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# Blood Pressure Measurement in Noise Intensive Environments Using Adaptive Interference Cancellation

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**Abstract**—The traditional auscultatory technique and current methodologies for measuring human blood pressure are limited when used in situations where extreme vibration or acoustic noise is present. In this study, human subjects were used to establish the effectiveness of a novel adaptive blood pressure monitoring (ABPM) system in determining systolic–diastolic pressure in vibration and noise intense environments To remove the effects of noise and vibration from the audible Korotkoff sounds, the proposed ABPM system employs two acoustic sensors in the pressure cuff. The primary acoustic sensor is placed on the brachial artery to record the Korotkoff sounds while the secondary acoustic sensor is placed away from the artery to record background noise and vibrations. The signals from the two acoustic sensors are provided to the input of an adaptive interference canceller to remove the noise effects in the signal of the primary acoustic sensor. In two phases of clinical testing, the ABPM system was first employed in a noiseless environment and then near and onboard search and rescue helicopters. The results from both phases deliver a successful demonstration of the ABPM system's capabilities to provide blood pressure estimates in noisy environments where the conventional auscultatory and other techniques have limited use. © *2002 Biomedical Engineering Society* [DOI: 10.1114/1.1481051]

**Keywords**—Noninvasive monitoring of blood pressure, Systolic blood pressure, Diastolic blood pressure, Auscultatory method, Adaptive interference canceller, Noisy intense environments

## INTRODUCTION

Blood pressure and heart rate are critical vital signs to health care practitioners. Measurements are taken under various conditions, from routine check ups to emergency evacuations. However, in the noisy environments of ambulances, helicopters, airplanes, or naval vessels, it is almost impossible to hear the patient's Korotkoff sounds and measure a patient's blood pressure when the traditional auscultatory method is used.[7]

A previous vital-signs monitoring system, called the Vitsem blood pressure monitor,[3] employed the following technique. Its estimation scheme was based on the fact that the heartbeat pressure signal was superposed as an ac signal on the deflated pressure signal of the cuff. Thus, the Vitsem device filtered out the dc component of the cuff's pressure deflation curve and obtained the blood pressure from the remaining ac component. In addition, an attempt was made to filter high-frequency components and remove single-point spikes from the signal. However, this approach proved quite unsuccessful, even in ideal conditions. On even a minimally tremulous platform, the method could not be attempted because the vibration would mask the pulses. Any slight movement of the patient's arm would further compromise the measurement, because it would register that movement as the systolic pressure, or mask the actual event. A study by Geddes *et al*[4] investigated the principle of oscillometry, using the auscultatory method as reference. The aim of this study was to determine the ability of the oscillometric technique to estimate blood pressure, using both human and animal subjects. The group found that the oscillometric method tended to overestimate human systolic pressure by 4%–10%. The conclusions were that when using this method, systolic pressure usually occurs at about one half the maximum oscillation amplitude (before the maximum occurs), and diastolic pressure occurs after the maximum, at approximately 80% of the greatest oscillation amplitude. Both these ratios were found dependent on the pressures, the systolic varying between 0.73 and 0.45, and diastolic between 0.69 and 0.83. It can be concluded that the parameters used in calculating the pressure using the oscillometric technique vary from individual to individual, and therefore, the accuracy of the results will also vary depending on the value of the systolic and diastolic pressures.

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A further refinement of the oscillometric technique was presented by Protocol Systems, under the trade name of Smartcuf.[5] The aim here was to improve the results in an unstable environment, i.e., in a moving vehicle, when the patient is shivering, in the presence of tremors, etc. This improvement involved synchronizing electrocardiogram (ECG) data with the pressure data in order to remove noncardiac pulses, and then processing these data in order to determine the patient's blood pressure. A comparative study of the Smartcuf (used with the Propaq 200 monitor) was reported by Protocol Systems at the end of 1998. This showed that the combination (Smartcuf with the Propaq 200) performed with 80% of its attempts at measuring blood pressure within ±10% error, 8% with error between ±10% and ±20%, and 12% of the attempts giving no reading. Six of 900 readings had error greater than ±20%. This experiment was not conducted using human subjects, because of the inability to verify results against the auscultatory method in a moving vehicle. The blood pressure was instead generated using a Bio-Tek simulator, combined with a Hewlett Packard Arbitrary Waveform Generator® for the artifact signal.

The Propaq is currently used in helicopters as a diagnostic tool. Synchronizing the oscillometric data with that of an ECG makes the blood pressure measurement much more complex. For a standard diagnostic ECG, up to 15 leads may be required. The minimum number of leads required is two. Affixing the leads may require cleaning the site, and shaving or clipping hair. The patient is usually required to remain still and hold his or her breath occasionally, and all jewelry must be removed. However, in a medical emergency, it is critical that medical staff can determine such standard information as blood pressure and heart rate with minimal hassle and in the least time. A technique is needed that accounts for noise and vibrations, yet, which is simple to operate and not time consuming.

The development of the adaptive blood pressure monitoring (ABPM) system, discussed in the present manuscript, addresses the above requirements. This new concept for blood pressure monitoring systems is based on a novel implementation of the adaptive interference canceller (AIC) to remove the effects of noise and vibration from the audible Korotkoff sounds. The system makes use of two acoustic sensors in the pressure cuff, as shown in Fig. 1. One sensor is placed over the brachial artery, where an examiner would place the bell of a stethoscope if the blood pressure were being measured conventionally. The other sensor is placed on the back of the patient's arm, where it detects noise only. Then, the adaptive interference canceller is used as a nonlinear filter to remove the noise (interference) from the audible Korotkoff sounds received by the first sensor, as depicted in the "processing unit" shown in the bottom half of Fig. 1. The AIC is useful in any situation where nonlinear noise interference, which is embedded in the signal of interest, can be accurately measured, as is the case in the field measurement of blood pressure. The use of a sound transducer (microphone) in the pressure cuff has been found very effective in measuring blood pressure when the detection of the acoustic signal by the unaided human ear is extremely difficult.[5]

The system concept of this novel ABPM method is discussed in the methodology and experimental setup section. In particular, this section details the processing algorithm of the ABPM system; it provides a general outline as to how the AIC fits into the overall scheme of this project and demonstrates how the processing algorithm responds to specific examples. The clinical trials section provides test results of the ABPM system from clinical trials in noiseless and noise intense environments, such as near and onboard helicopters, and compares the performance of the systems with respect to the corresponding conventional auscultatory results.

## METHODOLOGY AND EXPERIMENTAL SETUP

The uniqueness of the adaptive blood pressure monitoring system, discussed in this paper, consists of two acoustic sensors in the pressure cuff, as shown in Fig. 1. The *first sensor* is placed over the brachial artery to acquire the acoustic signals of interest (Korotkoff sounds), where an examiner would place the bell of a stethoscope if the blood pressure were being measured conventionally. In most of the search-and-rescue and emergency cases, the signal from this sensor is corrupted by external environmental noise, such as the noise of helicopters, ambulances and emergency departments.[7] The *second sensor* is placed on the back of the patient's arm, where it acquires only the environmental noise that corrupts the signal of interest (Korotkoff sounds), acquired by the first sensor. This kind of sensor configuration is essential for nonlinear filtering using adaptive interference cancellation algorithms to remove noisy effects from the corrupted signal of interest, as depicted in the processing unit shown in the bottom half of Fig. 1.

The AIC process[1,2,6,8] has been used in other kinds of applications where there is a noisy signal, and where it is possible to simultaneously measure both the noisy signal and its noise component individually.[2,6] For example, AIC processing has been used by the authors of this paper in x-ray CT scanners to remove motion artifacts for cardiac imaging applications,[1,2] in order to noninvasively detect coronary calcification. Adaptive processing has been also used in ultrasound imaging applications[9] to suppress the human-tissue nonlinear scattering (abberation) effects in order to improve image resolution and in sonar applications to detect weak signals in the presence of strong interferences.[8]

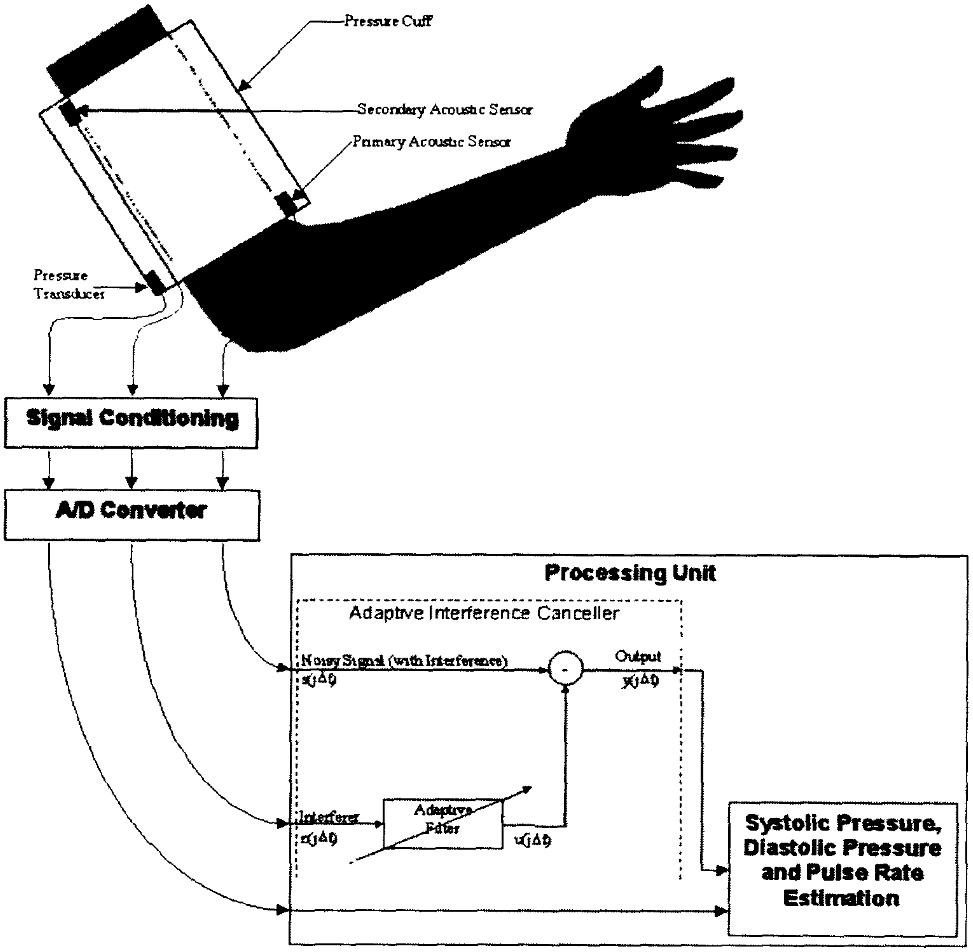

**FIGURE 1. Schematic representation of the system concept for the adaptive blood pressure monitoring system.**

Any attempt to implement the adaptive concept of this investigation in real-time systems should consider many other parameters such as the system errors associated with the implementation process and the correlation between the noise and the signal of interest. In particular, if there is a correlation-coupling term between them, then the AIC process will completely remove the signal of interest, and thus will fail to enhance the information of interest. Furthermore, the AIC technique is useful when any noise interference that is present in a signal is measured accurately.[2,6] Thus, in adaptive system applications considerable ingenuity is often required to find a suitable signal (or noise) to define the optimization process,[2] since if the actual desired response of the system were available one would generally not need the adaptive system, as a nonlinear filter. In our case, the measurements provided by the second sensor form the basis of the noise estimates for the adaptation process, as will be analyzed in the next section.

### *Adaptive Processing for Interference Removal*

The processing structure of the adaptive interference canceller[2] is shown in Fig. 1. The noisy signal, received by the primary acoustic sensor, is given by $y(j\Delta t) = s(j\Delta t) + n(j\Delta t)$ $(j = 1,2,\ldots,K)$, where $s(j\Delta t)$ and $n(j\Delta t)$ are the signal and noise components, respectively, and $K$ is the maximum number of samples to be processed. In an AIC system, it is essential that the signal and the noise components are either available or measured simultaneously with the received noisy signal. The algorithms used in this investigation are the least mean squares (LMS) and normalized least mean squares (NLMS) algorithms.[2,6,8] As discussed above, the primary sensor collects the noisy signal while the secondary acoustic sensor provides the noise component $n(j\Delta t)$ simultaneously. The output of the adaptive filter $u(j\Delta t)$, for noise input $n(j\Delta t)$, and $L$ adaptive weights $(w_1, w_2,\ldots,w_L)$ at time $j\Delta t$ is given by Eq. (1):

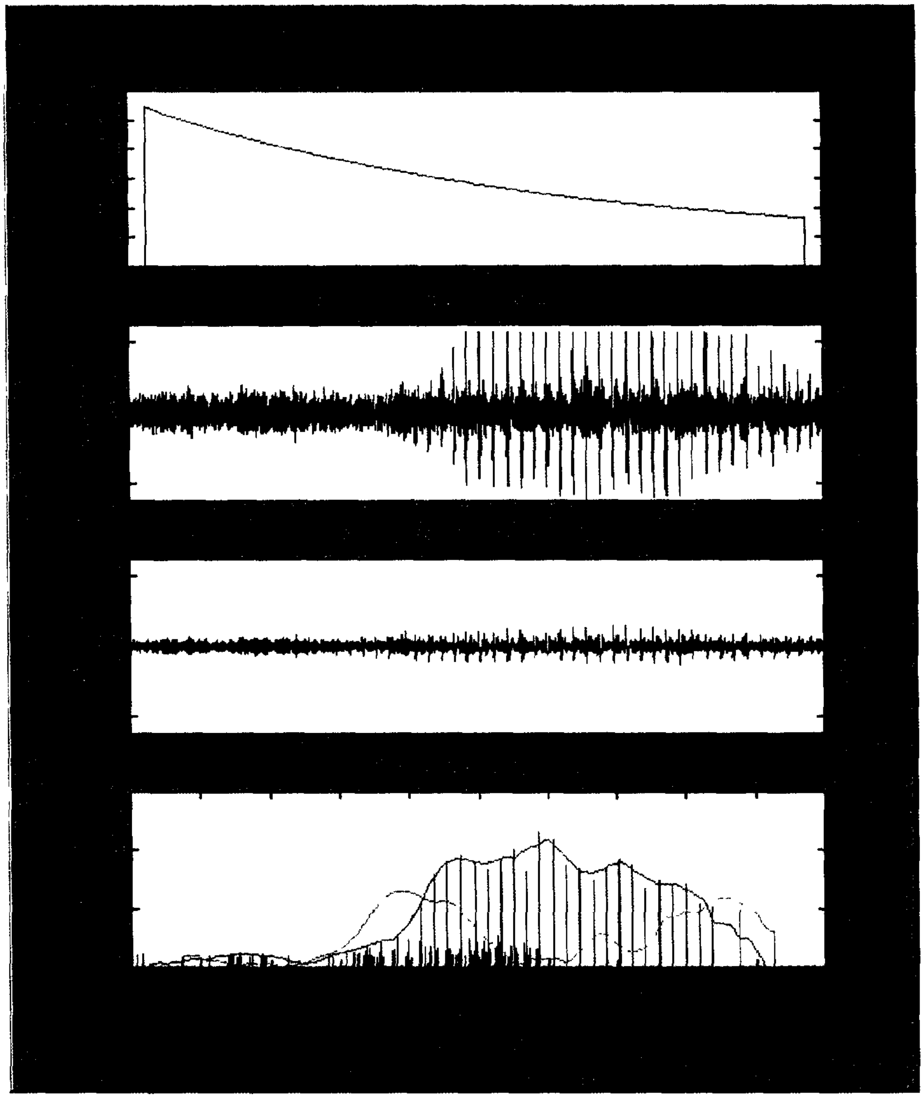

**FIGURE 2. Adaptive interference canceller demonstration using the adaptive blood pressure monitoring system.**

$$u(j\Delta t)=\sum_{i=1}^{L} w_i^{j\Delta t}\times n\left[\left(j+i-\frac{L}{2}\right)\Delta t\right]. \qquad (1)$$

The adaptive weight update equation for the adaptive algorithm is given by Eq (2)

$$w_i^{(j+1)\Delta t}=w_i^{j\Delta t}+\left(\frac{\lambda}{\alpha+|n|}\times n\left(\left(j+i-\frac{L}{2}\right)\Delta t\right)\times y(j\Delta t)\right) \qquad (i=1,2,..,L), \qquad (2)$$

where λ is an adaptive step size parameter, $\alpha$ is a stability parameter, and $|n|$ is the Euclidean norm of the vector

$$\left\{n\left[\left(j+1-\frac{L}{2}\right)\Delta t\right], n\left[\left(j+2-\frac{L}{2}\right)\Delta t\right), \ldots n\left(\left(j+\frac{L}{2}\right)\Delta t\right]\right\}.$$

To further reduce noise effects, bandpass filtering is used. The frequency band of the heartbeat signal is usually significantly different from the frequency band of noise Because of this, bandpass filtering will also aid in isolating the signal of interest from the noise and vibration effects. A measurement under relatively noiseless (acoustically quiet and vibration free) conditions is shown in Fig 2. A detailed description of the ABPM system component blocks follows.

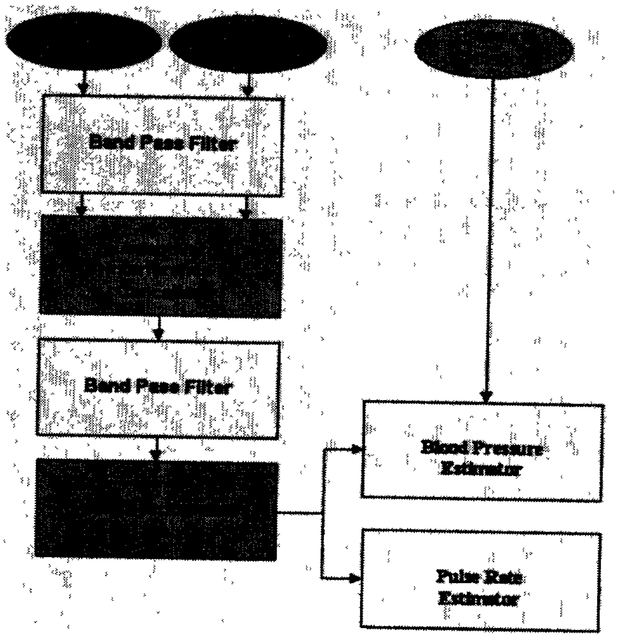

**FIGURE 3. Signal processing structure for the adaptive blood pressure monitoring system.**

### *System Concept and Implementation Processing Algorithm*

A schematic of the processing flow is shown in Fig. 3. The measured acoustic signals are first filtered with optional bandpass filters, then processed by the adaptive interference canceller, and this is followed by a second stage of optional bandpass filtering. The signal processing blocks that follow isolate valid pulses, and use this information along with the data measured by the pressure transducer to estimate the systolic and diastolic blood pressure, and the pulse rate during the measurements. Below is a more-detailed description of the individual modules and their purposes.

*Bandpass Filter.* This module isolates signals that are in the frequency range of interest. Since the frequency range of the acoustic signal of interest is well localized, the bandpass filter is a useful tool in removing excess noise from outside this range of frequency.

*Adaptive Interference Canceller.* The theoretical details of this module are defined in the preceding section. The primary function is to remove any interference from a measured signal by measuring the interference in the absence of the signal of interest so it can be subsequently removed. The secondary acoustic sensor, as depicted in Fig. 1, supplies the interference signal in this application.

*Peak Discrimination.* The purpose of this module is to extract valid peaks in the acoustic signal resulting from heartbeats, from any background noise. The first step is to isolate peaks that are greater than a noise floor level that is determined by the peak discriminator. The peaks are then further examined to determine if they satisfy some periodicity and constancy in repetition (i.e., possible heartbeats), as would be expected from a human heart. Peaks that do not satisfy these constraints are discarded when they are isolated events, but a degree of arrhythmia would be accounted for if it occurred and if it forms a group of peaks. The result of the peak discriminator is a series of groups of constantly repeating periodic peaks. This process also eliminates random peaks that may be due to strong transient noise effects.

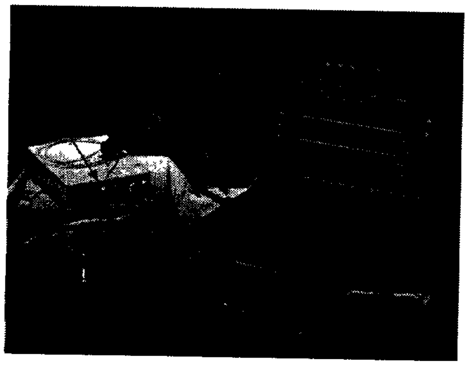

**FIGURE 4. Components of the ABPM system as shown in Table 1.**

*Pulse Rate Estimator.* The pulse rate estimator estimates the pulse rate of the subject. This is immediately available from the results of the peak discriminator.

*Blood Pressure Estimator* The systolic blood pressure is defined as the occurrence of the point of greatest magnitude of the positive derivative of the processed signal's envelope, which is the cyan curve in Fig. 2. This is synonymous with the blood pressure when the first heartbeat is heard, at the marked increase in the envelope (shown in green) on the same graph. The diastolic pressure is defined as the blood pressure when the last heartbeat is audible. This marked decrease is the point of greatest negative slope, which is shown in magenta. The times that these two events occur are referenced to the data acquired by the pressure transducer, which provides a measurement of the pressure in the deflating pressure cuff as a function of time. The corresponding pressures are the systolic blood pressure, and the diastolic blood pressure. A mercury sphygmomanometer was used to calibrate the ABPM system and it was the same device used for the auscultatory measurements.

### *System Concept and Implementation. Equipment*

The ABPM system prototype is implemented with the equipment shown in Fig. 4, and its items are labeled and

**TABLE 1. Components of adaptive blood pressure monitoring system.**

| | Components of the blood pressure monitoring system |
|---|---|
| 1 | Primary acoustic sensor acquires signal of interest and noise |
| 2 | Secondary acoustic sensor acquires reference noise for adaptive processing |
| 3 | Pressure transducer provides data for deflation curve |
| 4 | Sphygmomanometer and pump indicates current pressure level in cuff to operator |
| 5 | Signal conditioning unit filters and amplifies signals |
| 6 | Temperature probe (optional) |
| 7 | Oximetry sensor (optional) |
| 8 | PCMCIA card for data acquisition |
| 9 | Portable PC |

shown in Table 1. The prototype utilizes a portable PC operating on an MS Windows 95 platform. Data were acquired using a data translation PCMCIA card and software development kit. Each acoustic sensor consists of a stethoscope bell housing a miniature electric microphone.

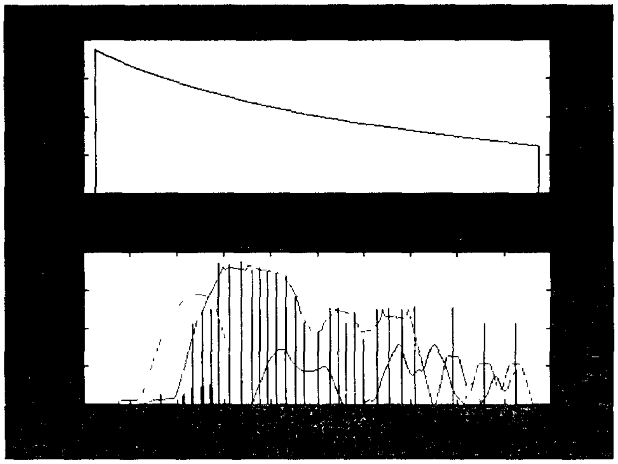

FIGURE 5. Performance of the ABPM system in the case of arrhythmia.

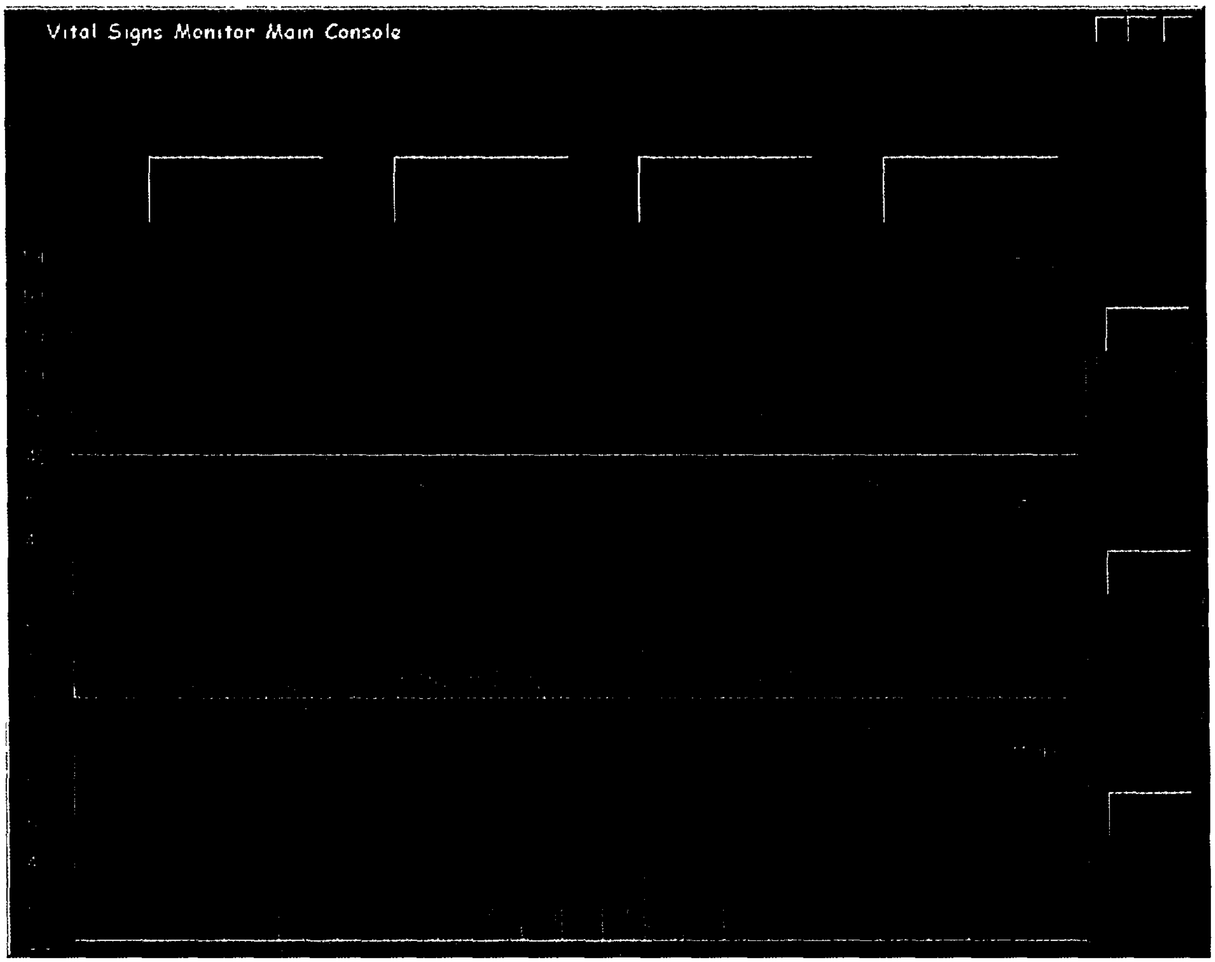

FIGURE 6. Performance of the ABPM system in the noisy environment outside a helicopter.

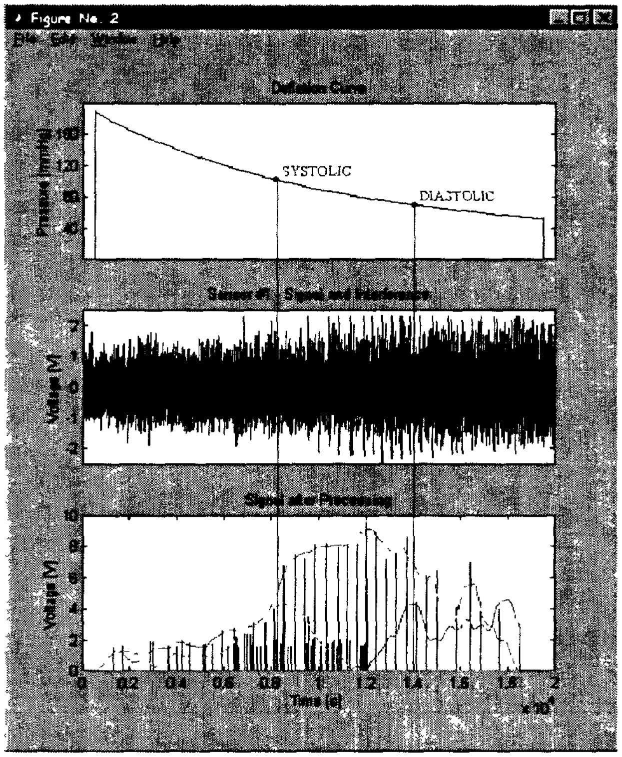

**FIGURE 7. Performance of the ABPM system in the noisy environment inside a helicopter.**

Three single-ended input channels were used, one channel carrying the signal of the primary sensor, one carrying the signal of the secondary sensor, and the third signal relaying information from a pressure transducer attached to the bladder of the cuff. These signals were amplified and filtered—the pressure transducer's signal passed through a 10 Hz low-pass filter, and the two microphone signals were bandpass filtered (10–500 Hz). A graphical interface was designed using a TCL/TK software kit to simplify the use of the ABPM system acquisition and processing, as shown later in Fig. 6. Once the pressure cuff with the sensors in place was inflated, the acquisition process was started, taking 30 s, and sampling at a rate of 2000 Hz per channel. Next, the dataset was processed by a C++ program compiled by Microsoft Visual C++ 6.0, and interfaced with the user via the TCL/TK GUI. Finally, the results (systolic and diastolic pressures, and heart rate) were displayed on the screen.

At this point, it is important to note that in most of the cases, the commercial systems fail to estimate systolic and diastolic pressures for patients with arrhythmia.

### *Performance Characteristics of ABPM System for Special Cases*

*Arrhythmia* Figure 5 shows the processed signal, and corresponding pressure deflation curve of a subject with arrhythmia. Arrhythmia is an alteration in rhythm of the heartbeat that can cause pulses to disappear within the pressure margin of the patient. The processing algorithm of the blood pressure measurement system updates its heart rate estimate with each pulse it finds as it searches for the systolic and diastolic pressure. It also keeps track of the number of "missed" heartbeats and will output a new value for the systolic or diastolic pressures if it finds a new sequence of heartbeats after the gap.

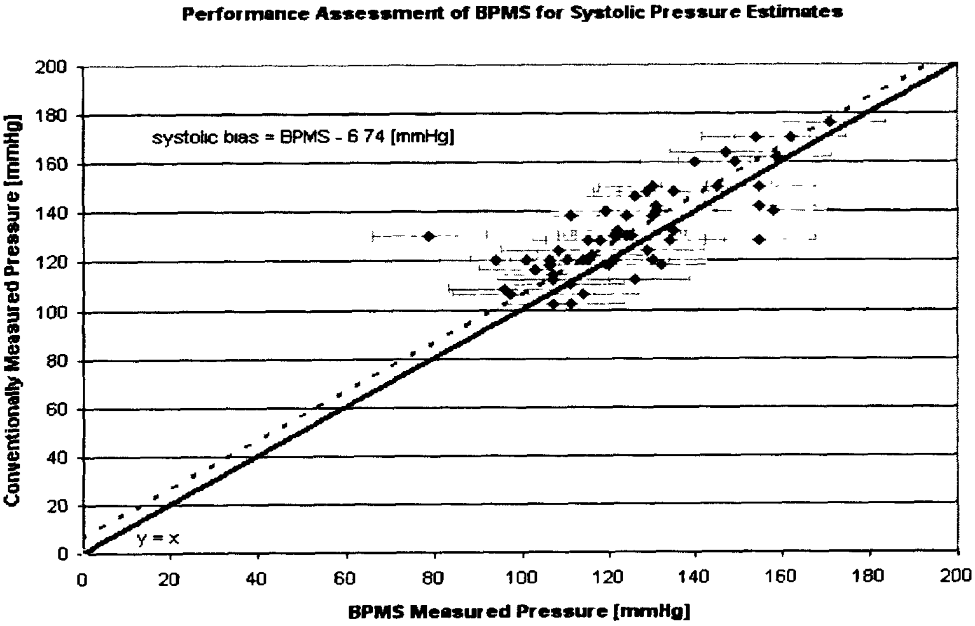

**FIGURE 8. Comparison of the ABPM system with the conventional auscultatory method for systolic pressure estimates in noiseless environments.**

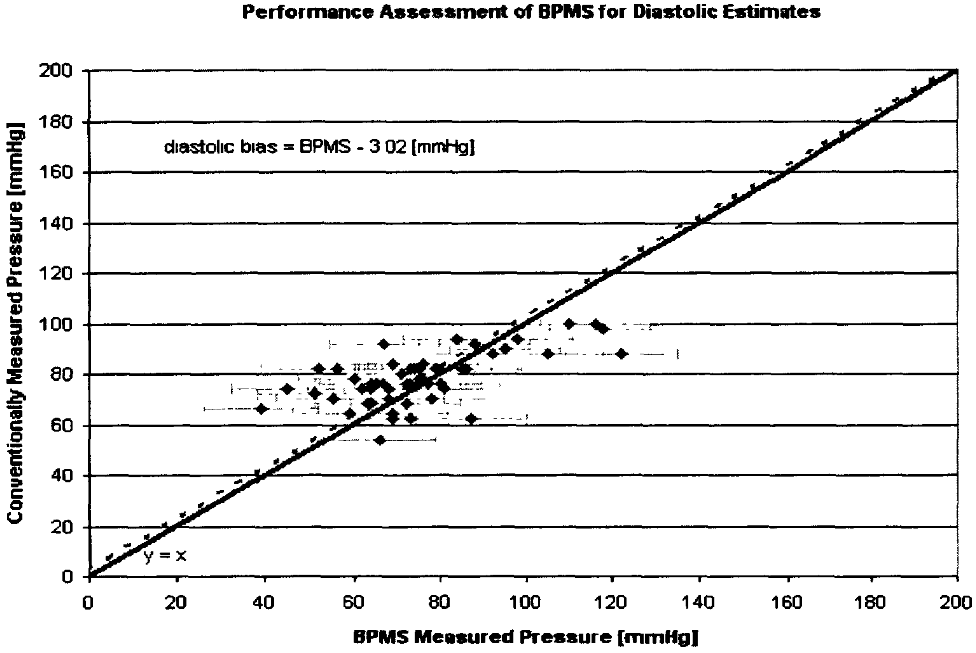

**FIGURE 9. Comparison of the ABPM system with the conventional auscultatory method for diastolic pressure estimates in noiseless environments.**

*Helicopter Noise.* Figures 6 and 7 show noisy blood pressure signals $y(j\Delta t)$, containing interference $x(j\Delta t)$. These measurements were taken just outside (Fig. 6) and inside (Fig. 7) a Labrador helicopter, with motor running and rotors turning, to demonstrate the efficiency of the AIC processor at removing interference in a relevant situation. The received signal from the primary acoustic sensor, the secondary acoustic sensor, and the output of the adaptive interference canceller (after software processing) are shown for both cases. Also shown in Figs. 6 and 7 are the pressure deflation curves for both subjects. From this information the blood pressure is readily obtained. It is evident from Figs. 6 and 7 that the AIC is successful at completely removing the interference while leaving the signal of interest undistorted.

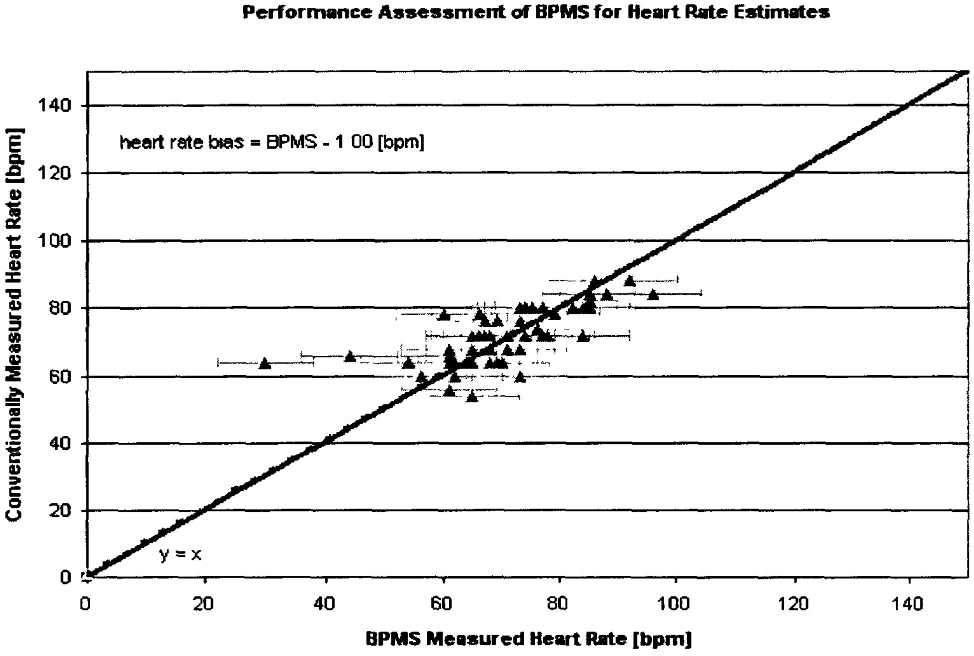

**FIGURE 10. Comparison of the ABPM system with the conventional auscultatory method for heart rate estimates in the noiseless environment.**

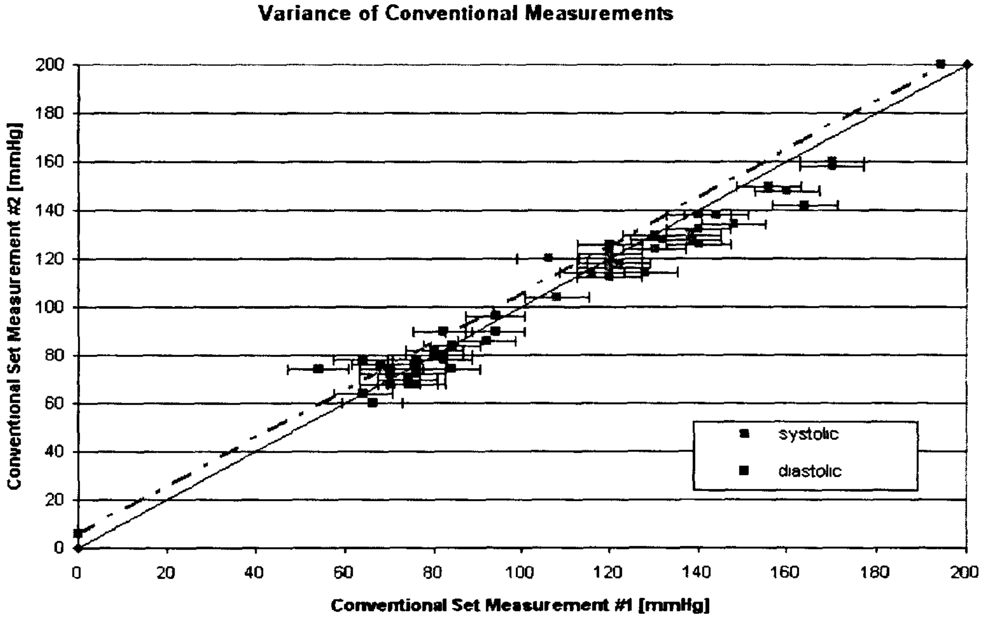

FIGURE 11. Variance of two consecutive systolic and diastolic pressure estimates using the conventional auscultatory method.

The above implementation concept of the AIC process demonstrates that it is a practical tool for removing any noise and vibration effects in the measured acoustic signal of interest (Korotkoff sounds). The noise measured by the second sensor placed away from the artery is simply treated as the interference $n(j\Delta t)$, and is introduced into the adaptive interference canceller. The measurement made by the sensor that measures the pulses from the occluded artery is treated as the "noisy" signal in the adaptive algorithm.

## CLINICAL TRIALS

### *Phase I. Operation in Noiseless and Vibration Free Environment*

In the clinical trials using the prototype ABPM system, 57 subjects were used. They spanned a broad range of physical characteristics, ranging from 22 to 73 years in age, 155 to 193 cm in height, and from 50 to 107 kg in weight. The subjects were taken to an examining room where health care professionals measured their blood pressure and heart rate. Each patient was asked to assume the supine position. Blood pressure measurement was taken by the auscultatory method first, using a stethoscope and column sphygmomanometer. Heart rate was obtained by taking a pulse at the wrist for 15 s, and extrapolating a beats-per-minute figure from that count.

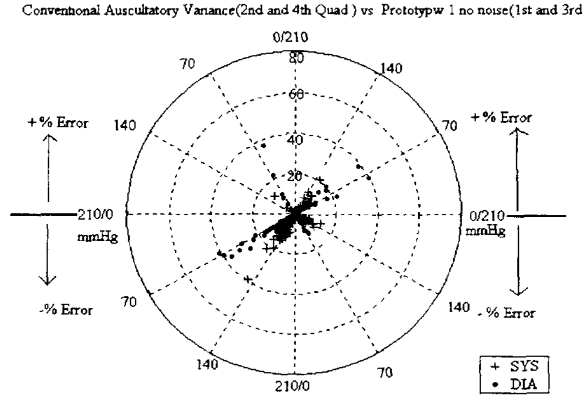

FIGURE 12. Comparison of variance of blood pressure estimates provided by the conventional auscultatory method and ABPM prototype 1, noiseless environment (distribution plot).

The ABPM system was used next to determine blood pressure and heart rate. The system's cuff houses the two acoustic sensors mentioned earlier inside stethoscope bells. These were attached on the inside of the material by hook and loop adjustable fasteners. The health care practitioner placed the cuff on the patient, palpating the region to insure that the primary sensor was placed directly over the brachial artery. The secondary sensor was placed on the upper back portion of the patient's arm. The cuff was pumped to an approximately suprasystolic pressure, and then released at a generally constant rate of 2–4 mm Hg per second. It was very important to palpate the region in order to place the sensor correctly; datasets

TABLE 2. Pearson correlation coefficients.

| | Systolic pressure | Diastolic pressure | Heart rate |
|---|---|---|---|
| Conventional auscultatory method and ABPM system | 0 72 | 0 77 | 0.65 |
| Conventional method two measurements | 0 93 | 0 73 | 0.82 |

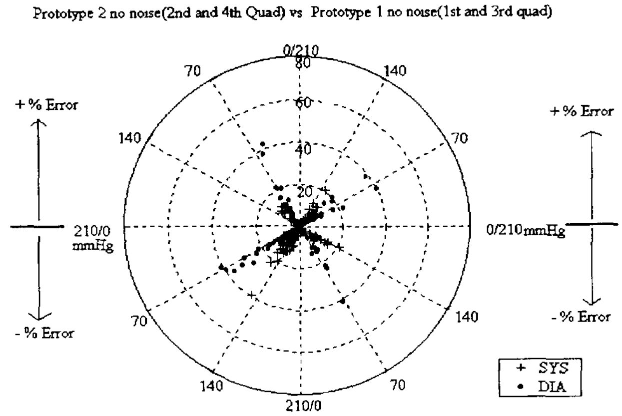

**FIGURE 13. Comparison of variance of blood pressure estimates provided by prototypes 1 and 2 of the ABPM system, noiseless environment (distribution plot).**

were rejected because the signal was too weak and, therefore, the reading could not be considered valid. If this was the case, the sensor was placed again with more caution, and the measurement was taken a second time. At this point, it is important to note that during the trials the graphical interface of the system (Fig. 6) provided visual indications from the display of the signal wave form (second wave form from the top of Fig. 6) whether the first sensor acquiring the Korotkoff sounds was placed directly over the brachial artery. More specifically, this graphical interface can be used as a trouble-shouting tool to assess the various cases when the system output is incorrect. Our experience from these clinical trials is that if the results of the ABPM system are incorrect then this will be due to the fact that the primary sensor has not been placed directly on the brachial artery.

Twenty-seven of the subjects had their blood pressure taken once more after the ABPM system attempt, by the auscultatory method. Three different health care professionals were present at random during the trials. During this first phase of clinical trials, neither method was subjected to noise or vibration.

*Results.* Figures 8–10 contain the results of the auscultatory method plotted against the results from the ABPM system, with separate graphs for systolic and diastolic pressures and heart rate. To illustrate the variance of measurements taken by the auscultatory method, the first results obtained by the auscultatory method are plotted against those from a second auscultatory measurement. These are shown in Fig. 11. In addition, the figures show any bias present in the results tabulated.

Another method of presenting the data first developed by Protocol Systems Inc.,[5] is shown in Fig. 12. In this polar distribution plot, the percentage error distribution of a measurement is presented as a point on the graph. The further a point is from the origin of the circle, the greater the percentage error. In each graph, two different sets of data can be compared to see if one set of results is superior to the other. For example, in Fig. 12, the result from the conventional auscultatory variance is plotted on the second (for + % error) and fourth (for − % error) quadrants of the circle. On the first and third quadrants, the noiseless data collected by using our prototype ABPM system are presented. From the plot, the distributions of the points show that more than 75% of

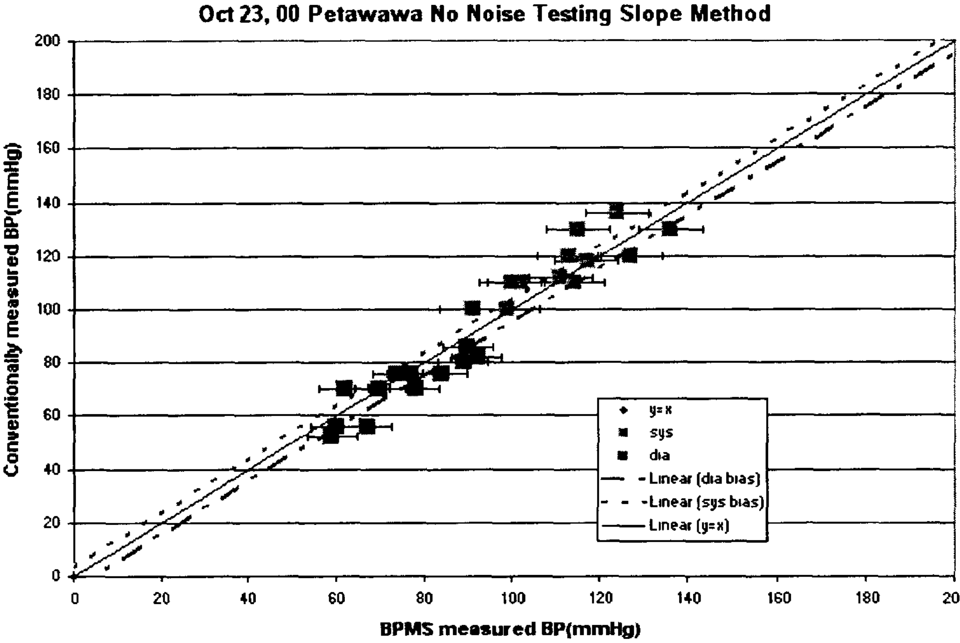

**FIGURE 14. Results from phase II of the clinical trials. Comparison of the ABPM system (prototype 2) with the conventional auscultatory method for systolic and diastolic pressure estimates in noiseless environment.**

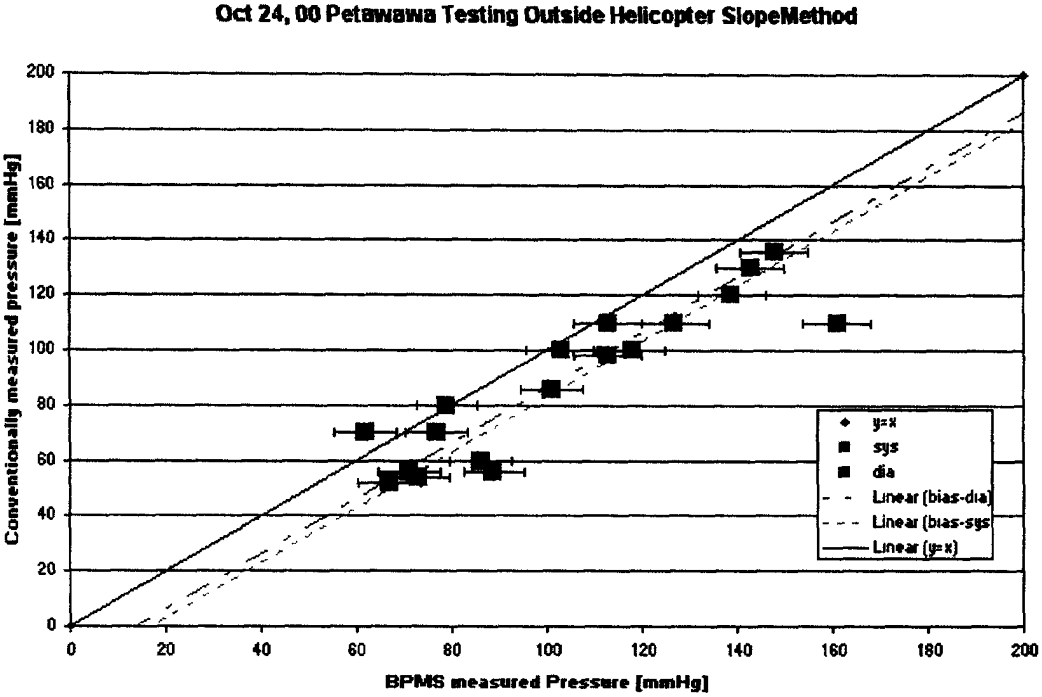

FIGURE 15. Results from phase II of the clinical trials. Comparison of the ABPM system (prototype 2) with the conventional auscultatory method for systolic and diastolic pressure estimates in the noisy environment outside a Griffin helicopter.

measurements are within 20% error and all the measurements are within 40% error

The Pearson correlation coefficient was also calculated for heart rate, systolic and diastolic pressure measurements, and for the two sets of auscultatory measurements. The coefficients are shown in Table 2 phase I Pearson correlation coefficients

*Discussion on Results of Phase I* Initially, the ABPM system's algorithm sought out the electronic equivalent

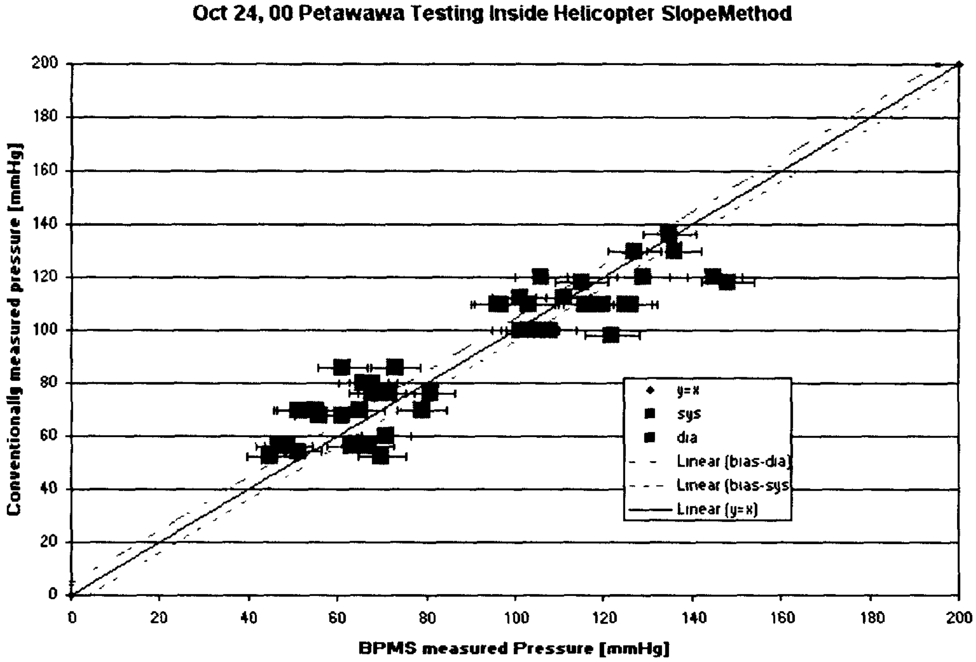

FIGURE 16. Results from phase II of the clinical trials. Comparison of the ABPM system (prototype 2) with the conventional auscultatory method for systolic and diastolic pressure estimates in the noisy environment inside a Griffin helicopter.

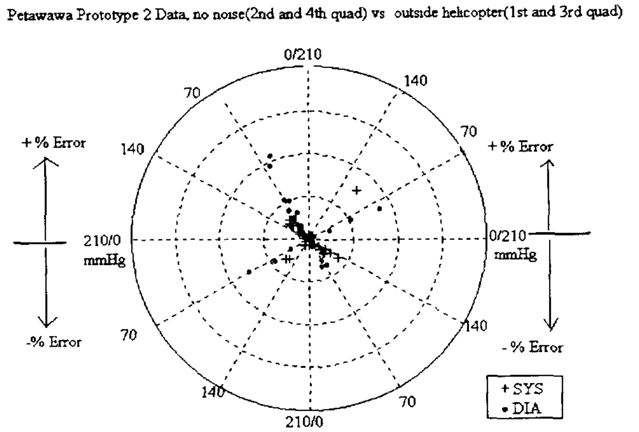

**FIGURE 17. Comparison of variance of blood pressure between estimates provided by the ABPM system (prototype 2) in the noisy environment outside a Griffin helicopter and the noiseless estimates using the conventional auscultatory method (bias removed, distribution plot).**

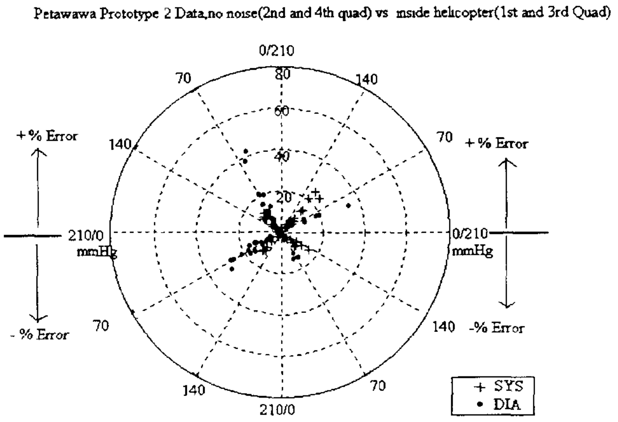

**FIGURE 18. Comparison of variance of blood pressure between estimates provided by the ABPM system (prototype 2) in the noisy environment inside a Griffin helicopter and the noiseless estimates using the conventional auscultatory method (bias removed, distribution plot).**

of the corresponding medical definitions of systolic and diastolic pressures. That is, systolic pressure occurring at the onset of a train of pulses perceptible to our microphones, thus perceptible to the computer as several sharp voltage spikes, and diastolic pressure occurring when these pulses disappeared completely. Upon consultation with the health care professionals, these definitions were specified more explicitly as the appearance and disappearance of a train of auditory pulses perceptible to the human ear. This required some changes to the processing, but drastically improved the correlation between the ABPM system's diastolic result and the auscultatory method's diastolic result. The results of this study contain data processed with this consideration.

The most obvious bias shown in the figures is the −6.74 mm Hg difference between the ABPM system's measured systolic pressure and the conventionally measured systolic pressure shown in Fig. 8. The diastolic pressure was also measured lower repeatedly by the ABPM system, by 3.02 mm Hg on average. Plotted measurements of the patients' heart rates did not reveal any substantial bias. The consistent difference in blood pressure measurement can be attributed to the positioning of the stethoscope bell, which rests underneath the inflated

**TABLE 3. Performance summary of ABPM system for prototypes 1 and 2 under different noise conditions.**

| Performance summary of ABPMS prototypes 1 and 2 under different conditions | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Conventional auscultatory variance | | Prototype 1 no noise | | Prototype 2 DCIEM noise room | | | | Prototype 2 Petawawa force base | | | | | |
| | | | | | No noise | | Noise | | No noise | | Inside helicopter | | Outside helicopter | |
| Condition | SYS | DIA | SYS | DIA | SYS | DIA | SYS | DIA | SYS | DIA | SYS | DIA | SYS | DIA |
| Average % error | −3.9% | 0.7% | −6.7% | −3.0% | −0.31% | −2.6% | −7.6% | −13.6% | 3.5% | 8.1% | 3.7% | −5.8% | 0.0% | −1.8% |
| Standard deviation | 7.2 | 6.6 | 12.72 | 12.8 | 9.2 | 11.3 | 11.1 | 11.5 | 8.5 | 8.6 | 12.1 | 11.0 | 14.1 | 12.7 |
| Error ≤10% | 85.2% | 81.5% | 63.2% | 52.6% | 75% | 43.8% | 60% | 30% | 81.8% | 40.9% | 66.7% | 25.0% | 66.7% | 44.4% |
| Error >10% ≤20% | 14.8% | 11.1% | 31.6% | 28.1% | 21.9% | 37.5% | 30% | 40% | 18.2% | 45.5% | 25.0% | 54.2% | 22.2% | 22.2% |
| Error >20% ≤30% | 0% | 3.7% | 3.5% | 8.8% | 3.1% | 9.4% | 10% | 20% | 0% | 4.5% | 8.3% | 16.7% | 0% | 11.1% |
| Error >30% | 0% | 3.7% | 1.8% | 10.5% | 0% | 9.4% | 0% | 10% | 0% | 9.1% | 0% | 4.2% | 11.1% | 22.2% |
| Total number of trials | 27 | 27 | 57 | 57 | 32 | 32 | 10 | 10 | 22 | 22 | 24 | 24 | 9 | 9 |

bladder and, therefore, exerts some additional pressure on the artery. This effect is more apparent at the higher pressures, affecting the systolic pressure to a greater degree, as shown, but can be minimized by using a bell that is flatter against the patient's arm. To be more specific, a single-sided, flat bell can be used instead of the double bell that was used in this study.

To illustrate the degree of the ABPM system's success, the results shown in Figs. 8–10 must be compared with those of Fig. 11, which presents the results of two consecutive traditional measurements. Note that the systolic bias is present in the results of Fig. 11, and that there is still some variation between measurements, though it is of smaller magnitude than the variation between the ABPM system and the auscultatory method. Comparing these two sets of data shows that the difference between the system and the auscultatory method is of a reasonable scale. Comparing these two figures also shows the effect of having blood pressure measured repeatedly by occluding the same brachial artery, as all measurements were done on each patient's right arm within a span of 10–15 min. This accounts, in part, for the systolic bias described above. Systolic pressure is more variable than the diastolic, and this is reflected in the lack of a diastolic bias.

Another method of determining the overall success of the ABPM system is to compare correlation coefficients for the two sets of data. Note that the correlation indicators are quite encouraging, displaying that although the systolic attempts were not quite as consistent with the auscultatory measurements, the diastolic attempts correlated well, expressed in the approximately equal Pearson coefficients.

Several issues affecting the actual acquisition component of the blood pressure measurement process should also be mentioned. It was found that when taking a blood pressure measurement using the ABPM system, placing the primary sensor correctly was of utmost importance. Misaligning this sensor and the brachial artery did not yield valid results, and it can be concluded that this would represent an important item to be stressed if training new users for this system. In addition to this issue, pumping up the cuff with one hand, while keeping an eye on the sphygmomanometer gauge, and beginning the acquisition software on the laptop with the other hand, required a great deal of dexterity. It would be ergonomically beneficial to utilize an automatic pump in a future prototype, making the task of acquiring the data less arduous.

### *Phase II: Operation in Noisy and Vibration Intensive Environment*

A further test of the ABPM system's capabilities was performed outside a Griffin helicopter using the Prototype ABPM system under adverse weather conditions (precipitation, and approximately 8 °C before wind chill). The position change of the secondary sensor in the ABPM system is necessary since the performance of the AIC is highly dependent on whether a pure noise interference signal is collected. If the interference signal contains some Korotkoff sounds, the AIC will cancel the signal of interest as well, leaving a train of muted pulses after processing. Figure 13 illustrates the performance of two different prototypes including the ABPM system concept implemented on two different positions of the secondary acoustic sensor placed inside and outside the cuff, respectively. Obviously, the position change of the secondary sensor enabled the system to measure blood pressure in a noisy and vibration intensive environment without affecting the performance of the ABPM system.

In phase II of the clinical trials, nine subjects aged 21 to 31 years, weighing 50–109 kg, and 155–188 cm in height, had their blood pressure measured by the traditional auscultatory method indoors. Heart rate was obtained by taking a pulse at the wrist for 15 s, and extrapolating a beats-per-minute figure from that count. Up until this point in the session, the method used was identical to that of phase I. Next, measurements were taken by the ABPM system. The participants were then moved outdoors where their blood pressure and heart rate were measured using the ABPM system both outside and inside the running helicopter. All measurements were done on the brachial artery, and in the supine position.

*Results.* Figure 14 displays the results of the auscultatory method plotted against the results from the ABPM system in the noiseless situation. Figures 15 and 16 show the systolic and diastolic pressures measured by the ABPM system, outside (Fig. 15) and inside (Fig. 16) the Griffin helicopter versus the auscultatory measurements made indoors. Since it is not possible to verify the ABPM system results in this noisy helicopter environment against the auscultatory method results, the ABPM results were compared with the auscultatory measurements shown in Fig. 14, which were taken 4 h earlier. In particular, for the measurements taken outside the helicopter, the subjects had an elevated blood pressure due to the body's shivering response to cold weather and this is clearly shown by the bias in Fig. 15. Again, the figures show any bias present in the results tabulated. Figures 17 and 18 show the polar distribution plots of outside and inside the Griffin helicopter data versus the noiseless data of the same subjects, respectively. Since the blood pressure of the subjects were elevated in the outside-helicopter setting, the distribution plot of outside the helicopter is plotted with bias removed to give a comparable view with the data that were taken under normal room temperature. Note that in Fig. 18, when inside the helicopter, above 80% of the data points are concentrated within the 20% error region. After the bias was removed from the outside-helicopter data set, about 70% of the data points are within the 20% error region, as shown in Fig. 17.

## CONCLUSION

The blood pressure monitoring (ABPM) system has proven successful in noisy and vibration intensive conditions with adverse weather; these are environments in which traditional auscultatory methods fail or are unreliable. The performance summary of two ABPM system prototypes is shown in Table 3. The adaptive interference canceller adeptly removed noisy elements and vibration to provide the user with an instantaneous reading of systolic and diastolic pressure and heart rate. There is an immediate need for the use of this device as a field deployable vital signs monitor for the Canadian Forces.

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