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Comparison of Arterial Tonometry with Radial Artery Catheter Measurements of Blood Pressure in Anesthetized Patients

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Background: **Arterial tonometry has been introduced for continuous noninvasive measurement of blood pressure. The accuracy of this method depends on the performance of two components: a piezoelectric crystal array and an oscillometric cuff. This study evaluates overall performance of arterial tonometry in terms of the performance of these two components by comparing it with simultaneous recording of blood pressure from an intraarterial catheter.**

Methods: **Seventeen adult patients were studied during general anesthesia. Blood pressure was measured with an intraarterial catheter and with an arterial tonometry system. Analog pressure waveforms were sampled at 100 Hz. Blood pressure measurements obtained by oscillometry were recorded by computer. Comparisons of mean blood pressure on a beat-by-beat basis were made with and without correction for the calibration error introduced by oscillometry.**

Results: **The difference between pairs of blood pressure determined by arterial tonometry and intraarterial measurement was 1.3 ± 9.4 mmHg (mean ± SD, bias ± precision) with 88,158 pairs of measurements. The difference between blood pressure determined by oscillometry and intraarterial measurement was 2.4 ± 7.5 mmHg (mean ± SD) with 401 comparisons. After correcting for calibration error, the difference between the tonometry measurements and intraarterial measurements was −1.0 ± 5.6 mmHg. Continuous episodes of discrepancy from intraarterial measurements in excess of 10 mmHg and lasting 5–60 s occurred 4.6 ± 0.8 times per hour with tonometry and 12.6 ± 1.4 times per hour with oscillometry.**

Conclusions: **Discrepancies in blood pressure readings by arterial tonometry *versus* intraarterial measurement result from both the piezoelectric crystal array and the oscillometry used for calibration. Accuracy for individual measurement is inferior to oscillometry alone. The ability to detect significant changes of blood pressure more rapidly than with oscillometry alone is limited by the accuracy of the piezoelectric crystal component but is enhanced by the reduced interval between measurements. (Key words: Measurement techniques, arterial blood pressure: oscillometry; tonometry.)**

THE need for frequent determinations of blood pressure is common in clinical care. Intraarterial (IA) measurements are indicated when rapid changes in blood pressure are anticipated and when accurate measurements during low flow states are needed. Radial arterial tonometry (AT) has been introduced to provide continuous, noninvasive measurement of blood pressure[1] and to allow detection of changes of blood pressure more rapidly than with intermittent oscillometric measurement alone. The method of AT is now commercially available and combines two transducer systems. An inflatable bladder flattens the radial artery against underlying bone and holds an array of piezoelectric crystals against the flattened portion of the artery. The electrical outputs of the crystals are processed by computer to identify the crystal element that is in the best position to sense arterial pressure. The second transducer system is an inflatable arm cuff that is used for oscillometric blood pressure measurement. The oscillometric measurements are used to calibrate the output of the piezoelectric crystals. Previous reports have provided some information about the performance of AT in clinical application.[2–5] The purpose of this study was to examine the accuracy of the overall AT system and to evaluate the roles of the two transducer systems separately. Understanding the limitations of these two systems may guide future enhancements and help delineate the appropriate application of this technology to patient care.

Materials and Methods

With approval of the Stanford University Institutional Review Board on the Use of Humans in Research and

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individual informed consent, 17 adult patients undergoing elective noncardiac surgery while supine and horizontal were studied. Only patients requiring insertion of a radial artery catheter as deemed necessary by their attending anesthesiologists were included. No patient known to have blood pressures differing between the arms was studied. Mean blood pressure measured with oscillometry did not differ between the arms by more than 10 mmHg. A 5.1-cm, 20-G catheter was inserted in a radial artery and connected *via* 152 cm saline-filled high-pressure tubing to a transducer (DTX/Plus, Viggo-Spectramed, Oxnard, CA) connected to a physiologic monitor (7010RA, Marquette Electronics, Milwaukee, WI, or PB 240, Puritan Bennett, Kansas City, MO). All visible air bubbles were eliminated from the system. The transducer was mounted at the level of the midaxillary line. It was at this level that the zero pressure point was determined. The AT system (N-CAT, version 1.0, Nellcor, Hayward, CA) was applied to the contralateral arm. Analog outputs of blood pressure from the arterial catheter system and the AT system were filtered with a 200-Hz low-pass filter and sampled at 100 Hz with a 16-bit analog-to-digital converter (DT-2827, Data Translations, Marlboro, MA) in a microcomputer (5200, Toshiba, Tokyo, Japan).[6] The blood pressure measurements determined by the oscillometric cuff of the AT system were also collected by serial communication with the microcomputer. Calibration of the AT system with the oscillometric cuff was scheduled to occur at 5-min intervals. All patients received general anesthesia without regard to their participation in this study.

For each patient, the IA measurements were reviewed and segments lacking pulsatile data were excluded. Thus, intervals when blood was being aspirated *via* the catheter were excluded. Periods during which the AT system did not provide pulsatile measurements were also excluded. Each signal from IA and AT was evaluated for pulsatility independently of the evaluation of the other signal to determine which periods to exclude from further analysis. Data were compared for intervals during which both the IA and the AT measurements were valid. No other data were excluded. A computer was used to calculate mean IA on a beat-by-beat basis. Individual beats were identified by an algorithm that noted the occurrence of local minima of IA consistent with a heart rate of 20–180 beats/min. Mean IA was calculated as the average of the 100-Hz samples during the identified beat interval. Mean AT was calculated as the average of the 100-Hz samples of AT during the identical interval. Thus, mean IA and mean AT were based on averages over identical intervals. We chose to focus our analysis on mean blood pressure to avoid problems of differences in frequency response and because mean pressure is less susceptible to corruption with noise than are systolic and diastolic pressures. Oscillometry is most accurate when measuring mean pressure and the AT tonometer uses the mean pressure from oscillometric measurement for determining the calibration offset; thus, the performance of the instrument has been designed to optimize measurement of mean pressure.[7]

Several methods of analysis were used for the data from each subject. The variability of IA was determined by comparing each IA measurement with the mean for the entire case and categorizing the difference into a specific range spanning 5 mmHg. For each patient, the distribution was computed as a percentage of the total number of measurements. All of these distributions were then combined to produce an average distribution of the difference between IA and mean IA. This distribution describes the variability of IA that was observed in this study.

On a beat-by-beat basis, the mean and standard deviation of the difference between AT and IA (AT−IA) were calculated.[8] The Pearson product-moment correlation coefficient was calculated for the comparisons of mean AT−IA with age and weight. Each determination of AT−IA was categorized into a range spanning 5 mmHg (*e.g.*, −10 to −5, −5 to −0.1, 0 to 5, or 5.1 to 10 mmHg). For each patient, the distribution was computed as a percentage of the total number of measurements. All of these distributions were then combined to produce an average distribution of AT−IA.

The performance of the oscillometric cuff was evaluated. Mean IA pressure was calculated by averaging all of the IA pressure measurements obtained in the interval when the oscillometric cuff was inflated and deflated. The mean and standard deviation of the difference between the measured mean blood pressure as determined by the oscillometric cuff and IA measurement were computed. Standard deviations were compared with the variance ratio test. Significance was determined for $P < 0.05$.

For a period in which AT and IA differ by a clinically important amount, it is useful to know the duration of the discrepancy. For each patient, every interval in which AT and IA differed in magnitude by more than 10 mmHg for at least 5 s was classified by the duration as less than 1, 1–5, or greater than 5 min. For each

patient, these results were divided by the total time of study to determine the frequency of each type of discrepancy per hour studied.[9] These frequencies were averaged for the 16 patients. This method of analysis was repeated for comparison of the oscillometric measurement and IA. Each oscillometric measurement remained constant for 5 min. The frequency of each type of discrepancy for AT and for oscillometry were compared by using Wilcoxon's paired-sample test. This analysis was also conducted for the magnitude of the difference exceeding 20 mmHg.

One goal in developing AT is that it offers the promise of allowing the clinician to detect changes in blood pressure more rapidly than with intermittent oscillometric measurements alone. To evaluate this aspect of the device, we chose to separate the calibration introduced by the oscillometric cuff and consider the performance of AT in between oscillometric calibrations. To normalize the data to account for calibration errors, we considered the IA and AT measurements obtained immediately after oscillometric calibration, and for each subsequent beat computed ΔIA and ΔAT as

$$\Delta IA = IA - IA_0$$

and

$$\Delta AT = AT - AT_0$$

where IA_0 and AT_0 = measurements of IA and AT (respectively) obtained immediately after oscillometric calibration. The difference ΔAT−ΔIA shows how well changes in IA measurement were tracked by AT without regard to any initial calibration error between the two measurements. The mean and standard deviation of ΔAT−ΔIA were calculated for each subject. Using this procedure, one can determine the extent to which the lack of agreement between AT and IA is attributable to the oscillometric calibration and the extent to which it is attributable to the piezoresistive crystal array measurement.

Results

Of the 17 patients enrolled in this study, data from 1 patient were excluded because the surgeon frequently leaned on the patient's arm during surgery and the oscillometric cuff was affected. The remaining 16 patients included 10 women and 6 men aged 22–87 yr (54 ± 22 yr, mean ± SD) and weighing 48–100 kg (70 ± 14 kg). The distribution of IA measurements as compared with mean IA for the entire case is shown in figure 1. This figure demonstrates the observed variability of IA. IA differed from mean IA by 10 mmHg or more for 26% of the measurements.

From all 16 patients, there were a total of 88,158 simultaneous measurements of AT and IA, and AT−IA was 1.3 ± 9.4 mmHg (mean ± SD). The results for each patient are shown in table 1. AT−IA did not correlate with patient age (r^2 = 0.20) and did not correlate with patient weight (r^2 = 0.18). Figure 2 shows the frequency of various differences between AT and IA measurements. This distribution shows that the magnitude of AT−IA exceeded 5 mmHg for 53% of the measurements and exceeded 10 mmHg for 25% of the measurements.

Figure 3 shows the frequencies of discrepancies between the noninvasive measurements and IA for various durations. When discrepancies in excess of 10 mmHg were considered, the frequency of discrepancies of duration less than 1 min was significantly less for AT (4.6 ± 0.8 per hour) than for oscillometry (12.6 ± 1.4 per hour). A similar result was obtained for discrepancies of duration between 1 and 5 min. For discrepancies in excess of 20 mmHg, the frequency of discrepancies of duration less than 1 min was significantly less for AT (1.0 ± 0.2) than for oscillometry (2.4 ± 0.5).

Combining data from all patients ΔAT−ΔIA was −1.0 ± 5.6 mmHg. The results for each patient are shown in table 1. There were 401 comparisons of the oscillometric cuff blood pressure with IA and the difference was 2.4 ± 7.5 mmHg (mean ± SD). The results of these comparisons for each patient are shown in table 1. According to the variance ratio test, the standard deviation of AT−IA was significantly greater than the standard deviation of the difference between oscillometric measurement and IA with $P < 0.001$.

Discussion

Intermittent measurement of blood pressure with oscillometry may be inadequate for patients with rapid alterations in blood pressure. In those cases, IA measurements are advisable. AT has been considered as a noninvasive alternative method. AT provides beat-by-beat measurement and might have application in these cases. In this study, we considered the extent to which measurements with AT and simultaneous IA measurements agree. The AT method is calibrated by oscillometry; therefore, the agreement between AT and IA measurements should be limited by the degree to which

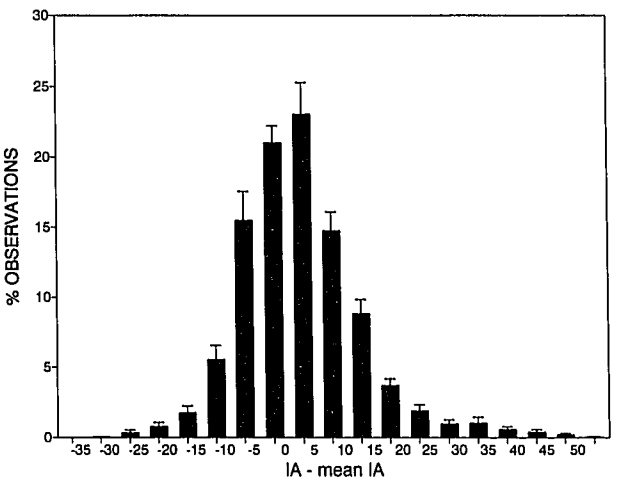

Fig. 1. The variability of intraarterial (IA) measurement was determined by comparing each IA value with the mean for the entire case and categorizing the difference into a specific range spanning 5 mmHg. For each patient, the distribution was computed as a percentage of the total number of measurements. All of these distributions were then combined to produce an average distribution of the difference between IA values and mean IA (shown as mean and SEM). This distribution demonstrates that IA values differed from mean IA by 10 mmHg or more for 26% of measurements.

oscillometry and IA measurements agree. After calibration by oscillometry, additional error may be introduced by measurement with the piezoelectric crystal array. Thus, the AT measurements may differ from the IA measurements either because of the calibration with oscillometry or because of the piezoelectric crystal array or a combination thereof. In the data analysis, the importance of these two components has been evaluated. The difference between the oscillometric blood pressure and IA was 2.4 ± 7.5 mmHg. The standards proposed by the Association for the Advancement of Medical Instrumentation suggest that the mean difference should be ±5 mmHg or less with a standard deviation of 8 mmHg or less; thus, it appears that the oscillometric component of the AT system meets this minimum performance standard.‡ Existing clinical instruments that perform oscillometry alone have been shown to meet this standard as well.[7,10-14] For example, Yelderman and Ream studied 19 patients undergoing cardiac surgery and found the difference between oscillometry and IA measurements for mean pressure was 1.4 ± 6.2 mmHg (mean ± SD).[12] In considering the overall performance of the AT system, AT−IA was 1.3 ± 9.4 mmHg. This larger standard deviation would suggest that the overall system does not meet the Association for the Advancement of Medical Instrumentation standard. The increase in standard deviation from 7.5 to 9.4 mmHg was produced solely by the piezoelectric crystal system. When the calibration error from oscillometry was eliminated and ΔAT and ΔIA were compared, the overall ΔAT−ΔIA was −1.0 ± 5.6 mmHg. For the entire system AT−IA was 1.3 ± 9.4 mmHg. The bias of 1.3 mmHg was produced by the combination of a bias of 2.4 mmHg from the oscillometric calibration and a bias of −1.0 mmHg from the piezoelectric crystal array. The positive bias of the calibration system was partially offset by the negative bias of the piezoelectric crystal array. The standard deviation of AT−IA was 9.4 mmHg, which may be interpreted as the combination of the variability from the oscillometry calibration, which had a standard deviation of 7.5 mmHg, and variability from the piezoelectric crystal array, which had a standard deviation of 5.6 mmHg. For independent variables, the variance of the sum of two variables is equal to the sum of the variances of the two variables. The variance for AT−IA was 88 $mmHg^2$, for oscillometry was 56 $mmHg^2$, and for the piezoelectric crystal array was 31 $mmHg^2$. One can readily appreciate that 88 ≈ 56 + 31. Thus, to the extent that AT and IA differ, approximately 64% of the disagreement can be attributed to the oscillometric calibration and 36% to the piezoelectric crystal array.

The major goal of AT is to provide information much more frequently than that available from intermittent oscillometry. With intermittent oscillometry, a clinically important change in blood pressure will not be detected until the next measurement cycle. This delay in clinical detection could be reduced with continuous blood pressure measurement. To evaluate the effectiveness of AT toward this goal, we considered the frequency of discrepancies observed with oscillometry and with AT. Comparable frequencies of discrepancies for durations in excess of 5 min would be expected because oscillometric measurement occurred at 5-min intervals.

These discrepancies represent inaccurate oscillometric measurement, resulting in erroneous calibration of the AT tonometer. A clinician might undertake inappropriate treatment during such a period. For discrepancies of duration less than 5 min, more frequent

‡ Association for the Advancement of Medical Instrumentation: American national standard for electronic or automated sphygmomanometers. Association for the Advancement of Medical Instrumentation SP10:1-25, 1987.

Table 1. Performance of Arterial Tonometry and Oscillometry

Patient	AT—IA					ΔAT—ΔIA				Oscillometric—IA	
	N	mean ± SD	a	b	r^2	mean ± SD	a	b	r^2	N	mean ± SD
1	5,086	−2.5 ± 6.5	30.1	0.62	0.40	−1.3 ± 3.0	−1.3	0.96	0.71	26	2.6 ± 7.6
2	650	6.4 ± 12.1	31.1	0.66	0.30	1.0 ± 3.8	0.3	0.58	0.67	10	4.9 ± 6.1
3	6,370	3.5 ± 8.3	21.5	0.73	0.31	0.6 ± 2.7	0.6	1.07	0.88	29	3.0 ± 5.1
4	4,252	2.4 ± 3.3	4.3	0.97	0.84	−0.9 ± 0.9	−0.9	1.02	0.99	19	1.1 ± 5.1
5	11,152	7.6 ± 8.0	26.7	0.74	0.72	0.2 ± 3.3	0.3	0.88	0.71	34	5.0 ± 5.7
6	10,846	3.7 ± 8.1	15.1	0.87	0.70	−0.4 ± 4.7	−0.4	1.01	0.76	49	0.1 ± 5.7
7	4,497	7.4 ± 8.8	53.1	0.43	0.33	−1.1 ± 3.6	−1.4	1.13	0.77	26	11.5 ± 7.0
8	1,684	−4.1 ± 7.6	33.3	0.49	0.71	−2.5 ± 4.0	−2.4	1.06	0.82	12	−2.4 ± 5.7
9	8,796	−1.3 ± 12.5	9.2	0.88	0.34	−4.4 ± 9.6	−4.6	0.67	0.21	39	3.9 ± 3.5
10	8,152	−2.0 ± 7.5	16.3	0.78	0.43	0.9 ± 5.3	0.9	0.71	0.75	21	−2.7 ± 6.8
11	4,896	−2.5 ± 5.5	3.1	0.94	0.68	−1.8 ± 4.9	−2.3	0.81	0.47	21	1.3 ± 6.1
12	5,612	−0.3 ± 7.5	19.7	0.80	0.47	−0.5 ± 8.4	−1.3	0.56	0.21	20	−0.2 ± 3.1
13	5,406	−1.7 ± 8.2	40.3	0.54	0.32	−1.1 ± 3.6	−0.9	1.09	0.85	20	−0.2 ± 8.6
14	3,078	9.0 ± 6.2	63.8	0.11	0.01	−1.1 ± 3.0	−0.9	0.56	0.60	16	12.9 ± 4.0
15	4,046	−8.3 ± 10.5	21.9	0.69	0.42	−1.8 ± 6.6	−1.7	0.71	0.63	37	−4.3 ± 9.0
16	3,635	0.3 ± 9.0	27.8	0.63	0.50	−2.3 ± 6.6	−2.9	0.70	0.65	22	5.3 ± 6.2
Overall	88,158	1.3 ± 9.4				−1.0 ± 5.6				401	2.4 ± 7.5

The unit of pressure is mmHg.

measurements made with AT produced lower frequencies of discrepancies than with oscillometry alone. These analyses can be synthesized as follows. Errors in the AT system are a combination of errors caused by the oscillometric calibration system and the errors caused by the piezoresistive array; therefore, for individual measurement, the accuracy of the AT system must be poorer than that of oscillometry alone. For subsequent measurements, blood pressure may change and the accuracy of oscillometry is reduced because of infrequent measurement and the long measurement intervals. Arterial tonometry has a very brief measurement interval and thereby remains more accurate in the face of changing blood pressure.

One limitation of the current study is that we considered only measurement of mean pressure. Comparison of mean pressure is likely to be more favorable than systolic or diastolic pressure because calibration is optimized for mean pressure and matching of frequency response is not required. The ability of AT to reproduce IA measurements of systolic and diastolic pressures should be less than that for mean pressure. The results of the current study may be compared with those from other investigations. Kemmotsu and colleagues reported on 60 anesthetized patients studied with an arterial tonometer supplied by Colin Electronics (Komaki, Japan).[2] For mean arterial pressure, the AT−IA difference was 0.0 ± 4.7 mmHg for 3,036 measurements. In another report by Kemmotsu's group, 28 patients undergoing orthopedic surgery with deliberate hypotension were studied with the Colin CMB-3000 arterial tonometer.[3] For mean pressure, the AT−IA difference was 0.65 ± 5.0 mmHg for 2,039 measurements. Burkhardt and colleagues studied 10 patients with the CBM-3000 (software version CBP020, Colin Medical Instruments, Komaki, Japan) and found that for mean pressure the AT−IA difference was −1.77 ± 15.10 mmHg for 28,635 measurements.[4]

The results of the two studies by Kemmotsu and colleagues[2,3] suggest that AT may have closer agreement with IA measurement than even some oscillometry systems and may be of sufficient accuracy for clinical use. These results are very surprising because the accuracy of AT should be less than that for oscillometry for individual measurements and previous studies of oscillometry have not demonstrated this degree of accuracy. Results of the current study suggest that AT cannot be used as a direct replacement for IA measurements. The current results are consistent with what would be predicted from the use of oscillometry for calibration. It

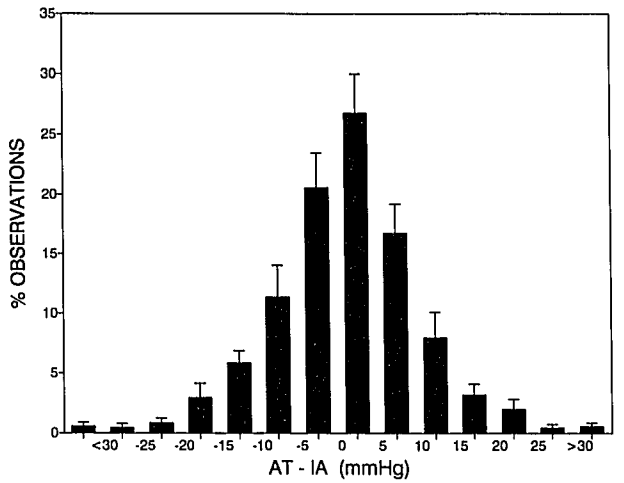

Fig. 2. On a beat-by-beat basis, each difference between arterial tonometric (AT) and intraarterial (IA) measurements was categorized into a specific range spanning 5 mmHg (*e.g.*, −10 to −5, −5 to −0.1, 0 to 5, or 5.1 to 10 mmHg). For each patient, the distribution was computed as a percentage of the total number of measurements. All of these distributions were then combined to produce an average distribution of AT−IA (shown as mean and SEM). This distribution shows that the magnitude of the difference between AT and IA exceeded 5 mmHg for 53% of the measurements and exceeded 10 mmHg for 25% of the measurements.

is not apparent why Kemmotsu and colleagues achieved results substantially better than the expected performance of the calibration component. The AT software used in these various studies were not identical, perhaps accounting for some of the observed differences. All studies comparing IA measurements with AT on the contralateral arm have the potential for bias related to physiologic differences between the two arms. Such differences would also affect comparison studies with oscillometry. Burkhardt's study population included patients with vascular disease and may have had chronic differences in blood pressure between the two arms; however, patients were excluded from the study if systolic pressure readings in the two arms differed by more than 10 mmHg. With noninvasive methods, it is difficult to establish that the blood pressures in two arms are identical because the reproducibility of noninvasive measurement is limited. Chronic differences would be unlikely to occur in our study population or in Kemmotsu's study[3] of patients undergoing orthopedic surgery. Some of the bias observed in the current study may be attributable to differences in pressures between the two arms; however, the variance within a patient is unlikely to be affected. Our analysis helps to control for this potential physiologic phenomenon by accounting for calibration error and by comparing rates of discrepancies. By considering mean pressure in the comparisons we eliminate any potential importance of differences in frequency response of the catheter systems used in the various studies. Differences in patient population, operative environment, patient position, AT software, AT hardware, data collection, or data processing may explain the range of results found by the investigators.

To enhance the performance of AT, efforts may be directed at improving the performance of the oscillometric calibration and of the piezoelectric crystal array. In the current study, we demonstrated that oscillometric calibration is the largest source of error. Further improvement may prove difficult because the overall error can be no better than the error produced by the oscillometric calibration. Potential users of this technology should best view it as an augmented form of oscillometry rather than as a replacement for IA measurement. Improved design of the piezoelectric crystal array by development of smaller transducers for more precise positioning over the artery may enhance the performance of this component. Modifications to AT

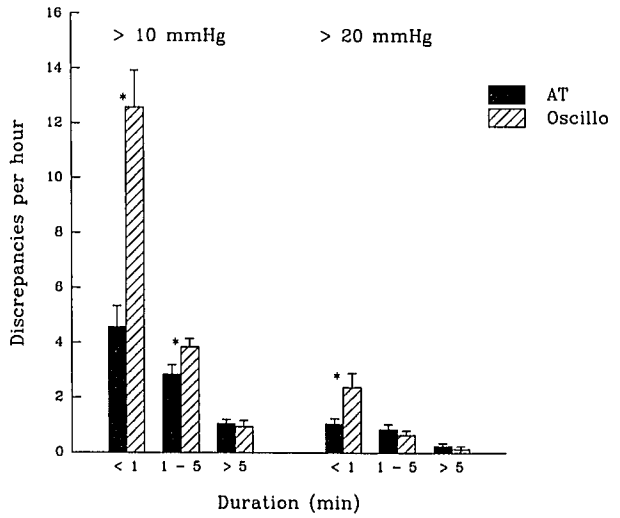

Fig. 3. The frequency of discrepancies between the noninvasive measurements and intraarterial (IA) measurements for durations less than 1, 1–5, and more than 5 min. When discrepancies in excess of 10 mmHg were considered, the frequency of discrepancies of duration less than 1 min was significantly less for arterial tonometry (AT) than for oscillometry. A similar result was obtained for discrepancies of duration between 1 and 5 min. When discrepancies in excess of 20 mmHg were considered, the frequency was significantly less for AT than for oscillometry for discrepancies of duration less than 1 min.

software may alter performance; clinicians should be aware of what version is in use or under consideration. Future studies should consider the two sources of error to improve performance. Clinicians should be aware of the issues identified in this study when considering future development of this technology to best understand its ultimate role, if any, in patient care.

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