Accuracy of a Continuous Blood Pressure Monitor Based on Arterial Tonometry

Takayuki Sato, Masanori Nishinaga, Akiko Kawamoto, Toshio Ozawa, and Hiroyoshi Takatsuji

A validation study of the continuous noninvasive tonometric blood pressure monitor called JENTOW was performed in 20 normotensive subjects and 10 hypertensive patients. Tonometric and intra-arterial blood pressures were simultaneously recorded at supine rest and during a Valsalva maneuver and tilting test. The results of the strict evaluation of the instrument’s capacity for reproducing intra-arterial blood pressure were as follows: 1) The overall frequency response of the transcutaneous blood pressure-monitoring system based on arterial tonometry was flat, with negligible delay to intra-arterial blood pressure in the range of 0–5 Hz. 2) The largest discrepancy between intra-arterial and tonometric pressure waveforms was found at the early systolic phase; except for this phase, the tonometric waveform was almost equal to the intra-arterial waveform. 3) The beat-to-beat variability of tonometric pressure corresponded to that of intra-arterial pressure almost perfectly in the physiologically significant frequency range of 0–0.5 Hz. 4) During resting conditions, the averages of the systolic and diastolic values measured tonometrically corresponded well to those measured intra-arterially. 5) The changes in the between-method discrepancy of blood pressure values during the Valsalva maneuver were statistically significant but small (<5 mm Hg). 6) No significant effect of postural tilting was found on the between-method discrepancy. We conclude that this method is clinically acceptable and reliable except for its limited capacity for recording the higher frequency intra-arterial waveform and for responding to the relatively rapid and large transient changes in blood pressure. (Hypertension 1993;21:866–874)

KEY WORDS • blood pressure monitors • blood pressure • tonometry

The establishment of noninvasive alternatives to invasive methods for continuously monitoring arterial blood pressure has been expected for many years. A noninvasive technique, arterial tonometry, was invented in 1963.1,2 A tonometric device has been recently improved and has resulted in an instrument called JENTOW. The objective of this study was to evaluate the accuracy of the tonometer JENTOW in reproducing intra-arterial blood pressure. Our interests in the comparison of the blood pressures measured by the two methods were focused on the following points: 1) the correspondence of the waveforms of blood pressure, 2) the correlation of beat-to-beat variabilities, and 3) the agreement of blood pressure values during resting conditions and during laboratory maneuvers that induced rapid and large transient changes in blood pressure. This study demonstrated the reliability and limitations of the noninvasive method for reproducing intra-arterial blood pressure.

Methods

Subjects

Twenty normotensive volunteers and 10 patients with uncomplicated essential hypertension (26 men, four women; mean age, 42.3 years; range, 20–74 years) were studied. All the hypertensive patients had received no medication at least 14 days before the study. In every subject, a between-arm difference in sphygmomanometric blood pressure was <5 mm Hg. Informed consent was given by each participant.

Hemodynamic Recordings

The subject was placed on a tilt table with a footrest. A splint kept the right wrist slightly extended to make the right radial artery more palpable and to reduce movement artifacts. Surface electrodes for the monitoring of electrocardiograms and respiratory movements were attached to the chest.

Intra-arterial blood pressure was recorded by a routine invasive method. After local anesthesia with 2% lidocaine, a Teflon 22-gauge 11-cm-long cannula was inserted percutaneously into the left radial artery and connected to a physiological pressure transducer (P23XL, Spectramed Medical Products, Singapore) through a 13-cm-long piece of low-compliance pressure tubing. The pressure transducer was connected to amplifying and monitoring equipment (BSM-8502, Nihon Kohden, Tokyo). This system provided adequate performance for the accurate measurement of the waveform of intra-arterial blood pressure (natural frequency, >50 Hz; damping coefficient, <0.10).

Tonometric blood pressure was measured with a continuous noninvasive blood pressure–monitoring instrument (JENTOW, Colin Electronics, Komaki, Japan). A tonometric sensor was attached to the right extended wrist. A cuff was wrapped around the left brachial artery; the output of the tonometric sensor was...
calibrated by the oscillometric blood pressure measured on the brachial artery.

The principles of arterial tonometry are illustrated in Figure 1. The tonometric method is applied to a superficial artery on a bony structure. The radial artery is commonly used because of its large diameter and easy accessibility. An array of 30 piezoresistive pressure transducers with a frequency response >50 Hz (flat to 1.0 dB) and hysteresis <1.0% are embedded in a tonometric sensor.3 The sensor is pressed against the artery by hold-down pressure in an air chamber. The optimum hold-down pressure is given automatically to flatten a portion of the arterial wall and to maximize the pulse pressure measured by some pressure transducers located over the artery. Intra-arterial pressure can be measured by the pressure transducer centered over the flattened portion of the arterial wall, because the circumferential tension in the flattened arterial wall that acts transcutaneously to the transducer is negligible.

The oscillometric measurement of systolic and diastolic values is made by a continuous-deflation oscillometric module certified by the Federal Drug Administration. Two coefficients, gain and offset, are computed automatically from the oscillometric blood pressure values. The raw signal of the tonometric sensor is calibrated by these coefficients, and tonometric systolic and diastolic values are matched more closely to the oscillometric systolic and diastolic values.

Two points are critical for the accurate measurement of tonometric blood pressure.2,3 First, the pressure transducers must be placed accurately over the artery. This is achieved by the use of an array of 30 pressure transducers and an automatic mechanical sensor-positioning system, which determines the best position of the sensor automatically. Second, the wrist where the sensor is attached must be fixed during the continuous recording, because the instrument does not have sufficient resistance to movement artifacts. The immobilization of the wrist by a splint is recommended. If the instrument detects the significant movement of the wrist, it will raise an alarm.

The physiological signals of the electrocardiogram, respiratory movement, intra-arterial blood pressure, and tonometric blood pressure were recorded on a data recorder (MR-30, TEAC, Tokyo).

Recording Protocols

After the preparations for hemodynamic recordings were completed, oscillometric calibrations for tonometric blood pressure measurements were repeated at 5-minute intervals for 20 minutes. For the next 5 minutes, data were continuously recorded from the resting subject. After another oscillometric calibration, a Valsalva maneuver was performed; the subject blew into a plastic tube connected to a mercury column by 40 mm Hg for 20 seconds. The subject was passively moved to an upright 90° position 5 minutes after an oscillometric calibration was done again. If the tonometric instrument raised an alarm because of movement artifacts during the continuous recording, remeasurement was performed after recalibration.

Analysis of Blood Pressure

Off-line analysis was performed on a personal computer (PC-9801RA, NEC, Tokyo) and workstation (MC 6450, Concurrent Computer, Tinton Falls, N.J.). The electrical signals of intra-arterial and tonometric blood pressures were played back from the data recorder and were low-pass filtered through an electronic antialiasing filter with a cutoff frequency of 100 Hz and an attenuation slope of 80 dB per octave (ASIP-0260, CANOPUS Electronics, Kobe, Japan). The two filtered signals were digitized at 500 samples per second per channel through an analog-to-digital convertor (ADX-98H, CANOPUS Electronics).

Resting conditions. The procedures of analysis were as follows:

1) Waveform. An analysis of the two waveforms of intra-arterial and tonometric pressures during the resting period was done for each subject. The dynamic response of the tonometric method was estimated from x-y plots; intra-arterial pressure was on the x-axis, and tonometric pressure was on the y-axis. A discrepancy between intra-arterial and tonometric pressures was calculated; intra-arterial pressure was used as the zero reference. Plots of the discrepancy were made on the rate of change in intra-arterial pressure with respect to time.

Analysis in the frequency domain was performed; autospectra of intra-arterial and tonometric pressures, coherence and phase spectra, and gain spectra were estimated. The raw power spectrum was computed with the algorithm based on a fast Fourier transform and then was smoothed in the frequency domain.4 The final spectral estimate had approximately 120 degrees of freedom; the equivalent bandwidth was 0.2 Hz.

2) Beat-to-beat variability. Autoregressive component spectral analysis was used for the estimation of the
physiologically important spectral component of the beat-to-beat variability of arterial pressure. Systolic and diastolic values during the resting period were computed from intra-arterial and tonometric pressures. Component power spectral density functions of arterial pressure variations were estimated according to the modeling and decomposing algorithm of an autoregressive process described by Sato et al. Characteristics of a spectral component were given by a resonance frequency, power, and "normalized power" (power/total power-power of direct-current components). The direct-current component was defined as a spectral component with a resonance frequency <0.03 Hz. Only components >5% in normalized power were considered significant. Significant components with resonance frequencies between 0.03 and 0.15 Hz were designated as low-frequency components; those with resonance frequencies equal to the respiratory frequency were designated as high-frequency components.

3) Average value. Averages of systolic and diastolic values during the resting period were calculated from intra-arterial and tonometric pressures. The tonometric and intra-arterial values were compared.

Valsalva maneuver. According to the estimate method by Parati et al, averages of baseline systolic and diastolic values for 20 seconds, the peak values after the beginning (phase 1), the bottom values before the end (phase 2), and the overshoot values (phase 4) were computed from intra-arterial and tonometric pressures. A between-method discrepancy in each variable was calculated.

Tilting test. From intra-arterial and tonometric pressures, 20-second averages of systolic and diastolic values were calculated before and at 5-minute intervals for 20 minutes after the tilting test. A between-method discrepancy in each variable was calculated.

Statistical Analysis
The linear regression analysis of paired measurements and the analysis in the frequency domain described above were used. Differences in paired measurements were tested by one-sample \( t \) tests. A multiple-comparison test was made by a Tukey studentized range method for a least significant difference test. Differences were considered significant at a value of \( p < 0.05 \).

Results

Resting Conditions

Waveform. Figure 2A shows an example of the original tracings of the electrocardiogram (ECG), intra-arterial and tonometric blood pressures, the between-method discrepancy in blood pressure, and rate of change in intra-arterial blood pressure with respect to time (\( dIAP/dt \)) during resting conditions. Intra-arterial blood pressure was used as the zero reference. The discrepancy looks like a mirror image of \( dIAP/dt \). Panel B: Plot shows dynamic response of the tonometric method. Panel C: Plot of between-method discrepancy on \( dIAP/dt \). Data during one cardiac cycle was analyzed by linear regression analysis. \( r \), Correlation coefficient.
summarized in Figure 4. The system based on the arterial tonometry was considered to consist of the tonometric instrument and the membranelike tissues, including the arterial wall, subcutaneous tissues, and skin between the arterial lumen and the tonometric sensor (Figure 1). The input was intra-arterial pressure; the output was tonometric pressure. The frequency response of the system was computed for each subject. The ensemble-average spectra of the gain and the phase in 30 subjects show that the system could not reproduce the waveform of intra-arterial pressure with complete fidelity. In the frequency range <5 Hz, the gain was flat and the phase difference was negligible; however, in the higher frequency range, the gain attenuated with the frequency (−3 dB at 10 Hz).

Beat-to-beat variability. Examples of the results of linear regression analysis are shown in Figure 5. The correlation coefficients distributed from 0.96 to 0.99.

Examples of the autoregressive component spectra of the beat-to-beat variability of arterial pressure are presented in Figure 6. A one-sample t test indicated no significant difference in the resonance frequency or the component power between the autoregressive spectral components estimated from intra-arterial and tonometric beat-to-beat variations (data not shown). A linear regression analysis of 30 pairs of the estimates charac-

**FIGURE 3.** Autospectra of intra-arterial and tonometric blood pressures (top panels) and coherence and phase spectra between the two signals (bottom panels). Note the high coherence nearly equal to 1 in the range of 0–5 Hz. Black-filled areas are means±95% confidence intervals.

**FIGURE 4.** Top: Diagram shows estimation of overall frequency response of the transcutaneous blood pressure-monitoring system based on arterial tonometry. The estimated system was considered to consist of the tonometric instrument JENTOW and the membranelike tissues, including the arterial wall, subcutaneous tissues, and skin between the arterial lumen and tonometric sensor. Bottom: Ensemble-average spectra of gain and phase in 30 subjects show that the frequency response was flat, with negligible delay to the input in the range of 0–5 Hz.

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FIGURE 5. Scatterplots of tonometric beat-to-beat values on intra-arterial beat-to-beat values for systolic (panel A) and diastolic (panel B) blood pressure. Data during a 5-minute resting period was analyzed by linear regression analysis. Examples showing lowest or highest correlation are presented. r, Correlation coefficient; α, intercept; β, regression coefficient.

terizing the spectral component indicated a regression coefficient nearly equal to 1 and an intercept close to 0 (Table 1).

Average value. A linear regression analysis of 30 pairs of the average values measured by the two methods during the resting period showed a regression coefficient nearly equal to 1. Individual between-method discrepancies distributed from −16.2 to 8.1 mm Hg for systolic and from −10.5 to 13.4 mm Hg for diastolic blood pressure; the means±SD were −5.6±5.2 mm Hg for systolic and −2.4±5.8 mm Hg for diastolic blood pressure (Figure 7).

Laboratory Tests

An example of the original tracings of intra-arterial and tonometric pressures and the between-method discrepancy during the Valsalva maneuver is illustrated in Figure 8. On rough visual inspection, the two original

FIGURE 6. Autoregressive component spectra of intra-arterial (panel A) and tonometric (panel B) beat-to-beat variabilities of systolic (SBP) and diastolic blood pressure (DBP). Both low-frequency (LF) and high-frequency (HF) components are observed in all spectra.
TABLE 1. Linear Regression Analysis of the Estimates Characterizing the Autoregressive Spectral Component of Beat-to-Beat Variability

<table>
<thead>
<tr>
<th></th>
<th>α</th>
<th>β</th>
<th>r</th>
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<tbody>
<tr>
<td>Systolic arterial pressure</td>
<td></td>
<td></td>
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<tr>
<td>Low-frequency component</td>
<td>0.0000 Hz</td>
<td>1.00</td>
<td>1.00</td>
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<tr>
<td>Component power</td>
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<td>0.96</td>
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<tr>
<td>High-frequency component</td>
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<td>1.00</td>
</tr>
<tr>
<td>Component power</td>
<td>-0.0067 mm Hg²</td>
<td>1.00</td>
<td>0.99</td>
</tr>
<tr>
<td>Diastolic arterial pressure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-frequency component</td>
<td>0.0000 Hz</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Component power</td>
<td>0.0124 mm Hg²</td>
<td>0.99</td>
<td>0.96</td>
</tr>
<tr>
<td>High-frequency component</td>
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<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Component power</td>
<td>-0.0059 mm Hg²</td>
<td>0.99</td>
<td>0.99</td>
</tr>
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In the regression equation $y = α + βx$, the dependent variable $y$ and the independent variable $x$ represent estimates from tonometric and intra-arterial pressures, respectively. α and β are the intercept and slope of the regression, respectively; $r$ is the correlation coefficient.

Intravascular tracings of blood pressure appeared to correspond well. It was found, on closer inspection, that the between-method discrepancy varied with time significantly, but the changes in the between-method discrepancy were <5 mm Hg (Figure 9A). The changes in the between-method discrepancy during the tilting test were small and not significant (Figure 9B).

**Discussion**

The main results are as follows: 1) The overall frequency response of the transcutaneous blood pressure-monitoring system based on arterial tonometry is flat, with negligible delay to intra-arterial blood pressure in the range of 0–5 Hz. 2) The largest discrepancy between intra-arterial and tonometric pressure waveforms is found at the early systolic phase; except for this phase, the tonometric waveform is almost equal to the intra-arterial waveform. 3) The physiologically significant beat-to-beat variability of tonometric blood pressure corresponds to that of intra-arterial blood pressure almost perfectly. 4) During resting conditions, the averages of the systolic and diastolic values measured tonometrically correspond well to those measured intra-arterially.

**Figure 8.** Original tracings of RR interval calculated from electrocardiogram, intra-arterial and tonometric blood pressures, and between-method discrepancy in blood pressure during Valsalva maneuver. Intra-arterial blood pressure was used as the zero reference. On rough visual inspection, the two tracings of blood pressure appear to correspond well.

**Figure 7.** Top panels: Scatterplots of 5-minute average systolic (SBP) and diastolic (DBP) values of tonometric blood pressure on those of intra-arterial blood pressure. Data obtained from 30 subjects were analyzed by linear regression analysis. $r$, Correlation coefficient; α, intercept; β, regression coefficient. Bottom panels: Scatterplots of discrepancies between intra-arterial and tonometric values in SBP and DBP on intra-arterial blood pressures. Intra-arterial blood pressure was used as the zero reference. Solid lines indicate means of between-method discrepancies in 30 subjects; broken lines, ±2 SD.
Figure 9. Graphs of intra-arterial and tonometric values and of between-method discrepancies during Valsalva maneuver (panel A) and before and after postural tilting (panel B). Intra-arterial blood pressure was used as the zero reference. Absolute blood pressure values are mean ± SEM. Between-method discrepancies are expressed as means ± 95% confidence intervals. SBP, systolic blood pressure; DBP, diastolic blood pressure. *p < 0.05 from baseline.

Intrinsic Errors in Comparison

The raw signal of the tonometric sensor positioned at the radial artery was calibrated by an oscillometric blood pressure taken at the brachial artery on the contralateral arm where radial arterial pressure was measured invasively. This method for the calibration of tonometric radial arterial pressure introduces intrinsic errors in the comparison between intra-arterial and tonometric pressures. In the comparison of blood pressure values, the effects of pulse amplification from the brachial to radial artery should be considered. In the comparison of waveforms, the difference between the right and left radial arteries also should be considered.

Waveform

The manufacturer of the tonometric instrument states that the tonometric sensor itself has adequate potency to record the intra-arterial blood pressure waveform accurately; if the pressure is given “directly” to the sensor, the frequency response of the sensor is flat in the range of 0–50 Hz (personal communication). It should be considered, however, that intra-arterial pressure actually transmits “indirectly” to the sensor through the membranlike tissues, including the arterial wall, subcutaneous tissues, and skin between the arterial lumen and the sensor (Figure 1). Our results showing the overall frequency response suggest the methodological limitations inherent in the transcutaneous pressure monitoring. The intra-arterial pressure waveform cannot be reproduced with complete fidelity by the transcutaneous tonometric method; the tonometric waveform at the early systolic phase is blunter than the intra-arterial waveform. Except for this phase, the tonometric waveform is almost equal to the intra-arterial waveform.

Beat-to-Beat Variability

The physiologically important information included in the beat-to-beat variability of blood pressure is in the frequency range of 0–0.5 Hz. Our results of the analysis of the beat-to-beat variability confirm the validity of the use of the tonometric instrument for reproducing the beat-to-beat variability of intra-arterial blood pressure during resting conditions.
**Average Value**

The between-method discrepancy shown in the present results may be ascribed partially to the intrinsic errors described above. During resting conditions, a linear relation and a small discrepancy between intra-arterial and tonometric average values satisfy the requirements for new blood pressure-measuring devices of the Association for the Advancement of Medical Instrumentation.

**Laboratory Tests**

The between-method discrepancy is small at each phase of the Valsalva maneuver but differs significantly among the four phases. Rapid and large transient changes in both systolic and diastolic blood pressures and pulse pressure occur during the maneuver; systemic arterial vasoconstriction or vasodilatation also occurs. The significant changes in the between-method discrepancy could be ascribed to these alterations in blood pressure, pulse pressure, and peripheral arterial tone. Further studies are required to identify the exact mechanisms of the between-method discrepancy. Whether the small but significant changes in the between-method discrepancy are acceptable or not is dependent on how precise measurements are required to be during the maneuver.

No significant effect of postural tilting is found on the between-method discrepancy. The tonometric method is acceptable for blood pressure monitoring during the tilting test.

**Limitations in Practical Use**

The wrist where the tonometric sensor is attached must be fixed during the continuous recording, because the instrument does not have sufficient resistance to movement artifacts. Therefore, this instrument available at present is not suitable for the ambulatory recording of blood pressure waveforms under freely moving conditions. This is not to say that the arterial tonometer is unusually sensitive to movement artifacts. Eckerle3 has shown that the tonometric sensor is less sensitive to subject movements than a photoplethysmographic, quadrupolar impedance plethysmographic, or sphygmomanometric sensor. If the tonometric instrument used in this study detects significant movement of the wrist, it will raise an alarm and recommend remeasurement after calibration. In the present study, no alarm was given during resting conditions, but remeasurements were needed for three subjects during the Valsalva maneuvers and for two subjects during the tilting tests.

The hold-down pressure to flatten a portion of the arterial wall should not be large enough to occlude the arterial lumen. In the present study, this pressure was well controlled by the signal-processing system of the tonometric instrument; no discomfort or pain was experienced by the subjects.

**Methodological Importance in Data Analysis**

The establishment of noninvasive alternatives to invasive methods for continuously monitoring arterial blood pressure has been expected for many years. Invasive intra-arterial cannulation may be accompanied with the risk of complications such as infection and thrombosis; only the continuous measurement of arterial pressure can provide information on its waveform and beat-to-beat variability, which are clinically important as well as its systolic and diastolic values.\(^5\) Much attention should be paid to the waveform and beat-to-beat variability measured by a newly developed noninvasive method; its validity should be confirmed by strict evaluation. In some earlier studies,\(^1\)\(^,\)\(^7\)\(^,\)\(^9\) however, the comparison between invasive and noninvasive waveforms was made only by visual inspection; the correspondence of the two beat-to-beat variabilities was tested only by linear regression analysis.\(^7\) In addition to these, more advanced analysis would be needed; the analysis in the frequency domain used in the present study would be suitable for the evaluation of its accuracy. For example, Mulder et al\(^10\) have recently shown that the decremental response of the midfrequency component (0.07–0.14 Hz) of the beat-to-beat variability of blood pressure to mental stress cannot be detected with a previously marketed noninvasive device.

**Comparison With Other Methods**

The noninvasive method based on Peñaz servo photoplethysmography has already been used widely.\(^7\)\(^,\)\(^10\) Its principles are briefly explained here. An inflatable cuff is wrapped around the finger. The finger arterial volume assessed by photoplethysmography is clamped at the set point corresponding to two thirds of the maximum arterial volume by the continuous and dynamic adjustment of the cuff pressure through a fast-reacting electropneumatic servo system. Under the volume-clamped conditions, transmural pressure is nearly equal to zero. Therefore, cuff pressure can reflect absolute intra-arterial pressure continuously.

Although we have never used other noninvasive methods for the continuous measurement of blood pressure, we speculate that the tonometric method could be expected to have more advantages than the Peñaz method. First, the Peñaz method senses the artery diameter wave volumetrically; the tonometric method, on the other hand, detects the pressure wave of arterial pulsation. It may be considered, therefore, that the Peñaz method cannot provide a good signal-to-noise ratio for the rigid artery of the elderly, because a pulsatile change in diameter due to pulsatile intra-arterial pressure is very small.\(^11\) Imholz et al\(^12\) have recently shown that vasocostriction induced by phentolamine, which can lower the compliance of the digital artery, has a significant effect on the reliability of the Peñaz method. Kemmotsu et al\(^13\) reported, on the other hand, that vasodilation induced by the infusion of nitroglycerin during anesthesia lacks a significant effect on the accuracy of the continuous tonometric monitoring of arterial pressure. Second, the Peñaz method is applied to more peripheral arteries than the tonometric method. In some subjects, the measurement of finger pressure may become impossible because of the absolute vasocostriction of the digital arteries due to a Raynaud attack.\(^10\) Central arterial pressure can be estimated more accurately from measurements at the radial artery than from those at the finger.\(^11\)

In summary, the transcutaneous method with the Colin JENTOW arterial tonometer for the continuous measurement of blood pressure could reproduce, with high fidelity, the intra-arterial blood pressure waveform in the...
frequency range of 0–5 Hz, the physiologically important beat-to-beat variability of intra-arterial blood pressure, and the average systolic and diastolic values of intra-arterial blood pressure. We conclude that this method accurately reproduces intra-arterial blood pressure in real time except for its limited capacity for recording the higher frequency intra-arterial waveform and for responding to the relatively rapid and large transient changes in blood pressure. Further investigation in which the performance of several devices is evaluated under various recording conditions in a large number of subjects will be required to confirm this conclusion.

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