Portable Blood Pressure Measurements: Performance of Korotkov Sound Analysis Techniques

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SUMMARY Noninvasive portable blood pressure systems (PBPS) are typically based on the Korotkov sound technique. The performance of related Korotkov sound analysis techniques was assessed in PBPS data obtained from nine normotensive and nine hypertensive men. Multiple-seated PBPS measurements were taken, each following 1 minute of quiet rest, moderate walking, and stair climbing; each PBPS measurement was accompanied by a simultaneous auscultatory measurement in the same arm. In subsequent manual PBPS data analysis, PBPS systolic and diastolic BPs were within 4 mm Hg of corresponding auscultatory BPs 86% and 88% of the time; BPs following rest and walking showed greater accuracy, while those following stair climbing were less accurate. Interestingly, automated analysis of diastolic PBPS data (using selective bandpass filtering, amplitude normalization, and comparator decision ratios) provided a level of accuracy similar to that obtained from manual data analysis. Overall, both manual and automated Korotkov sound analysis techniques can provide BP results that agree quite well with auscultatory determinations.

KEY WORDS • blood pressure measurement • Korotkov sound • automatic BP measurement • portable BP measurement

PORTABLE blood pressure systems (PBPS) are designed to measure blood pressure (BP) in free-ranging, human patients. PBPS are relatively new; since 1962 a dozen or so reports on this subject have appeared in the literature, with England and the United States the principal contributing countries.

In England PBPS have used direct, intraarterial BP measurements, which can be very accurate and provide a complete, continuous BP record for up to 24 hours. Unfortunately, use of intraarterial BP measurements restricts these PBPS to research environments where the patient, technique, and equipment all can be given proper attention. In the United States, PBPS have been designed around noninvasive BP measurements using the Korotkov sound technique. Although these BP measurements are discontinuous, the technique is clinically familiar and Korotkov sound-based PBPS are readily applied in conventional clinical settings. The practical advantages of noninvasive PBPS must be qualified, however, by uncertainty over the accuracy of their BP measurements.

A Korotkov sound-based PBPS requires two distinct operations: data acquisition and data analysis. Data acquisition involves the tape recording of Korotkov sounds and cuff pressure during each BP determination; current technology is more than adequate for this task. Data analysis is required because the noninvasive PBPS senses and records more Korotkov sounds than are heard by direct auscultation (fig. 1), i.e., the microphone sensor picks up high-amplitude, low-frequency components of the Korotkov sound that are largely below the threshold of hearing. Hence, an analysis scheme must be devised for identifying the Korotkov sounds associated with systolic and diastolic BPs, respectively. Since Korotkov sound amplitudes vary up to 40-fold between individuals, amplitude criteria alone are entirely unsatisfactory in this regard. A more sophisticated scheme is required and its efficacy has major impact on PBPS accuracy.

The present study was designed to evaluate the performance of Korotkov sound analysis techniques applicable to PBPS. A data base was developed of paired PBPS and auscultatory measurements taken at three different activity levels. PBPS Korotkov sound data were then analyzed by manual and by automated techniques, and the results of each compared with the auscultatory reference.
Methods

All PBPS using the Korotkov sound technique contain similar components: a microphone and preamplifier for sensing Korotkov sounds, an inflatable arm cuff with transducer and preamplifier for sensing arm cuff pressure, and a tape recorder for recording these variables. A separate tape playback unit is required for subsequent data analysis. Commercially available PBPS differ mainly in the way they record and/or subsequently analyze the recorded Korotkov sound data, and in whether the arm cuff is manually or automatically inflated. Design specifications and operating instructions for the noninvasive PBPS built and used in this study are given in the Appendix.

In the first part of this study, a data base was assembled of paired PBPS and auscultatory measurements, using the protocol shown in figure 2. Each "preliminary" and "free-ranging" measurement was taken at approximately 2-minute intervals: the first minute involved the subject in a specified activity (i.e., resting, walking, climbing) while the second minute was used for the paired BP measurement itself (subject seated). For each measurement, the PBPS was cycled for a routine measurement sequence; simultaneously, a trained observer performed auscultation (by stethoscope) in the same arm and keyed a bilevel marker at the appearance of each Korotkov sound (fig. 1). The first and last Korotkov sounds were used to calculate the BP, and served as a reference for subsequent PBPS data analysis techniques.

Nine healthy men (38 to 48 years old) were recruited from clinic technical and professional staff. Each subject completed the stated protocol on two separate occasions. Additionally, nine ambulatory clinic patients (24 to 43 years old) completed the protocol a single time: all of these patients were asymptomatic, had a history of mild essential hypertension, and were being treated with Aldactazide.

Manual analysis of PBPS Korotkov sound data was accomplished as follows. The Korotkov sound data were replayed from tape, bandpass filtered, and written to strip chart (strip chart speed was varied to provide sufficient waveform detail). Filter pass bands were specified by an earlier study (i.e., 18–26 Hz for systole, 40–60 Hz for diastole) that showed large shifts in Korotkov sound spectral energy as cuff pressure transitioned through systolic and diastolic BP respectively. The recorded 1-second timer, cuff pressure data, and auscultatory event marker were written to strip chart directly. Next, using data from the four "preliminary" BP measurements alone, we identified Korotkov sound waveform features that could serve as visual markers for the occurrence of systolic and diastolic BPs respectively. In effect, we developed visual templates from Korotkov sound waveform morphology and then applied these visual templates during our analysis of the eleven "free-ranging" PBPS BP measurements. This manual data analysis was accomplished without reference to corresponding auscultatory data. Results of this manual analysis were then compared with the auscultatory reference.

Automated Korotkov sound analysis involved the use of selective bandpass filtering, amplitude normalization, and comparator decision ratios as described in a previous report. As noted in that non-PBPS study, automated systolic BP decisions were somewhat more accurate than automated...
diastolic BP decisions. Hence, we decided to focus initial attention on the more difficult side of the problem — automating the diastolic BP decision. To this end, PBPS Korotkov sound data were again bandpass filtered (ie., 40-60 Hz). Then, Korotkov sound data from each of the four "preliminary measurements" were used to develop decision ratios, i.e., a ratio of the amplitude of the diastolic Korotkov sound to the amplitude of the largest Korotkov sound within that BP determination. Ratios from all four "preliminary" measurements were next averaged, and this averaged ratio was used for hardware identification of the diastolic Korotkov sound within each of the 11 "free-ranging" BP measurements. Results of our automated Korotkov sound analysis technique were compared with results from reference auscultatory measurements.

Results

Manual Korotkov Sound Data Analysis

The results of identifying and applying visual templates for the analysis of Korotkov sound data are documented in figures 3 and 4. These figures show the distribution of PBPS auscultatory BP measurement differences. Note that these differences are symmetrically distributed about zero in both figures, indicating an absence of directional bias with this manual analysis approach. Overall, BP differences are within 4 mm Hg for systolic and diastolic BPs 86% and 88% of the time respectively. Broken down by protocol condition (table 1), PBPS BPs following initial rest or moderate-paced walking agree very well with auscultatory BP measurements. PBPS BPs associated with and following stair climbing are less accurate, perhaps reflecting the fact that the visual templates were formed from Korotkov sound data taken only during the seated rest condition.

Automated Korotkov Sound Analysis

The average diastolic decision ratio computed for each patient range ranged 0.11-0.70, with a distribution skewed sharply toward the low end. The results of applying these individual diastolic ratios is shown in table 2. Interestingly, use of individual diastolic ratios led to BP measurements that were closer to the auscultatory reference than results provided by manual data analysis. This result is encouraging since an automated process promises a degree of repeatability that is inherently absent in a manual analysis technique.

Table 1. Percentage of PBPS Measurements within 4 mm Hg of Simultaneous Auscultation, Using Manual Data Analysis

<table>
<thead>
<tr>
<th></th>
<th>Rest (n = 79)</th>
<th>Walk (n = 79)</th>
<th>Stairs (n = 64)</th>
<th>Rest (n = 79)</th>
<th>All data (n = 277)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Systole</td>
<td></td>
<td></td>
<td></td>
<td>84</td>
<td>76</td>
</tr>
<tr>
<td>Diastole</td>
<td></td>
<td></td>
<td></td>
<td>74</td>
<td>90</td>
</tr>
</tbody>
</table>

Table 2. Percentage of PBPS Measurements within 4 mm Hg of Simultaneous Auscultation, by Analysis Technique and Protocol Condition

<table>
<thead>
<tr>
<th></th>
<th>Rest (n = 79)</th>
<th>Walk (n = 79)</th>
<th>Stairs (n = 64)</th>
<th>Rest (n = 79)</th>
<th>All data (n = 277)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual diastolic ratios</td>
<td>96</td>
<td>97</td>
<td>77</td>
<td>94</td>
<td>91</td>
</tr>
<tr>
<td>Group diastolic ratio</td>
<td>92</td>
<td>92</td>
<td>66</td>
<td>88</td>
<td>84</td>
</tr>
<tr>
<td>Manual analysis</td>
<td>97</td>
<td>95</td>
<td>74</td>
<td>90</td>
<td>88</td>
</tr>
</tbody>
</table>

Figure 3. The accuracy of PBPS systolic BPs (manual analysis) is shown referenced to simultaneous auscultatory BP measurements (n = 281).

Figure 4. The accuracy of PBPS diastolic BPs (manual analysis) is shown referenced to simultaneous auscultatory BP measurements (n = 281).
We took the automated analysis technique one step further: since a single, overall ratio would be easier to apply, we calculated a group decision ratio by averaging the ratios from all 27 studies (i.e., nine subjects studied twice plus nine patients studied once). We justified this averaging by the observation that, at least for subjects studied twice, the within-subject ratio variance was similar to the between-subject ratio variance. The calculated group ratio was 0.33. We then applied this group ratio to a new analysis of the "free-ranging" Korotkov sound data from all 27 studies. Interestingly, this group decision ratio was only slightly less successful than either the manual analysis or the automated analysis employing individual ratios. This slight reduction in performance of the group ratio must be weighed, however, against the savings in time and effort that use of a group ratio affords in the analysis of PBPS Korotkov sound data.

Discussion

Accurate assessment of an individual's BP status is important for defining the risk of having or acquiring cardiovascular disease, or in evaluating the efficacy of a prescribed treatment regimen. Unfortunately, this BP assessment is complicated by the physiological lability of human BPs, and by many confounding variables that include conditions under which the measurement is taken, importance of the measurement to the patient, and the patient-physician relationship. The PBPS was originally developed in part to answer these problems by providing BP measurements in the patient's own environment, independent of a medical observer. The value of these BP measurements, however, hinges on their accuracy; small PBPS errors, e.g., of 5 to 15 mm Hg, could easily alter the clinical assessment and this, in turn, could have a major impact on the patient's future, e.g., in fitness for employment, application for life insurance, need for antihypertensive therapy, etc.

Manual analysis of PBPS-recorded Korotkov sound data is inherently self-limiting — it is tedious, labor-intensive, and lacks precision because of appreciable within- and between-observer interpretive variability. Thus, automation of PBPS-recorded Korotkov sound data is attractive, and the present study explores two avenues in this regard. Interestingly, all three analytical approaches showed some divergence from the auscultatory reference during moderate activity (i.e., stair climbing). This divergence may be artifactual, reflecting the known divergence of our auscultatory standard from true intraarterial pressures during increasing activity. This loss could also be real but unimportant if, in fact, most patients wearing a PBPS seldom engage in more than minimal activity. Finally, the observed divergence with increasing activity may be real and important, in which case several diastolic decision ratios may be required that cover a range of patient activity levels (i.e., via heart rate).

Diastolic decision ratios from a previous study were reviewed, the group decision ratio for diastole, based solely on resting conditions (not published), was 0.30 and the respective range was 0.04 to 0.74. The agreement of these earlier ratios with those from the present study is encouraging — a group decision ratio of approximately 0.30 seems appropriate for automatic identification of diastole under resting and light activity conditions.

Conway et al. noted that 73% of their diastolic BPs were within 5 mm Hg of simultaneous auscultatory BPs. Their accuracy is considerably below the accuracy of resting BPs reported in this study (table 1) and is even below the overall accuracy of our PBPS data where all conditions were included. Conway used a commercially available PBPS for which there is no information regarding Korotkov sound recording, processing, or data analysis techniques.

In summary, PBPS BPs can be obtained that agree well with corresponding auscultatory BP measurements, and this agreement can be maintained while using automated Korotkov sound analysis techniques. Hence, the benefits associated with PBPS measurements — reduction in observer bias, removal of physician-patient interaction, increased number of readings taken across varying environmental conditions, — are available with current technology. It should be apparent, however, that availability of the technology does not insure its proper application, and the user of a noninvasive PBPS should carefully assess the accuracy of the system before relying on its output.

Acknowledgments

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Appendix

The present PBPS was built around a 4-channel cassette recorder (Model MR-14, InterMedCraft) and compatible cassette reproduce unit (Model IMR-24) purchased in 1973. Cassette recorder electronics were modified and enlarged as indicated for the following data channels:

Channel 1 An NE555 timing oscillator (Signetics) and associated circuitry was added to record 1-second timing marks on this tape channel.

Channel 2 A passband amplifier (-3 db at 15 and 100 Hz), with step gain settings of X6, 9, 13.5, 20, 30, and 46 was added to record Korotkov sounds on this tape channel.

Channel 3 A solid state pressure transducer (LX1601D, National Semiconductor) and associated circuitry was added to record arm-cuff pressure on this tape channel.

Channel 4 This channel was used to record a simple bilevel, auscultatory event marker and thus was not modified.

Additional circuitry included a second NE555 timing oscillator which keyed a 1.5 kHz audible oscillator every 15 minutes (signalling the patient to inflate his arm cuff). Other circuitry was added to turn on or turn off the tape recorder at an arm-cuff pressure preset to a threshold of approximately 40 mm Hg, and turn off the audible oscillator when the subject had pressurized his cuff to a preset maximum (between 160 and 260 mm Hg). The total PBPS package measured 2.5 X 4.5 X 10 inches, and weighed 4 pounds.

The PBPS is used in the following manner. First, the cuff pressure channel is calibrated with static pressures of 60 and 160 mm Hg. The subject or patient is then instrumented by placing a microphone (Narco Bio Systems, Inc.) over the brachial artery and under the distal edge of a standard BP cuff. The microphone cable and cuff tubing are then connected to the cassette recorder; the recorder is suspended by a strap from the individual's shoulder. The PBPS is turned on. At an audible tone, the patient sits down and pressurizes the arm cuff by squeezing a rubber bulb until the tone stops. The patient then relaxes as the arm cuff automatically bleeds down (160 to 60 mm Hg in 30-50 seconds) and BP data are recorded on tape. The bleed-down valve dumps arm cuff pressure at approximately 50 mm Hg, and the recorder electronics are switched off until the next cuff inflation cycle.
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