Anesthesiology
75:333–340, 1991

Arterial Tonometry for Noninvasive, Continuous Blood Pressure Monitoring during Anesthesia

Osamu Kemmotsu, M.D., Ph.D., F.C.C.M., Mitsuo Ueda, M.D.,† Hiroshi Otsuka, M.D.,† Takeyasu Yamamura, M.D., Ph.D.,‡ Dean C. Winter, Ph.D.,§ Joseph S. Eckerle, S.M.¶*

Arterial tonometry is a technique used to measure arterial blood pressure noninvasively. The authors developed a new tonometer system containing an array of 15 piezoresistive pressure transducers, a mechanical positioning system, signal conditioning and multiplexing electronics, and a display and control console. The authors evaluated the accuracy, reliability, and clinical acceptability of this system by comparing tonometric blood pressure measurements with intraarterial blood pressure measurements in 60 anesthetized patients. Blood pressure was measured intraarterially in either the right or left radial artery by a Gould P23XL calibrated transducer, whereas blood pressure was measured by tonometer at the radial artery of the other arm. The tonometric waveform was similar to the intraarterial waveform. Simultaneous tonometer and intraarterial systolic blood pressures of the 60 patients (3,036 data sets) had an overall regression coefficient, r = 0.97, and an equation, regression equation = 0.95X + 5.8. Similar values were obtained for mean and diastolic pressures. Regression analyses of the paired tonometric and intraarterial blood pressure values showed good correlations in both sexes and in ages ranging from 8 to 82 yr (r = 0.94–0.97). Mean absolute values of error (precision) for the systolic, mean, and diastolic measurements did not differ significantly among the five systolic, five mean, and four diastolic pressure groups and ranged from 3.6 to 6.6 mmHg, with negligible bias, with intraarterial pressure used as the reference. Bias for the various pressure groups was small: −0.9–3.6 mmHg for systolic; −3.0–0.7 mmHg for mean; and −2.1–4.5 mmHg for diastolic. The "limits of agreement" (mean difference ± two standard deviations) were within an acceptable range for clinical anesthesia. The authors' results indicate that tonometry provides accurate, reliable, and real-time blood pressure measurements, together with continuous display of the pressure waveform. It is potentially a useful method for continuous and noninvasive measurement of radial artery blood pressure during anesthesia. (Key words: Blood pressure: measurement; tonometry. Measurement techniques: blood pressure; tonometry.)

ARTERIAL BLOOD PRESSURE is one of the basic physiologic variables monitored during anesthesia. A noninvasive method providing a blood pressure measurement similar in form and content to that obtained with an intraarterial cannula would be beneficial for such monitoring. In this regard, the Penaz method[1] and arterial tonometry[2] recently have been introduced into clinical practice.

A tonometer instrument provides a continuous measurement of blood pressure, including the blood pressure waveform. In this regard, it is similar to a direct arterial blood pressure instrument. A technique advanced by Penaz in 1973 also can measure the complete blood pressure waveform.** Recently, Ohmeda and others have marketed instruments that use the Penaz method to measure blood pressure in the fingers.[1,3] It is important to make a clear distinction between tonometer instruments and those that use the Penaz method. Although both types produce a waveform that is similar to the blood pressure waveform, their principles of operation are quite different. The Penaz method is a volumetric measurement, so that the waveform is actually a plethysmographic waveform. Both the Penaz method and tonometry produce blood pressure waveforms by different bioelectric technologies.[4] In addition, it is noteworthy that the Penaz instruments measure blood pressure in the finger arteries, whereas tonometer instruments typically are applied to the radial artery. There may be significant differences between the pressures at these two sites.

The principles of arterial tonometry have been reviewed extensively in the literature[5,6] and are described here only briefly. Tonometric measurements require a

* Professor and Chairman, Department of Anesthesiology, Hokkaido University School of Medicine.

† Instructor in Anesthesiology, Hokkaido University Hospital.

‡ Associate Professor in Anesthesiology, Hokkaido University School of Medicine.

§ Principal Engineer, Department of Biomedical Engineering, Southwest Research Institute.

¶ Senior Research Engineer, Mechanical Design and Development Program, SRI International.

Received from the Departments of Anesthesiology, Hokkaido University School of Medicine and Hokkaido University Hospital, Sapporo, Japan; the Department of Biomedical Engineering, Southwest Research Institute, San Antonio, Texas; and the Mechanical Design and Development Program, SRI International, Menlo Park, California. Accepted for publication April 16, 1991. Supported by Colin Electronics Company, Ltd. Presented in part at the 1989 Annual Meeting of the American Society of Anesthesiologists, New Orleans, Louisiana.

The clinical test was performed at Hokkaido University Hospital using tonometers built by Colin Electronics. Each of the authors has participated in research projects funded by Colin Electronics, but none is employed by Colin Electronics. Dr. Winter and Mr. Eckerle are named as inventors on various patents related to tonometry. However, each patent is assigned either to the person's institution or to Colin Electronics.

Address reprint requests to Dr. Kemmotsu: Department of Anesthesiology, Hokkaido University School of Medicine, N-15, W-7, Kita-ku, Sapporo, Japan 060.

** Penaz J: Photoelectric measurement of blood pressure, volume, and flow in the finger. Digest of the 10th International Conference on Medical Engineering, Dresden, Germany, 1973, p 104.

superficial artery close to an underlying bone. Examples of such sites include the radial, dorsalis pedis, and temporal arteries. The radial artery is the most commonly used site because of its larger diameter and easy accessibility. Figure 1 illustrates the measurement principle. Figure 1*A* shows the radial artery and underlying bone, along with the surrounding tissue. The artery wall is assumed to be thin (*i.e.*, it can support only circumferential [not bending] stresses). Figure 1*A* also shows a segment of the artery wall with the forces that act on that segment. We assume that the only forces acting on this segment are the force exerted by the tonometer sensor (F), the force resulting from the blood pressure (P), and the circumferential tension in the wall (T). For tonometric blood pressure (TBP) measurements, the arterial wall must be flattened, as shown in figure 1*B*. The wall tension (T) then acts perpendicular to the blood pressure (P), so that the force sensed on the skin surface (F) must result from the blood pressure alone. Thus, a pressure transducer placed on the skin surface over the flattened portion of the artery should measure arterial blood pressure.

With the use of a single-element tonometer sensor, blood pressure may be measured as described above. However, it is difficult to manually position such a sensor precisely over the radial artery. Recently, tonometer sensors using an array of several sensor elements have been developed. These sensor arrays greatly simplify the task of positioning the sensor over the artery because the positioning tolerance is then the length of the sensor array (approximately 8 mm), rather than a fraction of the artery diameter (approximately 1 mm), as was the case for the single-element sensors. The sensor array is mounted in a housing that may be attached to the patient's wrist, as shown in figure 2. The arrangement of the sensor in the housing is shown schematically in figure 3.

Two points are critical for the accurate measurement of blood pressure with the use of arterial tonometry. First,

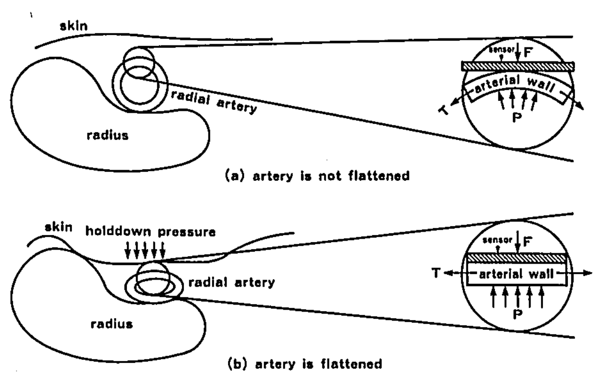

FIG. 1. The principle of arterial tonometry. *A:* The artery is not flattened. *B:* The artery is partially flattened. F = forces acting on the segment of the artery; P = force due to blood pressure; T = circumferential tension in the artery wall.

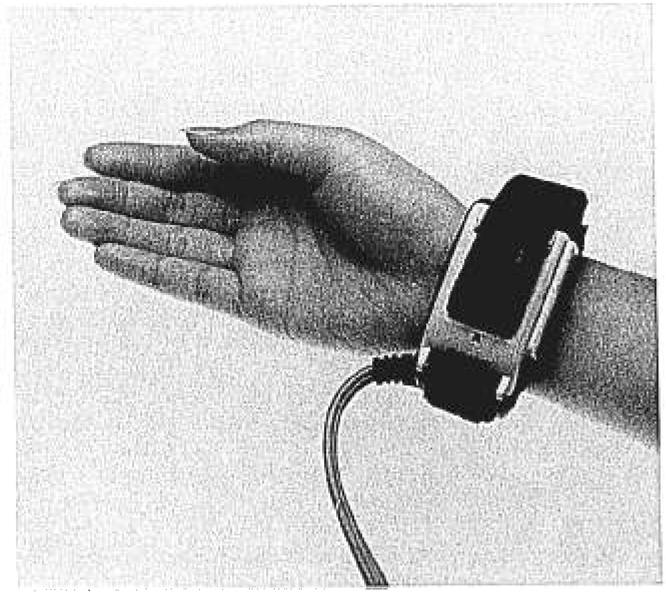

FIG. 2. Sensor housing positioned over radial artery.

the pressure transducer must be placed accurately over the artery, and it must be small enough to sense the pressure over only the flattened portion of the artery. This is achieved by use of the sensor array as described above. Second, the artery must be flattened to allow an adequate area for measurement. The instrument in this study uses a pneumatic system to flatten the artery by applying a downward force to the sensor.

As shown in figure 3, the volume above the sensor and below the sensor frame is pressurized with air to force the sensor down and flatten the underlying artery. The pressure within this volume is called the "hold-down pressure," and it is related directly to the amount of arterial flattening achieved. If the hold-down pressure is too great, the artery will be occluded. If the hold-down pressure is too small, the artery will not be flattened at all. Although the hold-down pressure is usually large enough to occlude venules and capillaries locally, it is not large enough to occlude arterial flow. The computer within the instrument automatically determines the proper hold-down pressure for each patient during the initial measurement period by monitoring the systolic, diastolic, and pulse pressures measured over a range of hold-down pressures. This determination uses an algorithm that seeks to maximize the pulse pressure measured by the sensor element located over the artery.

After the tonometer sensor is first placed on the patient, the instrument automatically performs a calibration using oscillometric measurements. After this first calibration has been completed, the instrument will perform calibration again if it detects significant patient motion. In addition, the instrument performs a cuff measurement periodically

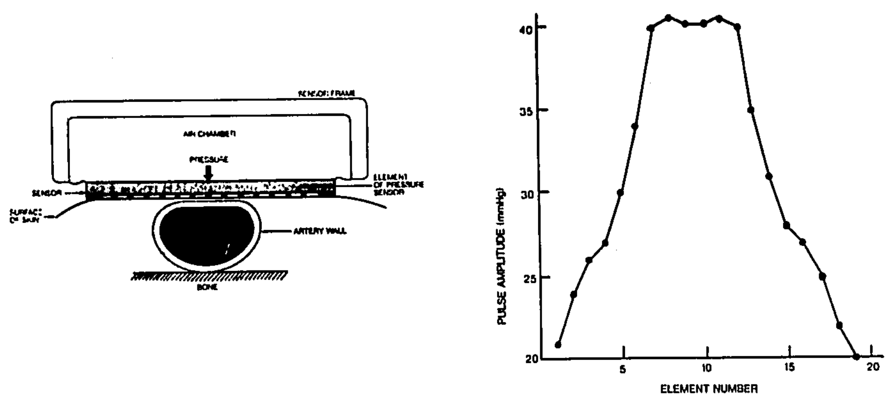

FIG. 3. *Left:* The means by which tonometer sensor flattens the artery against the bone. Transducer sensor elements over the flattened portion of the artery are used to measure blood pressure. *Right:* A typical graph for the pulse-pressure amplitude on each transducer element during blood pressure measurement.

(the interval is adjustable) as an additional check of the TBP measurement. Currently available tonometer instruments have a provision for preventing automatic calibration during critical periods such as intubation, but the instrument used for our study did not have this feature.

This study determined the accuracy, safety, and feasibility of arterial tonometry as a method for monitoring blood pressure during anesthesia.

Materials and Methods

We studied 60 patients, aged 8–82 yr, consisting of 30 female and 30 male patients undergoing elective surgery who required intraarterial blood pressure (IBP) monitoring as part of their anesthetic management. The study protocol was approved by the Institutional Ethics Committee, and informed consent was obtained from each patient.

For each patient, oscillometric blood pressure determinations were performed bilaterally before the study to exclude patients with blood pressure differences of more than 5 mmHg between arms. With the use of local anesthesia, a Teflon® 22-gauge cannula was inserted into either the right or left radial artery (based on a modified Allen's test) and connected to a Gould P23XL calibrated transducer to measure IBP. The measurement system consisted of the cannula, a 90-cm, high-quality, low-compliance pressure tubing; a continuous flush device; a disposable transducer dome (manufactured by Spectramed, USA); and the Gould transducer. This system has a natural frequency of 20–30 Hz and a damping coefficient of 0.3–0.5. Based on the values proposed by Gardner and Hollingsworth,[7] this performance should be adequate for one to obtain an accurate blood pressure waveform.

Blood pressure was monitored by tonometry at the contralateral radial artery. The blood pressure signals and ECG were monitored and recorded continuously on a digital magnetic tape recorder and by a computer. Data-acquisition software recorded pressure measurements every 30 s for later data analysis. Blood pressure data were sampled for 10–20 min during induction and intubation and 10–20 min during the recovery period. These are periods when blood pressure is expected to change.

Anesthesia was induced with thiamylal (5 mg/kg, intravenously) and maintained with either enflurane–nitrous oxide or a combination of enflurane–nitrous oxide and epidural anesthesia.

Regression analyses of the pressure data were performed separately for male and female patients and for three different age groups: patients younger than 30, those between the ages of 30 and 60, and those older than 60. Mean values for differences between TBPs and IBPs, as well as confidence intervals, were calculated. Precision (mean absolute value of error) and bias (mean error) also were calculated for systolic and diastolic TBPs, with IBP used as the reference value.[8,9]

Briefly, for systolic pressure for each data point denoted by the subscript i, error_i = systolic TBP − systolic IBP.

Then, for all the data belonging to each group,

$$\text{bias} = \frac{\sum_{i=1}^{n} \text{error}_i}{n}$$

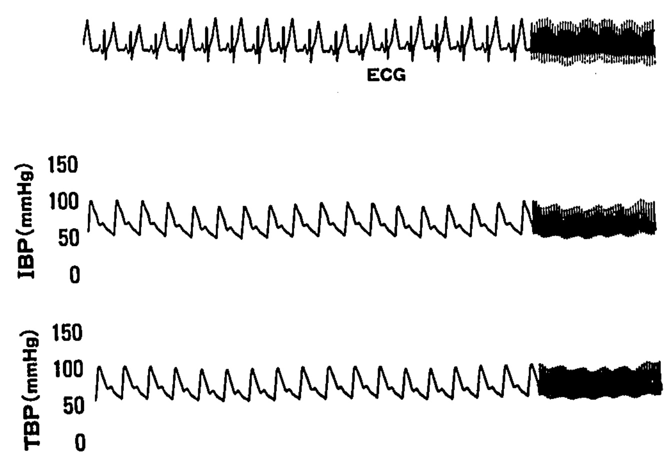

FIG. 4. Simultaneous tracings of waveforms obtained from a 10-yr-old 137.0-cm, 31.2-kg girl: ECG, intraarterial blood pressure (IBP), and tonometric blood pressure (TBP).

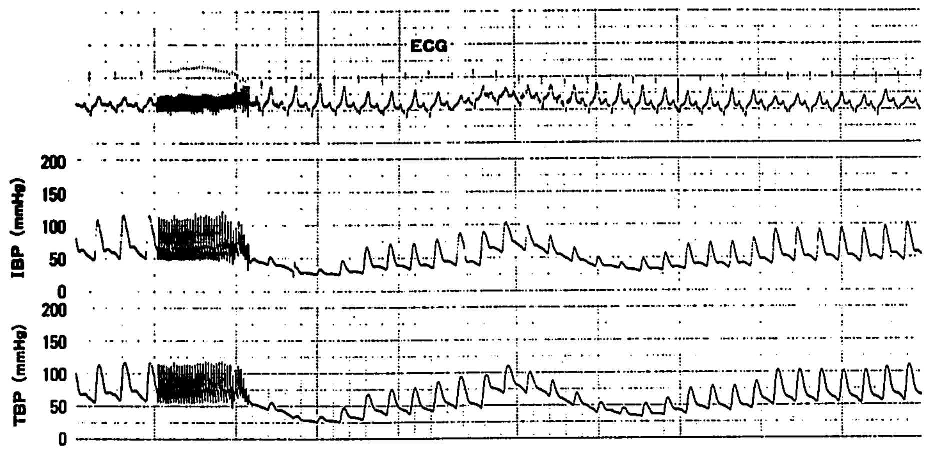

FIG. 5. Simultaneous tracings of ECG and intraarterial (IBP) and tonometric blood pressure (TBP) waveforms. A sudden drop in blood pressure is recorded in each pressure waveform.

and

$$\text{precision} = \frac{\sum_{i=1}^{n} |\text{error}_i|}{n}$$

The same equations are used for mean and diastolic pressures.

After bias and precision data from each group were computed, *t* tests were used to compare these parameters against the group with the best precision. Differences were considered significant when the mean values differed by more than 5 mmHg or when *P* was less than 0.05.

The data also were analyzed with the method proposed by Bland and Altman[10,11] for comparing two methods of measuring a parameter. To obtain the "limits of agreement," the average of measurements by the two methods, (IBP + TBP)/2, was plotted against the difference, IBP − TBP.

Results

Waveforms for IBP and TBP from a 10-yr-old, 31.2-kg girl are shown in figure 4. These two simultaneous waveforms show the typical characteristics of a peripheral artery pulse, such as the early systolic peak and the dicrotic notch. In figure 5, a sudden decrease in blood pressure during a liver resection is observed simultaneously in both IBP and TBP waveforms.

Regression analyses for TBP and IBP in 55 paired measurements obtained from a 57-year-old, 55-kg man show good correlations for systolic (r = 0.99), mean (r = 0.98), and diastolic (r = 0.95) pressures (see fig. 6.).Figure 7 presents the bias for these 55 measurements. Regression analyses of the pooled data for male and female patients and for patients in the three age groups are summarized in tables 1 and 2. The mean differences between tonometric and intraarterial measurements, together with confidence intervals for the means, also are shown in the tables.

Figure 8 shows the individual bias for all 3,036 pairs of measurements. The "limits of agreement" are −12.2 and +11.4 mmHg for systolic, −9.5 and +9.3 mmHg for mean, and ±10.8 mmHg for diastolic pressures.

Pooled precision and bias data are summarized in table 3. Systolic, mean, and diastolic precision values did not differ significantly among the five systolic pressure groups, the five mean pressure groups, and the four diastolic pressure groups. Precision was typically 3.6–6.6 mmHg, and the bias was insignificant.

Discussion

After the technique of arterial tonometry was invented in the early 1960s, various types of sensors have been used for TBP measurement. Pressman and Newgard used strain gauges attached to a miniature beam.[12] Bigliano *et al.*†† used a sensor consisting of a thin membrane that controlled air flow through a narrow passage. Stein and Blick[13] used a modified myographic force transducer. Petzke and Bahr‡‡'§§ used a semiconductor pressure transducer that was mounted in a cuff-like device to hold it on the wrist. Borkat *et al.*¶¶ used a "pressure capsule" consisting of a fluid-filled rubber bladder attached to a conventional pressure transducer. Each of these sensors consisted of a single sensor that was difficult to manually position precisely over the radial artery. This limitation made them impractical for routine clinical use.

†† Bigliano RP, Molner SF, Sweeney LM: A new physiological pressure sensor. Proceedings of the Annual Conference on Engineering in Medicine and Biology 6:82, 1964.

‡‡ Petzke JC, Bahr DE: Blood pressure measuring apparatus. U.S. Patent 3,926,179, December 16, 1975.

§§ Bahr DE, Petzke JC: The automatic arterial tonometer. Proceedings of the Annual Conference on Engineering in Medicine and Biology 15:259, 1973.

¶¶ Borkat FR, Kataoka RW, Silva J: An approach to the continuous non-invasive measurement of blood pressure. Proceedings of San Diego Biomedical Symposium, 1976.

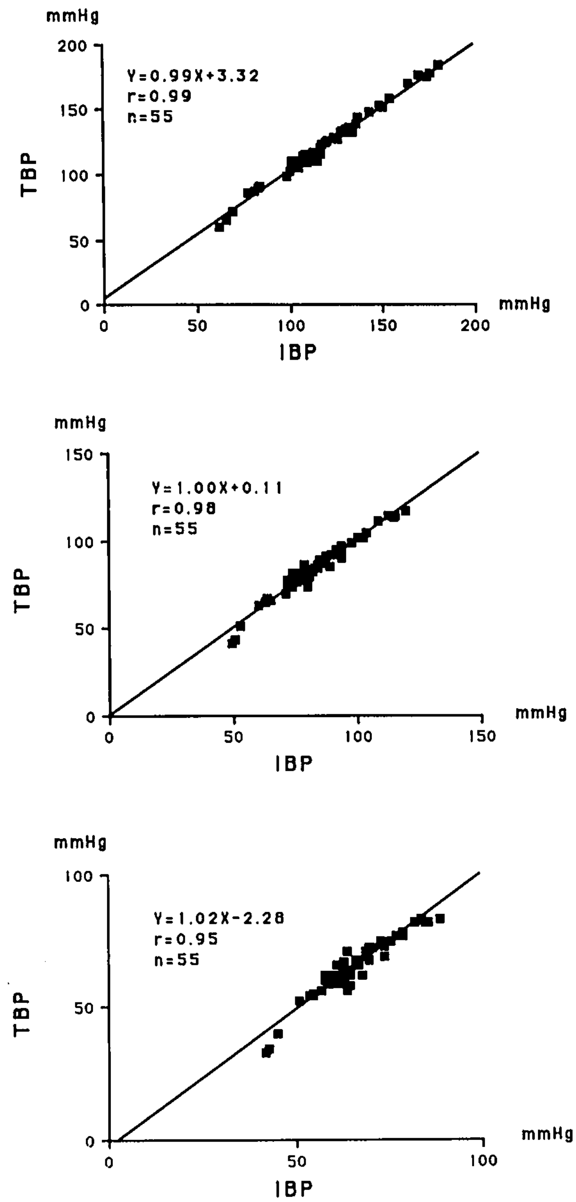

FIG. 6. Scatterplots of intraarterial (IBP) *versus* tonometric blood pressure (TBP) for 55 paired points from one patient. *Top:* systolic blood pressure. *Middle:* mean blood pressure. *Bottom:* diastolic blood pressure.

In principle, a tonometer sensor may consist of a single pressure transducer. As a practical matter, it is very difficult to position such a sensor properly, relative to the underlying artery, so our arterial tonometry system uses an array of 15 independent pressure transducers and a mechanical positioning system. Positioning of the sensor relative to the artery is less difficult because of these features. Our results indicate that proper positioning of the transducer array was accomplished by the mechanical positioning system incorporated in the sensor housing. Furthermore, the optimum transducer element was selected satisfactorily by the signal-processing system. The size of the transducer elements was small enough to allow the instrument to be operated over the radial arteries of patients of either sex, ranging in age from 8 to 82 yr.

The mechanical positioning system can move the 15-element transducer array approximately ±10 mm within the sensor housing. This movement is in the direction transverse to the axis of the artery and allows for some variation in the transverse (left/right) location of the sensor housing on the patient's wrist. However, there is no provision for automatic adjustment of the transducer lo-

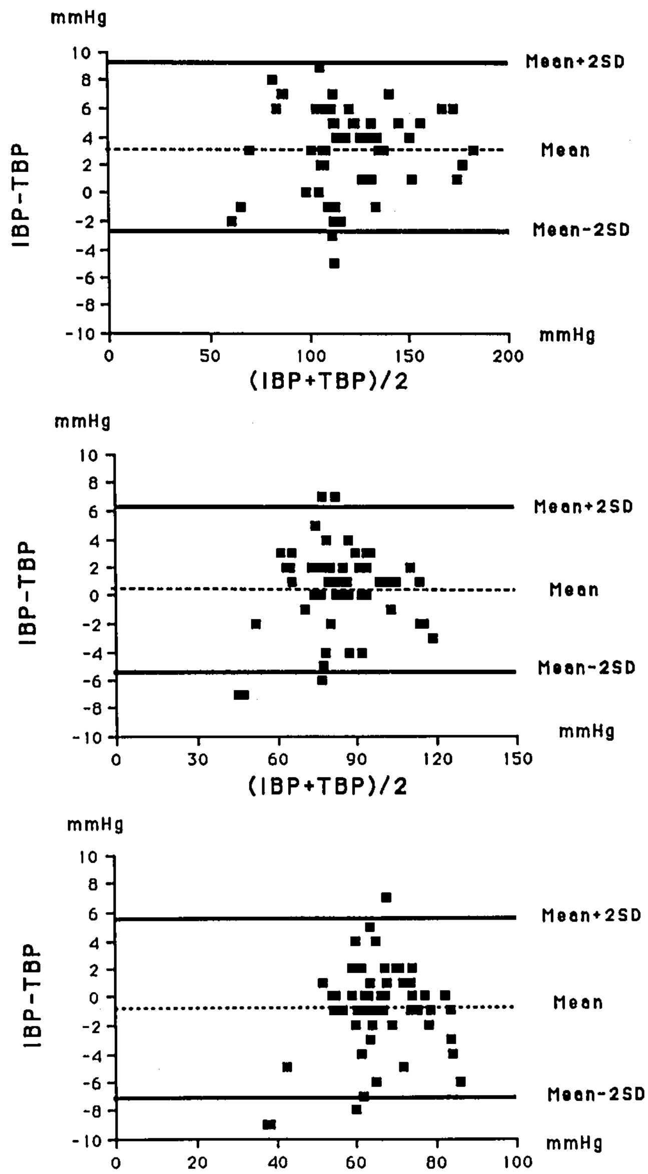

FIG. 7. Agreement between tonometric (TBP) and intraarterial blood pressures (IBP) in the same patient as in figure 6. Bias (the mean difference between the two measurements) is indicated by the dashed line.

TABLE 1. Regression Analysis Data by Sex

	Male (n = 1811)			Female (n = 1225)		
	Systolic	Diastolic	Mean	Systolic	Diastolic	Mean
Regression coefficient (r)	0.97	0.97	0.97	0.97	0.96	0.96
Regression equation	9.5x + 5.8	0.94x + 4.0	0.96x + 3.1	0.98x + 8.7	0.91x + 7.0	0.94x + 5.7
Mean (TBP − IBP)	−0.9	−0.5	−0.5	0.3	0.6	0.5
Standard deviation	5.9	4.7	4.7	5.9	5.5	4.7
Confidence interval for the mean						
95% confidence	±0.24	±0.21	±0.22	±0.24	±0.22	±0.26
99% confidence	±0.32	±0.28	±0.28	±0.31	±0.29	±0.35

TBP = tonometric blood pressure; IBP = intraarterial blood pressure.

TABLE 2. Regression Analysis Data by Age

	Age (yr)								
	≤30 (n = 631; 14 patients)			31–60 (n = 1334; 28 patients)			≥61 (n = 1071; 18 patients)		
	Systolic	Diastolic	Mean	Systolic	Diastolic	Mean	Systolic	Diastolic	Mean
Regression coefficient (r)	0.97	0.97	0.98	0.97	0.95	0.97	0.97	0.95	0.97
Regression equation (RE)	0.89x + 12.8	0.93x + 3.3	0.99x − 1.6	0.95x + 5.9	0.90x + 6.4	0.93x + 6.0	0.94x + 5.5	0.97x + 3.4	0.98x + 2.6
Mean (TBP − IBP)	−1.9	−2.9	−2.5	0.8	−0.1	0.2	−1.1	1.4	0.7
Standard deviation	6.2	4.9	4.5	5.8	5.4	4.8	5.5	4.7	4.4
Confidence interval for the mean									
95% confidence	±0.29	±0.25	±0.39	±0.28	±0.25	±0.26	±0.33	±0.28	±0.26
99% confidence	±0.38	±0.33	±0.51	±0.37	±0.33	±0.34	±0.43	±0.37	±0.35

TBP = tonometric blood pressure; IBP = intraarterial blood pressure.

cation along the axis of the artery (*i.e.*, proximally or distally). To obtain accurate measurements, the anesthesiologist must place the sensor housing in the proper axial location. This location is determined by palpation before application of the sensor.

By monitoring the signals from the 15 transducer elements, it is possible to determine which transducer is closest to the center of the artery and, therefore, is over the flattened portion of the artery. This transducer then is used to measure blood pressure. The selection of this "center element" is accomplished by using a weighted average of the pulse pressure measured by each element and is computed for each heartbeat. The transducer measuring the maximum weighted average pulse pressure then is used to measure blood pressure. (Details of the transducer selection algorithm appear in Wenzel *et al.****)

The size of each pressure transducer element in the tonometer instrument used for this study was not small enough to preclude artifact from arterial wall and tissue stresses. Estimates of the ratio of transducer element length to arterial diameter required for accurate tonometric measurements[6] range from 0.25 to 0.10. The instrument used has a ratio of 0.4, assuming a 1.5-mm radial artery diameter. (In currently available instruments, the effective element length is less, giving a ratio of approximately 0.3.) To compensate for the possible presence of these stress artifacts, the instrument uses a separate, oscillometric blood pressure measurement system to calibrate the TBP measurement. The oscillometric measurement is made by a continuous-deflation oscillometric blood pressure module (certified by the Federal Drug Administration) that uses proprietary algorithms to determine systolic and diastolic pressures. Mean arterial pressure is taken as the cuff pressure at which the amplitude of the cuff pressure oscillations reaches a maximum. The oscillometric measurements then are used to compute two coefficients (essentially a "gain" and "offset") that are used to modify the raw tonometer sensor signal to make its systolic and diastolic pressures agree more closely with the oscillometric pressures.

Our data clearly indicate that TBP measurement during anesthesia can provide accurate, reliable, and real-

*** Wenzel DJ, Winter DC, Honeyager KS: Active element selection for continuous blood pressure monitor transducer. U.S. Patent 4,893,631, January 16, 1990.

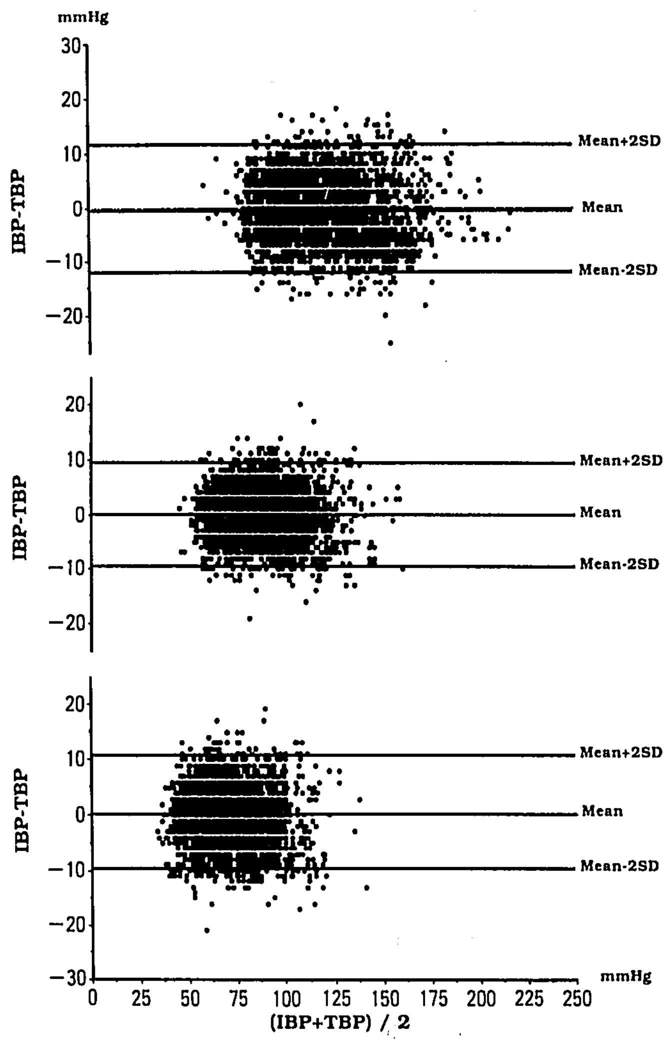

FIG. 8. Agreement between tonometric (TBP) and intraarterial blood pressures (IBP) for all 3,036 points obtained from 60 patients. *Top:* systolic. *Middle:* mean. *Bottom:* diastolic.

time blood pressure values and pressure waveforms that correlate favorably with IBP measurements. Differences between intraarterial and tonometric values were small for a wide range of systolic, mean, and diastolic blood pressure values. This was demonstrated not only by the similar precision values for the different pressure groups, but also by analysis in accordance with the method of Bland and Altman.[10] With this method, the "limits of agreement" were in a clinically acceptable range.

The variation between two different techniques measuring a single parameter can be evaluated by correlation or regression, or by bias and precision statistics. Bland and Altman have proposed that bias, the mean difference between the two techniques, is a more appropriate indication of the agreement between them.[10] The two values, bias $\pm$ 2 σ (where σ is the standard deviation), are called the "limits of agreement." If these limits do not exceed an acceptable tolerance, then the two techniques are judged to be in agreement and may be considered interchangeable as far as measurement accuracy is concerned. For the study reported here, the "limits of agreement" lie between −12.2 and +11.4 mmHg. This level of accuracy is sufficient for most clinical applications.

Monitoring of the blood pressure waveform is essential in anesthesia management, especially for patients whose blood pressure is expected to change greatly during anesthesia and surgery. This is one of the main reasons why IBP monitoring to obtain beat-to-beat pressure waveforms has become so popular in clinical practice. Because of the invasive nature of intraarterial cannulation, major problems such as infections and thromboembolic and traumatic complications accompany its use.[14,15] Our tonometry system, however, can noninvasively measure the entire arterial blood pressure waveform, in addition to determining systolic and diastolic pressures. Therefore, we conclude that this system may replace the conventional, invasive IBP monitoring system during anesthesia. Tonometry is especially useful if combined with pulse oximetry and capnography; this reduces the need for repeated arterial blood gas analyses for evaluation of oxygenation and ventilation.[16,17] Use of these noninvasive techniques certainly can help one avoid or reduce major complications attributable to intraarterial cannulation.

The hold-down pressure used to obtain partial flattening of the radial artery should not be large enough to occlude the arterial flow. This pressure was well controlled by the signal-processing system of the tonometer instru-

TABLE 3. Pooled Precision and Bias of Tonometric Blood Pressure for Various Intraarterial Blood Pressure Ranges

Range (mmHg)	Number of Points	Precision	Bias
Systolic			
All	3,036	4.9 ± 3.3	0.89 ± 5.8
≤89	248	4.5 ± 3.1	−2.3 ± 4.9
90–119	1,261	4.7 ± 3.3	−0.19 ± 5.8
120–149	1,104	5.0 ± 3.2	2.2 ± 5.5
150–179	387	5.6 ± 3.6	3.6 ± 5.5
≥180	36	6.6 ± 2.5	−4.4 ± 5.9
Diastolic			
All	3,036	4.3 ± 3.0	−0.41 ± 5.2
≤49	286	3.9 ± 3.0	−2.1 ± 4.5
50–69	1,278	4.6 ± 3.1	−0.53 ± 5.5
70–89	1,037	4.0 ± 2.9	−0.10 ± 5.0
≥90	435	4.1 ± 3.1	1.0 ± 5.1
Mean		3.8 ± 2.8	
All	3,036	3.6 ± 2.5	0.0 ± 4.7
≤69	557	3.7 ± 2.7	0.4 ± 4.4
70–89	1,172	3.7 ± 2.9	0.7 ± 4.5
90–109	898	4.0 ± 3.2	−1.0 ± 4.7
110–129	356	5.3 ± 3.3	−1.0 ± 4.9
≥130	53		−3.0 ± 5.4

Data are mean ± standard deviation.

ment. No damage (including disturbance of peripheral circulation as confirmed by plethysmography on the thumb) was observed in the area of the radial artery during this study. This included one anesthesia case of 18 h duration. Therefore, our tonometry system appears to be safe enough to use for long-term monitoring during anesthesia.

In conclusion, a noninvasive, continuous, radial arterial blood pressure monitoring system is available, permitting long-term monitoring without disturbance of peripheral circulation. This system may be applicable not only for clinical anesthesia, but also for patient care in the intensive care unit or coronary care unit.

References

1. Molhoek GP, Werseling KH, Settles J, van Vollenhoven E, Weeda HW, de Wit B, Arntzenius AC: Evaluation of the Penaz servoplethysmomanometer for the continuous, noninvasive measurement of finger blood pressure. Basic Res Cardiol 79:598–609, 1984
2. Kemmotsu O, Yokota S, Yamamura T, Takahashi T, Winter DC, Eckerle JS: A noninvasive blood pressure monitor based on arterial tonometry (abstract). Anesth Analg 68:S145, 1989
3. Kurki T, Smith NT, Head N, Dec-Silver H, Quinn A: Noninvasive continuous blood pressure measurement from the finger: Optimal measurement conditions and factors affecting reliability. J Clin Monit 3:6–13, 1987
4. Avolio A, Kelly R, Hayward C, Winter D, O'Rourke M: Noninvasive registration of the arterial pulse using high fidelity applanation tonometry (Abstract). FASEB J 2:A316, 1988
5. Drzewiecki GM, Melbin J, Noordergraaf A: Arterial tonometry: Review and analysis. J Biomech 16:141–152, 1983
6. Eckerle JS: Tonometry, arterial, Encyclopedia of Medical Devices and Instrumentation. Edited by Webster JG. New York, John Wiley and Sons, 1988, pp 2770–2776
7. Gardner RM, Hollingsworth KW: Optimizing ECG and pressure monitoring. Crit Care Med 14:651–658, 1986
8. Gorback MS, Quill TJ, Block EC, Granbert DA: Oscillometric blood pressure determination from the adult thumb using an infant cuff. Anesth Analg 69:668–670, 1989
9. Sheiner LB, Beal SL: Some suggestions for measuring predictive performance. J Pharmacokinet Biopharm 9:503–512, 1981
10. Bland JM, Altman DG: Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1:307–310, 1986
11. LaMantia KR, O'Connar T, Barash PG: Comparing methods of measurement: An alternative approach. ANESTHESIOLOGY 72:781–783, 1990
12. Pressman G, Newgard P: A transducer for continuous external measurement of arterial blood pressure. IEEE Trans Biomed Eng 10:73–81, 1963
13. Stein PD, Blick EF: Arterial tonometry for the atraumatic measurement of arterial blood pressure. J Appl Physiol 3:593–596, 1971
14. Savege TM: Complications of vascular catheterization, Hazards and Complications of Anesthesia. Edited by Taylar TH, Major E. Edinburgh, Churchill Livingstone, 1987, pp 356–378
15. Kaplan JA: Hemodynamic monitoring, Cardiac Anesthesia. Volume 1, 2nd edition. Edited by Kaplan JA. Philadelphia, WB Saunders, 1987, pp 179–185
16. Tremper KK, Baker SJ: Pulse oximeter. ANESTHESIOLOGY 70:98–108, 1989
17. Shapiro BA, Cane RD: Blood gas monitoring: Yesterday, today and tomorrow. Crit Care Med 17:573–581, 1989