Accuracy of an Ultrasound Doppler Servo Method for Noninvasive Determination of Instantaneous and Mean Arterial Blood Pressure

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SUMMARY A new noninvasive method for determining arterial blood pressure is presented. Using a fast servo system, the pressure in the arm cuff is controlled so that the flow is maintained at a low value. Transcutaneous ultrasound Doppler techniques are used to detect flow to the artery. Comparison with invasive pressure measurements demonstrated that the servo method reproduced beat-to-beat variations in arterial blood pressure faithfully. Mean arterial blood pressure was determined from the noninvasive recordings using the same mathematically valid procedure as was used for the invasive recordings. The deviation between the invasive and the noninvasive determinations of this measurement was $-0.6 \pm 2.2$ mm Hg (mean ± SD) in 23 subjects.

ACCURATE DETERMINATION of arterial blood pressure is frequently necessary for patient monitoring. It is also the basis for rational antihypertensive therapy. A noninvasive method is usually preferred because it is more convenient and avoids the risks associated with arterial puncture. Traditional indirect methods use a slow deflation rate of the cuff, 2-4 mm Hg per beat or per second. Therefore, information on the blood pressure is obtained only intermittently.

In principle, it is possible to control the cuff pressure so that it is tracking the pressure inside the artery continuously. Then, the transmural pressure over the arterial wall will be zero or very low throughout the pulse wave. Thus, the arterial wall will be maintained in an unloaded state, suspended between two nearly equal pressures.

Marey1 proposed that this could be achieved by maintaining a constant vascular volume in the limb. However, servo techniques were not developed in the nineteenth century, so he had to unload the arterial walls by enclosing the forearm in a stiff chamber filled with water. This method was not practical for clinical use. In recent years, Penaz et al.2,3 used the constant vascular volume principle to record the instantaneous blood pressure in the finger. The pressure in the finger cuff was under servo control to maintain a constant blood volume as detected by a photoplethysmograph under the cuff. However, it may be difficult or impossible to use this approach when the cuff is on the upper arm.

Methods

We investigated another method for recording the instantaneous arterial blood pressure: control cuff pressure so that flow in the artery is restricted at all instants. If the flow is restricted, the artery must be partially constricted under the cuff. When unaffected by calcification, the wall of the artery is flexible. This

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means that the arterial flow channel will be completely closed if the pressure on the outside of the artery only slightly exceeds that on the inside. Also, the artery will regain an open flow channel if the outside pressure is slightly lower than the intraarterial pressure. Thus, the degree of constriction is a sensitive indicator of the transmural pressure when this is close to zero. If we can restrict the flow in the artery under the cuff to a low value (but above zero) throughout the pulse wave, the transmural pressure will be maintained close to zero. When the cuff is wide enough so that the pressure in its bladder is transmitted without significant loss to the outside of the artery, the pressure time course in the artery will be closely represented by that in the cuff.

This principle is illustrated in figure 1. The cuff is wrapped around the upper arm. The pressure in the cuff bladder is controlled by a fast electropneumatic servo and monitored by a pressure transducer with associated amplifier and filters. The velocity of the flow in the brachial artery is detected 2–5 cm proximal to the cuff by transcutaneous ultrasound Doppler techniques. In this region of the artery, we may assume proportionality between the flow and the velocity, for inflation of the cuff is not likely to cause a significant change in the cross-sectional area of the artery proximal to the cuff. The mean (time-average) velocity is normally 5–10 cm/sec in the nonoccluded brachial artery (personal observations). The velocity in diastole is often close to zero.

We use the servo to restrict the velocity to a level selected by the operator. This level is the velocity reference, which is chosen well below the resting mean velocity. Figure 2 illustrates the measurement procedure, simultaneous pressure and velocity recordings.

Phase 1 corresponds to the state in the arm before the cuff is inflated. Then the pressure in the cuff is raised above the systolic arterial pressure, phase 2. This will completely occlude the artery under the cuff. However, the instantaneous flow velocity is not zero proximal to the cuff. Rather, it is oscillating, in accordance with the observations described by McCutcheon and Rushmer. The mean flow, however, is zero in this state.

Then the flow restriction, phase 3, is initiated. The reference velocity is 3 cm/sec. The velocity trace is still somewhat pulsatile because of limitations in the frequency response of the servo system. However, the pulsatile amplitude is considerably reduced compared with that in phase 1 and even phase 2. The mean velocity is almost equal to the reference velocity, 3 cm/sec, while it is approximately 5.5 cm/sec in phase 1. Therefore, the lower arm is underperfused and the pressure in the arteries distal to the cuff will be well below that in the axillary artery. The flow is thus restricted and the instantaneous pressure in the cuff corresponds to the intraarterial pressure.

The diastolic velocity of flow may need some further clarification. It is close to zero in phase 1. This does not mean that the tissues in the arm are not perfused in diastole; the systolic inflow has been stored in the elastic arteries, and this volume is sufficient to perfuse the tissues during diastole if the peripheral resistance is high or even normal. During phase 3, the inflow is restricted and considerably less blood is fed to the elastic arterial reservoir in systole. Therefore, a diastolic flow is required. If we deflate the cuff suddenly in diastole, flow increases. This demonstrates that the flow is restricted in diastole during phase 3.

However, if the peripheral resistance in the arm is so high that the lower arm actually requires less perfusion than that corresponding to the reference velocity, large errors in the pressure recording may result. Then the velocity in diastole will not increase above the reference value even if the cuff is deflated considerably below the blood pressure. This type of error may be detected by a testing procedure. A step increase of 3 cm/sec, lasting 3 seconds in the reference velocity, will result in a change in the mean cuff pressure of less than 3 mm Hg when the flow is properly restricted. However, if the flow is insufficiently restricted, the reference velocity step test will produce a large drop in the mean cuff pressure, typically 10–25 mm Hg. Thus, we use this procedure to check that the flow is properly restricted throughout the pressure wave.

**Figure 1.** Illustration of the ultrasound Doppler servo method for noninvasive recording of the instantaneous arterial blood pressure. The box in upper left shows a longitudinal cross-section with details of probe fixation. A concentric foam rubber adhesive disc is fitted over the upper part of the probe. The direction of the ultrasonic beam is indicated by parallel lines in front of the piezoelectric crystal. The axillary/brachial/radial/ulnar arteries are indicated by broken lines.
When the flow is insufficiently restricted, an obvious solution is to choose a lower value for the reference velocity. Then a valid recording will be possible even when the peripheral resistance is high. Another solution is to sustain phase 2 for 0.5–1 minute before phase 3. Then, a mild reactive hyperemia is induced, and the peripheral resistance is lowered. The flow velocity is controlled to a low value in the flow restriction phase, so we will not see the pressure loss that results from the high flow normally associated with reactive hyperemia.

In the comparison study, a standard arm cuff with Velcro fastenings was used. Its bladder measured 12 × 29 cm. One of the rubber tube connections was replaced with a 6-mm i.d. silicon rubber tube in order to give less resistance to air flow from the electropneumatic servo valve. The pressure in the cuff was measured through the other rubber tube, which was connected to a Statham P23Db pressure transducer. The mean pressure in the cuff was displayed on a meter. The cuff was wrapped tightly around the upper arm, but not so tight as to hinder venous flow.

A range-gated Doppler with direction discrimination was used for monitoring of the flow velocity. The emitted ultrasonic frequency was 10 MHz. We also tried a continuous-wave Doppler, but found that it gave an inferior performance in the system. The pulsed Doppler was only slightly more complex in circuitry than a corresponding continuous type, and it had a simpler and more efficient probe because the same piezoelectric crystal was used both for transmitting and receiving ultrasonic power was less than 100 mW/cm².

We tried different configurations of the ultrasound probe. First, we used a conventional, handheld pencil-type probe with an emitting surface of approximately 2.5 × 2.5 mm. We then changed to a flat type of probe with an emitting surface of 5 × 2.5 mm. Now we are using a probe which produces an ultrasonic beam which is 20 mm wide. This probe is designed to be taped over the artery using a standard adhesive foam rubber disc intended for ECG electrodes. (Hewlett Packard 14275A) (fig. 1). The probe should be located in the axilla, where the artery is rather superficial, to ensure a good signal-to-noise ratio in the Doppler signal.

The electropneumatic servo unit had proportional plus integral characteristics. We found that the response delay in the servo should be less than 5 msec to avoid instability of the feedback loop. This corresponds to a bandwidth of approximately 100 Hz. The servo also had to produce a high rate of change in

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**Figure 2.** Recordings of cuff pressure and velocity of the blood in the brachial/axillary artery 3 cm proximal to the upper edge of the cuff. Phase 1 is the normal velocity wave form in the resting arm. Phase 2 is inflation of the cuff above the systolic pressure in the artery. Phase 3 is flow restriction by servo control of cuff pressure. The reference velocity was 3 cm/sec.
the cuff pressure in order to track the upstroke of the arterial pressure wave. The reference velocity was 3 cm/sec for all patients.

The intraarterial pressure was measured through a catheter connected to an AME-840 pressure transducer with a disposable dome. The catheter and the dome were flushed by a very slow saline drip. The intraarterial and the cuff pressures were recorded simultaneously on magnetic tape. Calibration was performed immediately after the recording. The catheter was withdrawn from the artery, and its tip was placed on the same horizontal level as the brachial artery under the cuff. The tip of the catheter was connected to the cuff pressure, which was increased in steps of 40 mm Hg up to 200 mm Hg. The meter of the cuff pressure transducer-amplifier was used as a reference for calibration. This system was checked periodically against an adjusted mercury column.

The pressure recordings and the calibration signals were replayed on paper using an ink-jet recorder (Mingograph 62). The signals were low-pass filtered during replay (second-order Bessel filter at 10 Hz). Mean pressures were obtained by additional low-pass filtering to remove the pulsatility (third-order Bessel filter at 0.3 Hz). The same filters and the same channels on the paper recorder were used on successive replays of either intraarterial or cuff pressure signals. Another channel on the recorder was used to write out a synchronizing signal so identical beats could be used for comparison.

Mean, systolic and diastolic pressure measurements were taken from the paper approximately in the middle of the recordings. The average of two beats was used for plotting the relationship graphically or in the statistical calculations.

Twenty-three patients, ages 11-80 years, were studied. Their arm circumference ranged from 16-36 cm. All patients were studied in the supine position.

Twelve of these patients were referred to us for diagnostic intraarterial pressure measurements due to hypertension. In this group, the short catheter was inserted under local anesthesia into the left brachial artery at the antecubital fossa. The cuff was wrapped around the right arm. The frequency response of the catheter-manometer system was approximately flat to 10 Hz.

Eleven of these patients were undergoing catheterization for diagnostic angiography, and the invasive pressures were recorded in the descending aorta. We did not check the frequency response of the catheter-manometer system for this group, as only mean and diastolic pressures were used for comparison.

Results

Simultaneous recordings of intraarterial and cuff pressures are shown in figure 3. The peripheral resistance in the patient was decreased suddenly at the arrow by releasing occluding cuffs around both legs. A transient drop in the blood pressure followed immediately. The noninvasive recording reproduced the change faithfully in all patients who demonstrated spontaneous or induced changes in their arterial blood pressure level.

Figure 4 is a summary of the comparison between the invasive and the noninvasive measurements of the arterial blood pressure. The mean arterial blood pressure determinations were very accurate. The deviation between the two methods was $-0.6 \pm 2.2$ mm Hg (mean ± sd); the noninvasive value was higher. This deviation was almost within the specification of the transducer-amplifier-recorder system. The largest deviation was 6 mm Hg (invasive method higher) in a case where the standard cuff was applied to an arm which was only 16 cm in circumference. Among patients in the normal adult range, the maximum deviation was 4 mm Hg. The correlation coefficient was $r = 0.995$ between the invasive and the noninvasive determinations of mean arterial blood pressure.

The determinations of diastolic arterial blood pressure also correlated well ($r = 0.990$), and the deviation was low ($-0.2 \pm 2.7$ mm Hg) between the invasive and the noninvasive readings.

The comparison for the systolic pressure does not include the patients where the invasive recordings were made in the aorta, as the pulse pressure is changed when the pulse wave travels through the subclavian and axillary arteries. The invasive and the noninvasive systolic pressure determinations in the remaining 12 patients correlated well ($r = 0.995$). The deviation was $0.5 \pm 3.2$ mm Hg (invasive highest). The largest deviation was 6 mm Hg.

The described servo method was based on ultrasound Doppler detection of blood flow velocity. Therefore, the ultrasound probe had to be aimed properly at the artery. If the Doppler signal was temporarily lost during the flow restriction phase, the distal arterial system would fill up rapidly and the pressure recording could not be trusted. The art of aiming the probe properly was difficult for the pencil-type configuration and somewhat less demanding for the flat probe. We sometimes had to make repeated trials before a satisfactory recording was obtained. The probe that had a very wide beam (20 mm) was rather easy to position. It could be taped and strapped on to the arm and would stay in position even if the patient was exercising. Valid recordings of arterial blood pressure could be made under such conditions; most other noninvasive methods would detect only motion artifacts.

We obtained satisfactory noninvasive pressure recordings in all patients referred to us. Errors resulting from high peripheral resistance in the arm did occur in a few cases, but these errors were reliably detected by the step in the reference velocity as described in the Methods section. In the present investigation on the accuracy of the servo method, we wished to use the same value for the reference velocity throughout for all the patients, so we induced mild reactive hyperemia in the arm to obtain valid recordings in the cases where the peripheral resistance was high. Compared with intraarterial determinations of mean arterial
blood pressure, the noninvasive recordings during mild hyperemia were as accurate as in cases in which valid recordings were made at the first attempts.

The pulsating cuff was reported to be less uncomfortable than one that was deflated slowly in the conventional manner. If the recording was continued for more than 2–5 minutes, pain was sometimes reported in the lower arm. This was relieved immediately by deflating the cuff. Before the pain occurred, we could sometimes hear short bursts of venous flow in the Doppler signal. (We used stereo earphones to listen to the quadrature Doppler signals so that we could discriminate the direction of flow by ear.) These observations indicated that the pressure in the venous system distal to the cuff was high and that the pain was due to venous congestion. The venous outflow from the arm was practically stopped when the cuff was inflated to the level of the arterial pressure. A certain restricted inflow of blood was allowed to pass into the lower arm, and this was accumulated in the veins. These are normally compliant, so the venous pressure was raised slowly under these conditions. We found by experimenting on ourselves that to avoid discomfort and errors in the recordings due to venous contamination, we should deflate the cuff after a flow restriction period of 2 minutes. A rest period of only 5–15 seconds was necessary to restore the arm circulation sufficiently to continue the recording. When a fully continuous recording was required, we could apply cuffs and ultrasound probes to both arms and cycle alternatingly flow restriction with rest.

**Discussion**

The detection of blood flow velocity by ultrasound Doppler is a more direct indicator of arterial opening than Korotkoff sounds of oscillations in the cuff pressure. Alexander et al. demonstrated that the Doppler method for detecting blood flow distal to the cuff may give accurate estimates of systolic blood pressure, but measurement of the diastolic blood pressure is not feasible by this approach. The flow restriction principle and its implementation are an extension of the Doppler blood flow detection approach to be used for recording of the entire arterial pressure wave. It differs from the methods using ultrasound Doppler for detecting arterial wall movement. The servo approach does not need any large or fast
movements of the arterial wall to detect the opening of the artery. Rather, the artery is maintained in a relatively steady constricted state under the cuff. Thus, the properties of the arterial wall may be used continuously (or rather semicontinuously, as the flow restriction phase is limited to 2 minutes) as a very sensitive detector of the transmural pressure. These physiologic considerations explain the ability of the servo method to measure the arterial blood pressure with an accuracy which approaches that normally associated with invasive techniques.

One of the most significant advantages of the servo Doppler method is the possibility of determining the mean arterial blood pressure accurately by a noninvasive procedure. Mean arterial blood pressure measurements have not been used more extensively in clinical practice because of the problems of determining this measurement indirectly. An estimate of the mean arterial blood pressure may be calculated from systolic and diastolic readings, but certain assumptions concerning the shape of the pressure wave are included in the formula and add more uncertainty with the indirect pressure determinations.

A microprocessor-based oscillometric instrument has been introduced that is claimed to be able to determine the mean arterial pressure by displaying the lowest cuff pressure that gives maximum oscillations. The principle may give useful readings in many patient-monitoring situations. However, the oscillometric criterion is an empirical approximation and adds uncertainty to the measurements, especially when pronounced short-term fluctuations are present in the blood pressure level.

The true mean of a recording of instantaneous pressure can be calculated by measuring the area under the pressure curve and dividing this by the time baseline. One or a whole number of beats should be used. True mean pressure can also be obtained by hydraulic or electronic damping of the pressure wave. This approach was used in the present study. Our results indicate that the mean arterial blood pressure can be determined reliably within \( \pm 4 \text{ mm Hg} \) using the servo method.

A standard-size cuff was used in the present study. The width of the cuff bladder was at least 1.2 times the diameter of the limb (40% of the circumference) in all cases except one. Although the optimal size of the cuff...
was not investigated, the results indicate that this is not a critical factor for accuracy if generally accepted criteria are used.

Besides the improved accuracy, the servo method has other advantages over conventional indirect methods. A semicontinuous or even fully continuous recording of arterial blood pressure may be useful for monitoring patients during critical phases of surgical procedures. Furthermore, a valid reading of blood pressure may be achieved in a few seconds because the method does not depend upon a slow deflation of the cuff (fig. 2). Alternatively, averages of many systolic and diastolic readings may be calculated to minimize the effect of respiration and arrhythmias on the determinations. A representative average can be determined over a few respiration cycles; conventional indirect methods require repeated inflations and deflations of the cuff.

Two aspects of the Doppler servo method are problematic. First, a stable Doppler signal must be maintained throughout the recording. The probe design with a wide ultrasonic beam seems to be a practical solution to this problem. Since venous flow was stopped during the flow restriction phase, the veins did not contaminate the Doppler signal in the manner often experienced when recording the flow velocity in peripheral arteries. The possibility of fixing the probe in a stable position considerably extends the range of application of the method.

The second problem was that of restricting the flow in states of high peripheral resistance. We could detect errors reliably by step changes in the reference velocity, so we believe that this type of testing can be performed automatically in an improved version of the instrument. We are now using lower values of the reference velocity, 1–2 cm/sec lower than reported in this study. This seems to have reduced the problem. Valid recordings have been obtained in almost all cases without using reactive hyperemia to lower the peripheral resistance in the arm. However, we have not used the method to determine the arterial blood pressure in patients in shock. The reference velocity may have to be chosen very low in these cases.

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