An Automated System for Blood Pressure Determination During Exercise

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with the technical assistance of Blanche Price

SUMMARY Automation of blood pressure (BP) measurements during exercise has proved difficult because motion artifact is a major limitation in ultrasound techniques and noise artifact limits the application of sound transduction via microphone pickups. We assessed the value of a new automated system of indirect BP determination by comparing it with manually determined BP in 50 consecutive patients referred for treadmill testing. Automated BP determinations were blinded to the physician or technician who was simultaneously manually auscultating BP. The automated system uses acoustic transduction, but with ECG assist and microprocessing of nonsynchronous noise to overcome the limitations of other systems. The data were statistically analyzed and the correlation coefficient, mean difference and standard deviation of the difference for systolic and diastolic BP for differing levels of heart rate and treadmill stage were determined. The correlation between automated and manually determined BP was 0.964 for systolic BP and 0.848 for diastolic BP. Despite some limitations, this automated system offers significant advantages for exercise BP determination.

SINCE Korotkoff proposed auscultation of the sounds that bear his name, indirect measurement of blood pressure has achieved unparalleled importance in clinical medicine. Nevertheless, indirect measurement of blood pressure is subject to many sources of error. Attempts at automating auscultatory measurement of blood pressure have led to the development of two types of devices that detect and process signals analogous to Korotkoff sounds: one uses the application of ultrasound reflectance to detect arterial blood flow; the other uses the transduction of acoustical signals. Though these devices have been primarily evaluated in resting situations, their accuracy has been questioned. The application of automated blood pressure measurement during exercise has been even more unrewarding. Motion artifact is a major limitation in ultrasound techniques and noise artifact limits the application of sound transduction via microphone pickups, both common situations during treadmill exercise testing.

Because of the importance of monitoring the blood pressure response during exercise and the increased difficulty of obtaining reliable indirect blood pressure measurements during treadmill exercise testing, interest in an automated technique is great. We evaluated a system designed to overcome noise artifact by using electrocardiographic gating and microcomputer processing of nonsynchronous noise that allows for isolation of Korotkoff sounds by acoustical transduction. To test its reliability, we compared this automated method against manually determined pressure, because it is well known that intra-arterial pressure and indirect blood pressure correlate poorly with one another.

Methods

An automated system of indirect blood pressure determination (the Critikon 1165 exercise blood pressure monitor [EBPM]) was evaluated in 50 consecutive patients referred for treadmill testing. This noninvasive blood pressure device measures the systolic and diastolic pressures based on auscultation. Exercise tests were performed using the standard or modified Bruce protocol, and pressures were measured in the sitting and standing positions, at the end of each stage of uninterrupted exercise (or more frequently if abnormalities were present) and at 1 minute, 3 minutes, 6 minutes and 10 minutes after exercise. Automated pressure determinations were blinded to the technician or physician, who was simultaneously manually auscultating the pressure. This was accomplished in the following manner. The cuff was connected to the EBPM and a mercury manometer and was automatically or manually inflated and, using the same cuff (the deflation rate controlled by the automated device), the blood pressure was auscultated distal to the deflating cuff.

The disappearance of Korotkoff sounds (phase V) was used in the manual determination of pressure, because despite the controversy of phase IV and V, Korotkoff sounds relative to the “true” diastolic pressure, the determination of phase IV blood pressure during exercise is extremely difficult. The automated system, on the other hand, records phase V if the pressure is greater than 80 mm Hg but phase IV if the pressure is less than 80 mm Hg. The instrument is so programmed because at high levels of exercise the diastolic pressure may become very low and the Korotkoff sounds can sometimes persist to 0 mm Hg.

All technicians and physicians participating in

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the study had adequate training and experience in determining blood pressure during exercise by auscultation and were cautioned to avoid terminal-digit bias. The physicians involved in the study had a combined 15-year experience with obtaining blood pressure manually during exercise and had trained the two technicians (with a combined 8-year experience) in this technique. Checks on technician accuracy were maintained throughout the past 4 years and during the study. Thus we felt that using these four persons throughout the study was better than using only one individual, as this would reduce any chance for bias by any one individual.

Statistical Analysis

This study was performed to determine the correlation coefficient and least-squares regression line for the automated blood pressure determinations compared with the manual auscultatory technique. In addition, the mean ± SEM of the difference between these two techniques was calculated.

Instrument Description

An occluding cuff was wrapped snugly around the arm and a sensing microphone was positioned under the cuff directly over the brachial artery. Also, the patient was attached to a standard three-lead ECG.

The hose used for inflating and deflating the blood pressure cuff is connected to a reservoir of approximately 4 l contained within the instrument enclosure. This air reservoir minimizes the pressure fluctuations that occur with movement of the arm during exercise. (With this reservoir, moderate motion of the arm will produce fluctuations of only a few mm Hg; without it, fluctuations as high as 40–50 mm Hg may occur.) The deflation valve, pump and pressure transducer are also connected to the reservoir. The deflation valve is used for deflating the cuff system between 6–10 mm Hg. The pump automatically inflates the cuff (up to a pressure of 250 mm Hg) in approximately 4 seconds.

The pressure transducer converts the pressure level in the reservoir cuff system into an electrical signal, which is sampled by the analog-to-digital converter for use by the microprocessor. The signal from the brachial artery microphone is also filtered to remove unwanted frequencies before sampling by the microcomputer (fig. 1).

The instrument functions in two modes: the ECG-assisted mode, which requires an electrocardiographic signal for triggering purposes, and the non-ECG-assisted mode, which does not require this ECG trigger and, hence, can measure blood pressures without an ECG. However, because the ECG enables the microcomputer to distinguish between noise and signal, the blood pressure device measures accurate pressures during exercise only in the ECG-assisted mode. A typical determination during exercise takes 30–45 seconds, at the end of which the systolic and diastolic pressures, the heart rate, and the pressure-rate product are digitally displayed. The device can measure pressures as high as 245 mm Hg and as low as 50 mm Hg.

To verify any reading, the device also contains a strip-chart recorder. The strip chart records the incoming signal before microprocessing; that is, the ECG cuff pressure, Korotkoff sounds, microphone signals, and the motion artifact signals are directly recorded without any alteration. The digital display represents the data after microprocessing, allowing for an independent check of the system (fig. 2.) The strip-chart recorder functions in two modes. In the ECG-only mode, the device writes the ECG at 5, 10, 25 or 50 mm/sec. In this way, the device can be used as a single-lead stress test system. In the mixed mode, the strip-chart recorder displays a signal obtained by mixing the pressure signal and the Korotkoff sound signal from the microphone with or without the ECG signal. By mixing these signals and having them written on marked recorder paper that is calibrated in mm Hg, the systolic and diastolic pressures can be determined visually. If this visual means of corroboration is desired, a continuous tracing can be generated or the

![FIGURE 1. The components of the model 1165 exercise blood pressure monitor.](image-url)
Figure 2. (A) Strip-chart recording obtained during exercise. The paper speed is 5 mm/sec. The level of the isoelectric line of the ECG correlates with the blood pressure values on the left. The onset of the Korotkoff sounds (KS) (arrow) was 180 mm Hg (diastolic pressure not shown), the same as the digitally displayed blood pressure (BP). Simultaneous auscultatory systolic BP was 160 mm Hg. (B) Deviations in the ST segment or interference in visualizing the onset of KS by the ECG signal may exist, and the strip-chart recording may be made without the ECG signal as well. The strip-chart BP is 120/85 mm Hg, the same as the digitally displayed BP, while the manual BP was 116/82 mm Hg.

Table 1. Mean Difference and Standard Deviation of the Difference for Systolic and Diastolic Blood Pressure at Different Levels of Exercise

<table>
<thead>
<tr>
<th></th>
<th>Mean difference</th>
<th>Standard deviation of the difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SBP</td>
<td>DBP</td>
</tr>
<tr>
<td>Rest</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sitting</td>
<td>-3.063</td>
<td>-1.813</td>
</tr>
<tr>
<td>Standing</td>
<td>-3.733</td>
<td>-2.400</td>
</tr>
<tr>
<td>HR &lt; 100</td>
<td>-4.710</td>
<td>-1.581</td>
</tr>
<tr>
<td>HR 100–125</td>
<td>-8.312</td>
<td>-1.753</td>
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<tr>
<td>HR 126–150</td>
<td>-7.778</td>
<td>0.694</td>
</tr>
<tr>
<td>HR &gt; 150</td>
<td>-11.850</td>
<td>0.386</td>
</tr>
<tr>
<td>Stage I</td>
<td>-6.800</td>
<td>1.822</td>
</tr>
<tr>
<td>Stage II</td>
<td>-10.394</td>
<td>0.727</td>
</tr>
<tr>
<td>Stage III</td>
<td>-11.875</td>
<td>-0.423</td>
</tr>
<tr>
<td>R</td>
<td>-9.667</td>
<td>-0.771</td>
</tr>
<tr>
<td>R-3</td>
<td>-6.792</td>
<td>-3.042</td>
</tr>
<tr>
<td>R-6</td>
<td>-4.239</td>
<td>-0.913</td>
</tr>
<tr>
<td>R-10</td>
<td>-4.239</td>
<td>-2.261</td>
</tr>
<tr>
<td>Overall</td>
<td>-6.769</td>
<td>-1.156</td>
</tr>
</tbody>
</table>

Abbreviations: HR = heart rate (beats/min); ST = stage; R = recovery; SBP = systolic blood pressure; DBP = diastolic blood pressure.
microcomputer can automatically record the beginning and turn off at the completion of a blood pressure determination. In addition, signals used by the microcomputer and the mixed signal are available on a rear connector for permanent recording by the user’s other instrumentation.

Results

The pressures recorded both manually and automatically by the EBPM are shown in figure 3. The mean ± sd of the difference for all levels of exercise is shown in table 1. The overall mean difference was
−6.77 ± 8.32 for systolic and −1.16 ± 6.47 for diastolic blood pressure (r = 0.96 for systolic and 0.85 for diastolic blood pressure). Greater scatter was initially noted at higher pressure levels (especially systolic). This was the result of four marked (40 mm Hg or greater) differences in automated vs manual techniques. The records were reevaluated and the manually determined pressures were compared with the calibrated strip-chart recording. Four discrepancies occurred at high heart rates (greater than 150 beats/min and work loads greater than stage II) and the immediately subsequent pressure determinations correlated more closely. These outliers were, therefore, considered technical errors and were removed from final analysis, although inclusion did not significantly alter the results.

Sixty percent of the manually recorded blood pressures were determined by two physicians. The other 40% were obtained by two technicians and data were separately analyzed for comparison between each individual and between the physician and technician group. No statistically significant differences were noted, but technician-determined pressures compared slightly more favorably with the EBPM than physician-determined pressures (mean error of −9.48 ± 9.82 for physician-determined systolic pressure vs −5.00 ± 8.07 for technician-determined systolic pressure).

Figures 4 and 5 show the difference between manual and automated pressure determinations compared with the stage of exercise (fig. 4) and heart rate during exercise and recovery (fig. 5). For example, at a blood pressure of 200 mm Hg, the automated system may read 9–15 mm Hg higher than the simultaneously recorded manual systolic pressure.

**Discussion**

Measurement of arterial pressure by conventional sphygmomanometry is subject to error, including faults in the instrumentation and the use of an occluding cuff of incorrect size. However, two main sources of error lie with the observer: those caused by bias (from terminal digit preference) and those caused by uncertainty in interpreting the Korotkoff sounds.8 These problems (particularly the latter) may be further aggravated during exercise because of the problems of ambient noise and motion artifact. In addition, the blood pressure response to exercise is attaining increasing importance in the safety of testing and in the diagnosis and prognosis of patients with coronary artery disease.8,6 Thus, it would be advantageous if blood pressure determinations could be automated not only to improve reliability, but also to free personnel from the burden of manually determining pressure and to allow them to pay more attention to the subject.

Problems with motion and noise artifact have prevented reliable quantification of arterial pressure during exercise. The EBPM was developed to overcome these problems. This system uses acoustic transduction and ECG-assisted microprocessing of nonsynchronous noise. We compared the pressures obtained by this system with simultaneously recorded manual pressures taken in the same arm by physicians and technicians experienced in determining blood pressure during exercise. The correlation between this automated system and manually determined blood pressure was defined and the ease of use evaluated.

The automated system does have limitations. Because of the 4-l reservoir, inflation time is slightly longer than with the usual manual method. More important, deflation time is prolonged to allow time for signal sampling, so that the total time for pressure determination is 30–45 seconds, probably twice the time needed for manual determination. Also, the EBPM begins its sampling at systolic pressures 30 mm Hg higher than the last recording. If, as occurs in some individuals during exercise, the pressure rises by more than 30 mm Hg between determinations, the systolic pressure will not be registered. Although this would be obvious to the tester, the pressure determina-
tion must be recycled. Another limitation of the system is that it is apparently more sensitive in determining the onset of the Korotkoff sounds than the human ear, particularly in the setting of high ambient noise. This results in consistently higher pressures than those obtained by auscultation, but we did not feel that this difference was clinically significant. An abnormal blood pressure response includes a fall in systolic blood pressure or failure of the systolic blood pressure to rise by more than 10 mm Hg during exercise. With the automated system, systolic pressure readings may be 10–20 mm Hg higher than with the manual technique, but relative changes would still be apparent. Systolic pressures (and diastolic pressures) that become too high during exercise may define a hypertensive group and are used in the consideration of stopping exercise, but the levels dictating this action are vague, so that a 10–20-mm Hg discrepancy in systolic pressure should not affect this decision. Also, confidence limits are being developed for normal exercise blood pressure responses and the higher levels recorded by this automated system might have to be considered.

Limitations of the study include the method of simultaneously determining manual blood pressure. The deflation rate of the cuff (controlled by the automated system) is in increments of 6–10 mm Hg and not the smooth 2–3-mm Hg/sec deflation rate recommended by the American Heart Association. To overcome this problem, we considered the alternatives of recording blood pressure manually in the opposite arm or intra-arterially, but such measurements are associated with even greater limitations, such as the variability of pressures in opposite arms and discrepancies between intra-arterial and manual pressure determinations.

The automated blood pressure determinations were always higher than the manual determinations. This could be the result of many factors, such as the deflation rate, but particularly at higher work loads, surrounding ambient noise (from the treadmill, footsteps and motion) makes accurate manual determination of the onset of Korotkoff sounds difficult and would likely be heard at a level somewhat lower than that achieved by microprocessing of acoustic transduction. There was a wider mean difference in systolic pressure in the 1-minute and 3-minute recovery phase compared with other stages of exercise and recovery. We cannot explain this, but the recognized physiologic changes of the early recovery period might alter pulse wave and sound transmission in such a way as to cause this.

Despite the limitations in instrumentation and study design, the reliability and ease of this automated system, as well as its correlation with manual blood pressure, were such that it could provide a valuable asset to exercise testing.

Acknowledgment

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