SUMMARY  The reproducibility of ambulatory, home, and clinic blood pressures was compared in 13 untreated mildly hypertensive and 14 normotensive subjects. Each subject had two sets of daily ambulatory recordings, home self-measured readings (over 6 days), and clinic measurements taken 2 weeks apart. Comparisons over the 2 weeks within and among the methods of measurements were made using a repeated-measures analysis of variance. The results showed that there was no consistent average change in the ambulatory or home pressures and no change in clinic diastolic pressures, but the clinic systolic pressure of the hypertensive subjects dropped 6 mm Hg (p<0.05), while that of the normotensive subjects showed no significant change. Test-retest correlations of each of the three methods were similar in magnitude, indicating a similar level of reliability. Test-retest correlations of the ambulatory standard deviations, however, were low, indicating a low reliability of this measure of daily pressure variability. These results suggest that the reproducibility of ambulatory pressures may be as good or better than that of home or clinic measurements. They also suggest that the average ambulatory pressure may be preferable as the measurement in clinical trials, since it may be less influenced by measurement anxiety, particularly in hypertensive subjects.

KEY WORDS  • ambulatory blood pressure • blood pressure measurement • reproducibility

C ASUAL measurement in the clinic or office is the most common method used to determine blood pressure in clinical studies that examine the risks associated with hypertension and the benefits of treating it. Although they are easy to obtain, casual pressures have low reproducibility for a variety of reasons. One of the problems associated with interpreting results of large-scale trials of the treatment of mild hypertension has been that casually measured pressures tend to fall significantly with time, even in untreated persons.

Repeated measurements of blood pressure taken by the patient at home have also been used to evaluate hypertension. The averages of these readings tend to be lower than clinic pressures and may reflect the overall level of pressure more reliably than do measurements made by the physician. The reproducibility of averaged patient-measured home readings, however, generally has not been systematically investigated, although available evidence suggests that among hypertensive patients they may stay about the same or drop over time. In addition, little information is available as to the prognostic potential of home pressures.

There is also a growing body of evidence suggesting that average daily ambulatory recordings may give the best characterization of a person's level of blood pressure and the risks associated with it. The reproducibility of these recordings has been studied over periods as short as 48 hours and as long as 4 months using a variety of ambulatory pressure measurement systems. These studies have shown that the average pressure as well as the pattern of variation is reasonably reproducible.

In the case of casual and home pressures, the conditions of measurement are relatively standardized, whereas with ambulatory readings made in free-ranging subjects, the situation is much less controlled. It might be expected, therefore, that the reproducibility of ambulatory pressure averages would be lower than that of casual or home pressure averages. The purpose of the present study was to compare, in the same subjects, the reproducibility of averaged clinician-measurements made by the physician.
sured, home-measured, and ambulatory-recorded blood pressures using the same research design. The reproducibility of the variability of the ambulatory recordings was also assessed. Both normotensive and hypertensive subjects were included in the study.

Subjects and Methods

Design

A repeated-measures design was employed in which averages calculated from each of the three ways of assessing blood pressure were compared 2 weeks apart, with no intervention in the interim. A total of 27 subjects were recruited for the study. Fourteen were normotensive volunteers, and 13 were patients with mild essential hypertension from the Hypertension Center at New York Hospital, who were off medication for at least 2 weeks before the study. Both normotensive and hypertensive subjects were familiar with the clinic setting and none had previously worn the Spacelabs ICR ambulatory blood pressure monitor (Hillsboro, OR, USA). Table 1 presents some demographic characteristics of the study sample.

Procedures

Blood pressures were measured in each subject in three different ways: 1) with a standard Baumanometer mercury column (Baum, Copiague, NY, USA) and stethoscope by a clinician trained according to the criteria of the Multiple Risk Factor Intervention Trial (using the stethoscope diaphragm), 2) at home by the patient with an aneroid cuff and stethoscope (using the stethoscope diaphragm), and 3) with an automatic monitor (Spacelabs ICR 5200 model) over at least an 8-hour period during the course of a single day. At each of two visits (2 weeks apart) to the Hypertension Center of the New York Hospital, the same clinician took three readings. The average of each set of readings was used as the clinic measurement. For the home measurements, subjects were supplied with a calibrated aneroid sphygmomanometer (Bristol Freeport, NY, USA) and instructed by a trained medical technician in its proper use. The appearance of sound was recorded as systolic pressure, and the disappearance of any detectable sound (Korotkoff Phase V) was recorded as diastolic pressure. After an adequate session of practice and validation of their technique, subjects were instructed to take three seated pressure measurements at home twice daily (three in the morning on arising, and three in the evening before bed for a total of six per day) for 6 consecutive days. The average of these pressures was used as the home pressure. Each subject repeated this protocol twice, the week before and after the interim period of 2 weeks. Finally, the subjects were twice fitted with the Spacelabs ICR ambulatory automatic blood pressure monitor, before and after a 2-week interim. Most of the subjects were measured on the same midweek day, which for 23 of them was one on which they went to work. The recorder was worn for as long as possible over each of the 2 days. Blood pressure was recorded automatically every 15 minutes during awake hours and every 30 minutes during sleep. Machine readings were calibrated to those of a standard sphygmomanometer when subjects were fitted with the device. In this procedure, a T tube was used, which connected the machine to a mercury column. The automatic pump in the machine inflated the cuff, the pressure being registered on the mercury column as well as in the machine. A trained listener using a stethoscope placed just distal to the microphone from the recorder read the pressure from the column. This listener was blinded from the machine readings. The recorder was considered accurate when five consecutive readings from the monitor agreed to within 5 mm Hg of the listener's measurements for both systolic and diastolic pressure. Measurements recorded during the ambulatory period by the monitor were screened and edited for artifactual values based on previously described criteria. Only those readings that were taken during the same hours on each of the 2 days were used in the analysis. The arithmetic average of the edited pressures taken during the same hours was used as the ambulatory measurement. The standard deviation of these edited readings was also calculated for each subject and used as an indicator of the variability of that subject's daily recorded pressure.

Table 2 summarizes the number of readings taken each week for each pressure average. Although each subject was compared over an equal time span from the initial to the second week, different subjects wore the ambulatory monitor for different lengths of time. Additionally, while each subject was to have taken 36 readings at home, not all complied perfectly with this protocol. On average, 62 home pressures were measured and recorded by the subjects when 72 were required by protocol.

Data Analysis

To assess the reproducibility of the various pressure averages, the differences between the initial and second averages were first calculated for each of the methods of pressure assessment. These differences were then compared using a repeated-measures analysis of variance in which the method of pressure measurement (ambulatory recorded, home subject-measured, and clinician-measured) and hypertensive status (normotensive or hypertensive) were included as fixed fac-

Table 1. Selected Demographic Characteristics of the Study Sample

<table>
<thead>
<tr>
<th>Variable</th>
<th>Normotensive</th>
<th>Hypertensive</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n = 14)</td>
<td>(n = 13)</td>
<td></td>
</tr>
<tr>
<td>Sex (% men)</td>
<td>29</td>
<td>46</td>
</tr>
<tr>
<td>Ethnic group (% white)</td>
<td>79</td>
<td>85</td>
</tr>
<tr>
<td>Age (yr)*</td>
<td>24 ± 5</td>
<td>57 ± 12</td>
</tr>
<tr>
<td>Smokers (%)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Alcohol consumption (% nondrinkers)</td>
<td>29</td>
<td>39</td>
</tr>
<tr>
<td>Coffee consumption (% drinkers)</td>
<td>50</td>
<td>54</td>
</tr>
<tr>
<td>Duration of hypertension (yr)*</td>
<td>0 ± 0</td>
<td>7.6 ± 7.7</td>
</tr>
</tbody>
</table>

*Values are means ± SD.
Pressures than with clinician-measured pressures, tended to correlate better with home subject-measured pressures, that is, the distributions of pressure averages for each measurement. For both systolic and diastolic pressures, the test-retest correlations were similar among the different methods. A paired t test and test-retest correlations were used to examine the reproducibility and reliability of the standard deviation of the ambulatory averages.

Results

Table 3 shows the pressure comparisons from the analysis of variance models for all three means of pressure assessment in both the normotensive and hypertensive subjects. Pressures have been rounded to the nearest millimeter of mercury. As indicated, the average level of ambulatory and home subject-measured pressures (both systolic and diastolic) changed very little over the 2 weeks (all changes <3 mm Hg; p = NS). However, there was a statistically significant (p < 0.05) drop of 6 mm Hg in clinician-measured systolic pressure among the hypertensive subjects.

Table 4 shows the test-retest correlations for each method of pressure measurement to assess their reliability and the reproducibility of the average pressure distributions. A paired t test and test-retest correlations were used to examine the reproducibility and reliability of the standard deviation of the ambulatory averages.

Discussion

Although several studies have reported on the reproducibility of noninvasively measured ambulatory blood pressure, few if any have compared its reproducibility with that of the other two commonly used modes of assessing blood pressure (home and clinic readings). Comparisons of normotensive and hypertensive subjects in this context have also not been made. In the present study, the pressures compared were those most commonly collected in clinical practice: a set of clinic readings, several days of home readings (in this case, six), and a daily ambulatory recording.

The reproducibility of the ambulatory pressures was evaluated on days that were representative of a subject’s normal activity, which for most was a working day. No special instructions were given to the subjects as to how to spend their day. It was anticipated that, because the circumstances in which the ambulatory pressures were taken were more variable, the reproducibility of the average daily ambulatory pressures might be lower than that of the home and clinic pressures. This expectation was based on previous findings suggesting that activity is a major predictor of individual blood pressure measurements taken over 24 hours with an ambulatory monitor. It was gratifying to find that the ambulatory average was as reproducible as the clinic and home averages and that all three methods had high test-retest correlations.

Another important finding was that there was no what higher than those between subject-measured and ambulatory pressures. However, all the correlations among the different measurements were of the same magnitude, indicating a similarity in the distributions of the measurements of the different methods.

An examination of the reproducibility of the standard deviations of the ambulatory averages showed that there was no significant difference in this measure of individual pressure variability over the 2 weeks in either normotensive (systolic, 10 vs 10 mm Hg; diastolic, 9 vs 8 mm Hg) or hypertensive subjects (systolic, 14 vs 13 mm Hg; diastolic, 10 vs 8 mm Hg). The test-retest correlations were quite low (r = 0.36 for systolic, r = 0.16 for diastolic), which suggests that, in this study group, the position of subjects in the limited distributions of standard deviations changed over the 2 weeks.
Table 4. Correlations Among the 27 Pressure Measurements

<table>
<thead>
<tr>
<th>Associated variables</th>
<th>Systolic pressure</th>
<th>Diastolic pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMBP 1 vs AMBP 2</td>
<td>0.93</td>
<td>0.87</td>
</tr>
<tr>
<td>Home 1 vs Home 2</td>
<td>0.96</td>
<td>0.94</td>
</tr>
<tr>
<td>Clinic 1 vs Clinic 2</td>
<td>0.94</td>
<td>0.87</td>
</tr>
<tr>
<td>AMBP 1 vs Home 1</td>
<td>0.87</td>
<td>0.72</td>
</tr>
<tr>
<td>AMBP 1 vs Clinic 1</td>
<td>0.76</td>
<td>0.68</td>
</tr>
<tr>
<td>Home 1 vs Clinic 1</td>
<td>0.84</td>
<td>0.77</td>
</tr>
<tr>
<td>AMBP 2 vs Home 2</td>
<td>0.88</td>
<td>0.77</td>
</tr>
<tr>
<td>AMBP 2 vs Clinic 2</td>
<td>0.73</td>
<td>0.77</td>
</tr>
<tr>
<td>Home 2 vs Clinic 2</td>
<td>0.90</td>
<td>0.77</td>
</tr>
</tbody>
</table>

AMBP = ambulatory blood pressure; 1 = initial average; 2 = second average.

pronounced order effect in the ambulatory measurements, in contrast to the clinic pressures, which did show such an effect, particularly among hypertensive subjects. These results support the findings of most earlier studies. The implication of this result is that the average daily pressure may be a better measure than clinic readings for evaluating the effects of antihypertensive treatment, whether pharmacological or nonpharmacological, since any differences observed between successive recordings are likely to be due to the intervention, rather than random variation or an order effect. The stability of the daily ambulatory average also implies that it is likely to be a more valid measure for comparison with indices of target organ damage or psychosocial and biochemical variables.

The variability of blood pressure during ambulatory monitoring, as reflected in the standard deviation of the ambulatory average, had a low reliability, a finding consistent with other studies. This result is not surprising since blood pressure is subject to a number of sources of variation, some cyclical, others not. Possible cyclical sources include respiratory oscillations of pressure, ultradian rhythm, and diurnal variation. Noncyclic sources might include posture, activity, and emotional variation. Intermittent sampling of blood pressure at a frequency typically used with noninvasive ambulatory recorders (about one every 15 minutes for a total of perhaps 50 to 100 pressures depending on the length of time worn) can also only obtain a crude estimate of the true levels of variability; thus, estimates of variability from these measurements may be invalid as well. This point is readily apparent when one considers that, if it were possible to record each pressure beat to beat (approximately 1–2/sec), one would obtain some 90,000 to 100,000 measurements per person over a 24-hour period. It is highly unlikely that a nonrandom sample constituting 5/100ths of 1% of the possible measurements will reflect the true extent of the variability of pressure. There is considerable interest among behavioral scientists in the differences of cardiovascular reactivity to standardized physical and mental stimuli measured in laboratory studies. An unresolved question is the extent to which these responses are representative of blood pressure variability during everyday life. Because it is unreliable and invalid, the variability of blood pressure defined from intermittently sampled measurements should not be compared with laboratory measures of reactivity.

Finally, the methods of pressure measurement examined in this study may define different aspects of a person’s blood pressure; hence, comparisons of their reproducibility might be considered inappropriate. The average ambulatory pressure may reflect a central point around which pressure varies over the course of a day. The subject-measured home readings reflect an average level of pressure over an extended period (1 week), when measurements are made under similar and usually quiescent circumstances. The clinician-measured pressure reflects a point measure of pressure under a singularly peculiar circumstance. The inappropriateness of the comparisons may also extend to the fact that each of the three averages compared in this study are based on different numbers of measurements. For example, the fact that there are far more ambulatory measurements (even though they are collected under variable circumstances) than there are clinic measurements may make the ambulatory average more reproducible, since the greater number of measurements makes it less sensitive to extreme single readings. Among the hypertensive subjects, ambulatory, home, and clinic pressure measurements were different, yet the ambulatory and home measurements were very similar in their reproducibility. Despite the similarity in reproducibility, however, if change or percent change in pressure is the focus of study, the present findings suggest that the ambulatory pressure average may be the best measure to use, since it may reflect a central pressure of the cardiovascular system, is composed of a large number of readings taken under many circumstances, and is also likely to be independent of factors that increase measurement error, such as digit preference, observer-subject interaction, and measurement anxiety.

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Hypertension. 1988;11:545-549
doi: 10.1161/01.HYP.11.6.545

Hypertension is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0194-911X. Online ISSN: 1524-4563

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