 contained the handgrip diastolic measurements, with some loading of the handgrip systolic measures (as in Table 3). Factors 6, 8, and 9 contained standing diastolic measures, blood draw diastolic measures, and blood draw pulses, respectively.

To test the effects of a family history of hypertension on these results, factor analysis was performed.
separately for 79 adults with strong family histories (score > 1.0) and for 457 adults without strong family histories. The results for the latter sample were virtually identical to those given in Table 3. For the sample with strong family histories of hypertension, the results were again essentially identical with those of Table 3: all systolic blood pressure measurements appeared on the first factor, pulse measurements appeared on Factor 3, and the different types of diastolic blood pressure were distributed on the other seven factors. Thus, family history of hypertension appears to have little effect on the covariance patterns of different types of blood pressure.

Discussion

Evidence from past studies indicates that systolic and diastolic blood pressure each provide useful information. Each has shown independent contributions to risk predictions based on multivariate analysis of risk factors for coronary disease. This study shows homogeneity of information in diverse systolic blood pressure measurements (except among young children). Correlation coefficients for all pairs of systolic measurements ranged from 0.65 to 0.95. On the other hand, these data suggest major heterogeneity for the information in diastolic blood pressures measured while subjects were sitting, standing, supine, or performing handgrip exercises and before blood drawing. Although all of the diastolic blood pressure measurements were positively correlated with one another, the correlations were considerably higher (0.70–0.80) among those that loaded on the same factor than among those that loaded on different factors (0.30–0.60). Diastolic blood pressure measurements may thus be a more finely tuned indicator of population heterogeneity than are systolic measurement or pulses. It would be interesting to know how these separate diastolic blood pressure measurements would associate with risk of hypertension, stroke, and coronary disease.

A second finding of interest is that young children had very different patterns of correlation than older children and adults. In particular, the dichotomy between systolic and diastolic pressure was not observed in young children. This finding is consistent with the common finding that blood pressures tend not to “track” as well in children as in adults.

Results of recent clinical trials have motivated physicians to seek better methods for defining who needs antihypertensive therapy and which type of treatment is best for certain types of patients. These results suggest that measuring several different types of blood pressure may eventually provide more useful information than does the current practice of making decisions based only on sitting measurements. In a subsequent study, we analyzed correlations of this battery of defined blood pressure tests with risk variables associated with hypertension.

Acknowledgments

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