Anesthesiology
81:1162–1168, 1994

J. B. Lippincott Company, Philadelphia

Noninvasive, Continuous Blood Pressure Measurement by Arterial Tonometry during Anesthesia in Children

Osamu Kemmotsu, M.D., Ph.D., F.C.C.M., Mikio Ohno, M.D., Ph.D.,† Koichi Takita, M.D.,† Hisashi Sugimoto, M.D.,‡ Hiroshi Otsuka, M.D.,† Yuji Morimoto, M.D., Ph.D.,‡ Takahisa Mayumi, M.D., Ph.D.§*

Background: **The authors' previous study of arterial tonometry in children demonstrated poor agreement of tonometric blood pressure (TBP) measurements with intraarterial blood pressure (IBP) measurements. The aim of the current study is to evaluate the feasibility of TBP measurements in children aged 1–6 yr using a newly designed pediatric sensor housing, by comparing TBP values with values obtained by IBP measurements.**

Methods: **Thirty-four children (aged 1–6 yr, ASA physical status 1–2) were studied undergoing elective abdominal or urologic surgery under general anesthesia. A 22- or 24-G cannula was inserted into the right radial artery. A TBP sensor housing was positioned over the left radial artery. TBP and IBP were continuously monitored and data were periodically sampled during and after intubation, during surgery, and during the recovery period.**

Results: **TBP waveforms were similar to those of IBP. Limits of agreement (bias ± 2 SD) were 12 and −13.3 mmHg for systolic, 11.6 and −10.4 mmHg for mean, and 13.2 and −10.8 mmHg for diastolic pressures for 3,400 paired points. Measurements could not be made in ten children because of insufficient pulse contour.**

Conclusions: **When pulse contour is sufficient for analysis, TBP monitoring provides an apparently safe and accurate method for the continuous measurement of arterial blood pressure during anesthesia in children aged 1–6 yr. (Key words: Anesthesia: pediatric. Blood pressure: measurement; tonometry. Measurement techniques: blood pressure; tonometry.)**

ARTERIAL tonometry is an indirect method that can provide beat-to-beat blood pressure measurements. We previously reported that arterial tonometry provides clinically acceptable blood pressure measurements noninvasively and continually in basically healthy patients aged 8–82 yr.[1] This also was shown to be true during controlled hypotension in adults.[2] It has been reported, however, that a large difference exists between intraarterial blood pressure (IBP) and tonometric blood pressure (TBP) measurements.[3,4] In addition, we previously reported that arterial tonometry did not perform as well in children as in adults.[5] Accordingly, we tested a new 30-element sensor housing (Nippon Colin, Komaki, Japan) built to improve the performance of arterial tonometry. The aim of the current study was to evaluate clinical acceptability of TBP measurement in children using the new multiple-element sensor by comparing it with IBP measurements.

Methods

After Institutional Ethic Committee approval and informed consent from parents were obtained, we studied 34 children undergoing elective abdominal or urologic surgery lasting 2–3 h under general anesthesia. Their ASA physical status was 1–2, mean age was 3.2 ± 2.2 yr, and mean body weight was 17.2 ± 6.8 kg. Anesthesia was induced with 5 $mg \cdot kg^{-1}$ intravenous thiamylal, and the trachea was intubated following 0.1 $mg \cdot kg^{-1}$ intravenous vecuronium. Anesthesia was maintained with either sevoflurane/nitrous oxide in oxygen or a combination of isoflurane/nitrous oxide in oxygen and caudal epidural anesthesia. For each patient, oscillo-

* Professor and Chairman of Anesthesiology and Intensive Care.

† Instructor in Anesthesia.

‡ Assistant Professor of Anesthesiology and Intensive Care.

§ Associate Professor of Anesthesiology and Intensive Care.

Received from the Department of Anesthesiology and Intensive Care, Hokkaido University School of Medicine, Sapporo, Japan. Accepted for publication August 1, 1994. The clinical test was performed at Hokkaido University Hospital using tonometers built by Nippon Colin. The pediatric sensor housing used in this study was designed and built by Nippon Colin at the request of Dr. Kemmotsu. No financial support was provided by Nippon Colin. Presented in part at the 67th annual meeting of International Anesthesia Research Society, San Diego, California, March 19–23, 1993.

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

metric blood pressure was measured before the study to exclude patients with blood pressure differences of more than 5 mmHg between arms. After induction of anesthesia, a 22- or 24-G Teflon cannula (2.5 cm in length, Baxter, Deerfield, IL) was inserted in the right radial artery and connected to a disposable transducer (Uniflow system, Utah Medical Products, Midvale, UT) to measure IBP. The measurement system consisted of the cannula, 90 cm of low-compliance pressure tubing (Baxter, Tokyo, Japan), a continuous flush device, and a disposable transducer. The system was filled with saline, and all visible air bubbles were eliminated. The dynamic response of the system revealed a mean natural frequency of 37.6 Hz with a range of 31.3–40.0 Hz and a mean damping coefficient of 0.21 with a range of 0.209–0.224. The dynamic response of the fluid-filled catheter and pressure transducer system was measured by the fast-flush method. The pressure transducer was connected to amplifying and monitoring equipment built in a CBM tonometer system. The natural frequency of the system was >50 Hz, and the damping coefficient was <0.10. TBP was measured at the left radial artery by a CBM-7000 tonometer whose software is basically the same as N-CAT (Nippon Colin) with a sensor housing specially designed for children (fig. 1). 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.[6] IBP and TBP waveforms were recorded by a digital magnetic tape recorder (Rp-882, NF Circuit Design Block, Tokyo, Japan), and IBP and TBP digital values were recorded by a computer (NEC-9801UX, Nippon Electric, Tokyo, Japan) for subsequent data analysis. The arterial tonometer sensor was positioned over the skin and held with sufficient pressure (the hold-down pressure) to flatten the radial artery between the sensor and the underlying radius as previously described in detail.[1] With this system, radial arterial blood pressure is measured by detecting the pressure change (amplitude) in the adequately flattened artery with an array of 30 piezoelectric pressure transducer elements. Each transducer element is an independent measuring device. The array allows the sensor to be located over the artery and to use the element producing the strongest signal. The transducer elements on the sensor array are not calibrated to measure an absolute pressure but give off a voltage signal that changes with the amount of pressure applied to the sensor. To translate these voltage signals into pressure readings, the sensor must be calibrated. The system calibrates its sensor to a standard oscillometric cuff, which is integrated into the unit. The calibration takes approximately 30 s. The system periodically checks whether the sensor is sufficiently centered over the radial artery and the "hold-down pressure" is in a proper range, comparing values with those from the oscillometric measurement. The hardware block diagram of the system and a calibration example are shown in the Appendix. For this purpose, an oscillometric cuff was placed on the same side of the arm as the tonometric sensor. The cuff calibration interval was 5 min in this study. Data sampling was started 2.5 min after each cuff calibration. Paired data were sampled from the computer every 30 s for 20 min during and after intubation (20 points), 60 min during surgery (60 points), and 20 min during the re-

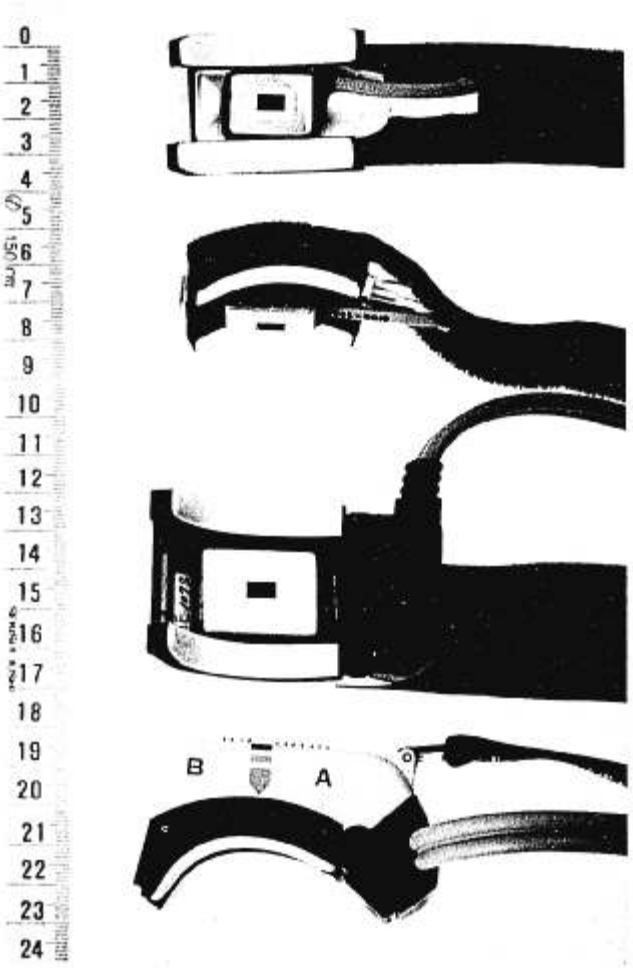

Fig. 1. Pediatric (upper two) and conventional (lower two) sensor housing (see text for details).

covery period (20 points). These are periods when the blood pressure is expected to change.

Data analyses for 8 children with body weight less than 10 kg (8.7 ± 0.7 kg) and for 26 children with body weight more than 10 kg (21.1 ± 6.6 kg) were achieved separately. Precision (mean absolute value of error) and bias (mean error) were calculated for systolic, mean, and diastolic pressures of TBP, with IBP used for the reference values. Changes in precision and bias as a function of pressure were calculated by dividing the systolic data points into five groups (≤79, 80–99, 100–119, 120–139, and ≥140 mmHg), the mean data points into five groups (≤59, 60–69, 70–79, 80–89, and ≥90 mmHg), and the diastolic data points in four groups (≤49, 50–59, 60–69, and ≥70 mmHg). After bias and precision data from each group were obtained, Student's *t* test was performed. The difference was considered significant when the mean values differed by more than 5 mmHg or when *P* was less than 0.05. TBP and IBP also were compared by the "limits of agreement" for comparing two different measurements. In this method, the difference (TBP − IBP) was plotted against mean of TBP and IBP (TBP + IBP)/2.[7]

Results

Simultaneous waveforms for TBP and IBP with the electrocardiogram from a 3-yr-old, 12.2-kg male patient are shown in figure 2. IBP and TBP waveforms are similar. Precision and bias for both groups of children (weight less than and greater than 10 kg) and the entire group are summarized in table 1. Precision was distributed between 1.8 and 6.6 mmHg, and the bias was insignificant. There were no significant differences among these values between the two groups of children as shown in the table.

The "limits of agreement" analysis of the 800 paired points for 8 children (body weight <10 kg), 2,600 points for 26 children (body weight >10 kg), and 3,400 paired points for 34 children are shown in figures 3, 4, and 5, respectively. Bias and standard deviation for each group are also shown in the figures.

TBP measurement was difficult in ten additional children because of difficulty obtaining a good recording site due to a weak radial pulse. These children were excluded from the study. We used a pulse oximeter probe on the thumb of the TBP measurement side to assure peripheral circulation, and we found no alterations in plethysmograms and oxygen saturation values during TBP monitoring. Although a transient compression mark on the skin by the pressure applied by the sensor was observed in most of the children, no disturbance of peripheral circulation, nerve injury, or other complication was observed.

Discussion

Our data indicate that TBP measurement during anesthesia in children can provide apparently accurate, reliable, and real-time blood pressure information. These results are in accordance with our previous reports.[1,2] Values and waveforms of TBP correlate favorably with those of IBP measurement.

Our findings indicate that TBP waveforms have features similar to those of IBP in children during anesthesia. This agrees with the results of other researchers using similar transducers.[8,9] The systolic wave of TBP

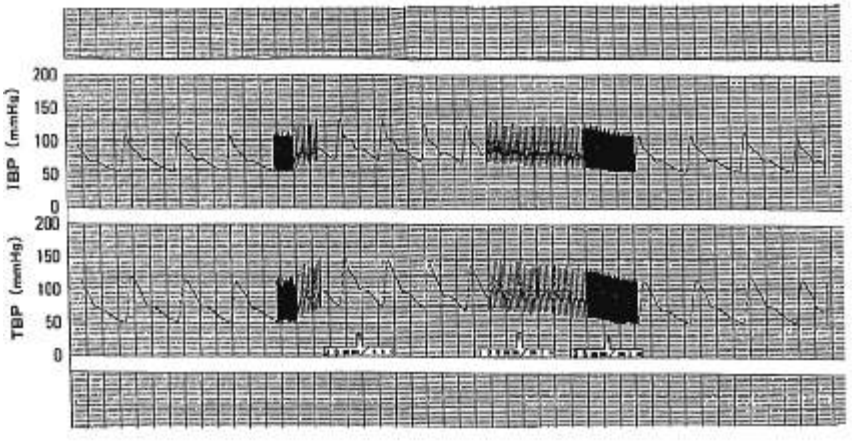

Fig. 2. Simultaneous tracings of waveforms obtained from a 3-yr-old, 12.2-kg boy. ECG = electrocardiogram; IBP = intraarterial blood pressure; TBP = tonometric blood pressure.

Table 1. Precision and Bias

Range	Body Weight < 10 kg			Body Weight > 10 kg			All		
	n	Bias	Precision	n	Bias	Precision	n	Bias	Precision
Systolic pressure (mmHg)									
All	800	1.1 ± 6.2	5.2 ± 3.6	2,600	−1.4 ± 6.2	5.3 ± 3.5	3,400	1.0 ± 6.2	5.3 ± 3.5
>140	163	4.1 ± 6.1	5.8 ± 4.0	507	−3.6 ± 6.0	5.2 ± 3.2	670	1.7 ± 6.0	5.3 ± 3.4
120–139	287	−3.1 ± 5.0	4.2 ± 3.2	966	−1.7 ± 5.4	4.9 ± 3.7	1,253	0.1 ± 5.3	4.7 ± 3.6
100–119	268	0.4 ± 6.4	6.6 ± 3.1	869	1.2 ± 6.3	4.8 ± 3.4	1,137	0.9 ± 6.3	5.2 ± 3.3
80–99	57	1.1 ± 4.3	3.6 ± 2.5	185	1.3 ± 5.2	4.2 ± 3.2	242	1.0 ± 5.0	4.1 ± 3.0
<79	25	2.3 ± 3.6	3.2 ± 3.4	73	2.2 ± 3.1	6.2 ± 3.1	98	1.4 ± 3.2	5.4 ± 3.2
Mean pressure (mmHg)									
All	800	1.6 ± 5.2	4.3 ± 3.4	2,600	0.3 ± 5.6	4.4 ± 3.5	3,400	1.1 ± 5.5	4.4 ± 3.5
>90	308	−1.6 ± 4.2	3.6 ± 2.2	1,262	0.6 ± 3.2	4.7 ± 2.9	1,571	0.5 ± 3.4	4.5 ± 2.8
80–89	123	4.7 ± 6.3	5.5 ± 3.2	683	−0.6 ± 4.1	4.2 ± 3.2	805	1.6 ± 4.5	4.4 ± 3.2
70–79	134	−3.4 ± 4.7	5.8 ± 3.3	470	3.2 ± 4.5	4.7 ± 3.5	604	0.0 ± 4.5	4.9 ± 3.5
60–69	174	1.6 ± 3.2	2.2 ± 1.7	123	0.4 ± 5.8	5.3 ± 5.0	297	1.4 ± 4.5	3.5 ± 3.5
<59	61	3.4 ± 2.6	3.5 ± 2.8	62	0.3 ± 2.1	1.8 ± 1.1	123	2.2 ± 2.4	2.6 ± 2.1
Diastolic pressure (mmHg)									
All	800	2.0 ± 5.9	5.0 ± 3.8	2,600	1.1 ± 6.1	5.1 ± 3.5	3,400	1.2 ± 6.1	5.1 ± 3.6
>70	404	−1.1 ± 6.2	4.2 ± 2.8	1,269	1.8 ± 4.5	3.8 ± 2.9	1,673	0.5 ± 5.0	3.9 ± 2.9
60–69	131	1.1 ± 6.4	5.0 ± 3.9	466	1.2 ± 5.7	5.5 ± 2.9	597	1.0 ± 5.9	5.4 ± 3.1
50–59	110	0.4 ± 3.8	4.5 ± 3.8	472	1.5 ± 6.1	5.0 ± 3.1	582	0.9 ± 5.7	4.9 ± 3.2
<49	155	3.4 ± 3.2	3.3 ± 2.1	393	1.7 ± 6.0	5.2 ± 3.7	548	1.7 ± 5.4	4.7 ± 3.3

Data are mean ± SD.

n = number of points.

appeared 16 ms after that of IBP, whereas diastolic waves of both TBP and IBP appeared simultaneously. This may be due to reasons apart from the difference of the propagation delay along the arteries from the heart to the recording sites. There are viscous and elastic components, subcutaneous adipose, and connective tissues between the tonometric sensor and the radial artery that may affect the damping and resonance factors of the recording system. The dynamic response of the IBP and TBP measurement systems in our study should be adequate to obtain accurate blood pressure values and waveforms.[10] Although there is a slight delay in the systolic wave monitored by the TBP compared with the IBP system, the difference is negligible in clinical application.

Differences between IBP and TBP values were small over a wide range of systolic, mean, and diastolic blood pressure values. Similar results were obtained in children whose body weight was less than 10 kg and those weighing more than 10 kg. In evaluation of a new technique compared with a standard method, the "limits of agreement" (the mean difference between the new and standard techniques ± 2 SD) can provide more reliable information than correlation coefficients.[7,11] This is because the "limits of agreement" better define the precision and accuracy of the new technique. If these limits do not exceed an acceptable tolerance, the two techniques are judged to agree and can be considered interchangeable as far as measurement accuracy is concerned. In the current study, the "limits of agreements" are between 12 and −13.3 mmHg for systolic, 11.6 and −10.4 mmHg for mean, and 13.2 and −10.8 mmHg for diastolic pressure in the pooled data. This means that, on average, 95% of the TBP readings were between 12 mmHg greater and 13.3 mmHg less than the IBP readings for systolic blood pressure. However, there was little difference between the bias ± 2 SD in the different pressure groups, as shown in table 1. These values are similar to our previous findings[1] and are thought to be sufficient for most clinical settings. Our results are quite different, however, from recent reports from other institutions.[3,4] One of the main reasons for the discrepancy may be the differences in the study populations. Burkhardt *et al.*[3] studied patients under-

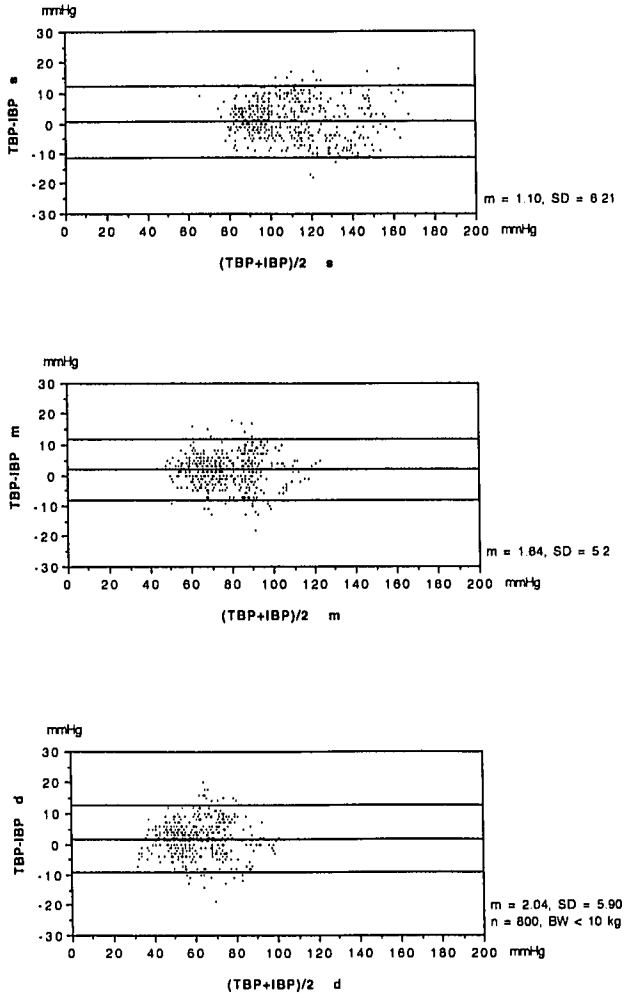

Fig. 3. Agreement between tonometric blood pressure (TBP) and intraarterial blood pressure (IBP) for 800 paired data obtained from eight children with body weight less than 10 kg. (*Top*) Systolic. (*Middle*) Mean. (*Bottom*) Diastolic.

going thoracic or vascular surgery, whereas our patients were undergoing abdominal or urologic surgery.

In this study, we used a sensor housing specially designed for children. The new design permits fabricating a 30-element piezoelective tonometer sensor that is smaller than the previous 15-element design.[1] The size of each sensor element is 0.2 × 0.25 × 0.8 mm. To reduce size and weight, the sensor-positioning mechanism was removed from the housing so that we could not use the automatic positioning feature of the instrument. Although sensor elements remain the same, the size and weight of the housing were reduced: the weight of the new sensor housing is 20 g; that of the conventional housing is 75 g. Before application of the sensor housing, the site of application on the radial artery was examined carefully by palpation. Once the site was decided on, the sensor housing was attached tightly to the skin surface over the radial artery with a double-sided adhesive tape. The housing was held firmly on the wrist with a beltlike device to avoid any shift of sensor position during TBP monitoring. The new design achieved better performance in blood pressure measurement during anesthesia in children than our previous results.[5]

Kelly *et al.* reported that a high-fidelity applanation tonometer using a pencil-type probe incorporating a

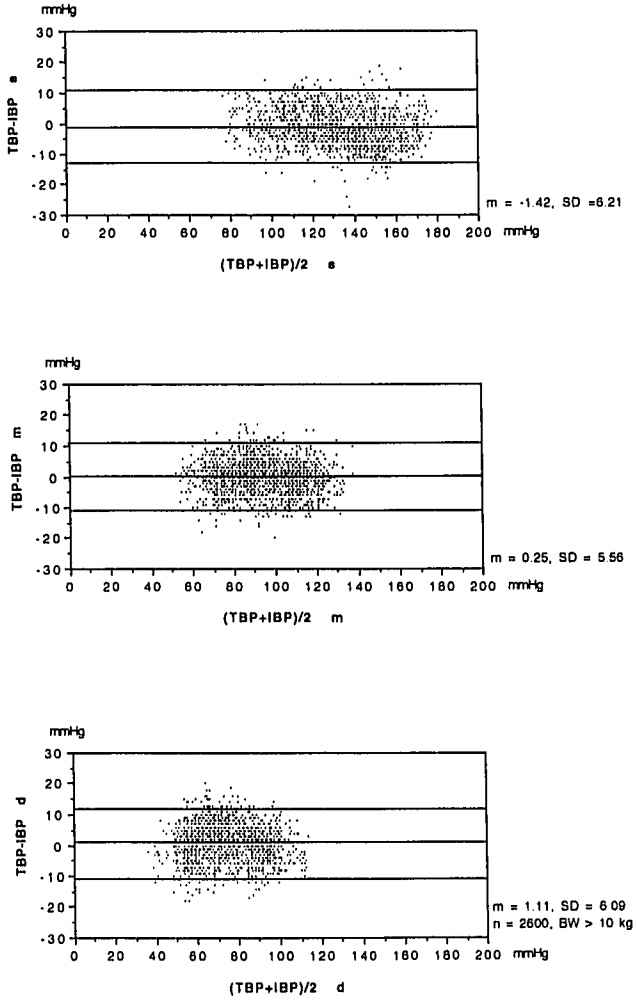

Fig. 4. Agreement between tonometric blood pressure (TBP) and intraarterial blood pressure (IBP) for 2,400 paired data obtained from 24 children with body weight more than 10 kg. (*Top*) Systolic. (*Middle*) Mean. (*Bottom*) Diastolic.

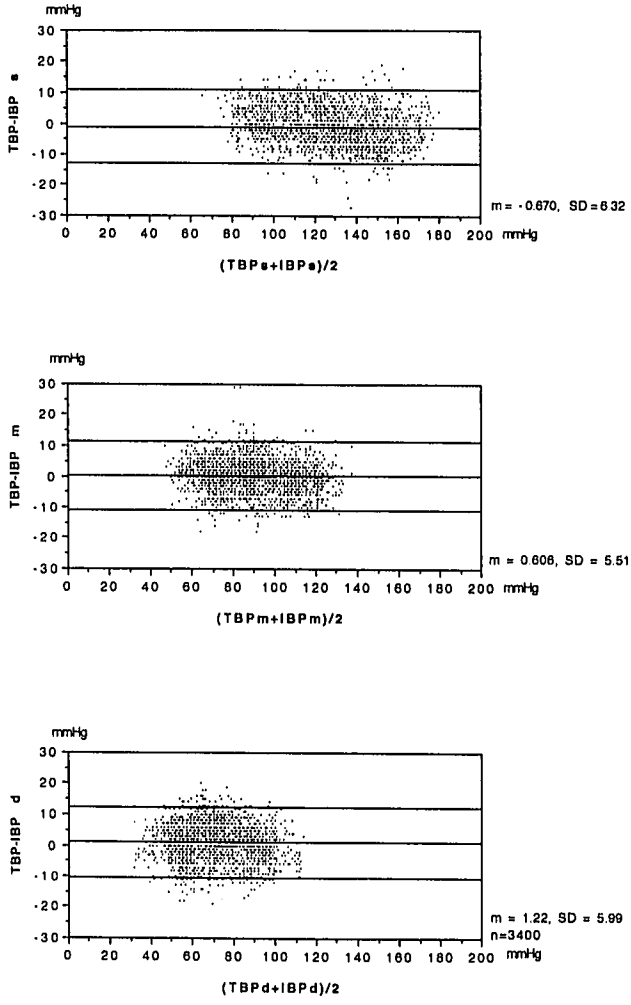

Fig. 5. Agreement between tonometric blood pressure (TBP) and intraarterial blood pressure (IBP) for 3,400 paired data from 34 children. (*Top*) Systolic. (*Middle*) Mean. (*Bottom*) Diastolic.

high-fidelity Millar strain gauge transducer showed a good performance with measurement of arterial pressure pulse contour in both dogs and humans.[9] As their tonometer does not need cuff calibration, it does not interfere with blood flow through the vessel and allows the continuous monitoring of arterial pressure on a beat-by-beat basis. However, positioning of the transducer over the site of the artery seems to be difficult in clinical settings, because the probe should theoretically be kept as close as possible to perpendicular to the arterial axis for accurate tonometric measurement.[1,9] Our multiple-element sensor is designed to hold one element at least close to the center of the partially flattened radial artery. Accordingly, positioning of the sensor is easier using our tonometer than a single-probe tonometer. Our tonometer needs periodic cuff calibration during which blood flow through the radial artery is interrupted. When we use the tonometer alone, cuff calibration can be done on the other arm so as not to interfere with the blood flow. The cuff calibration is beneficial in TBP monitoring because we can confirm pressure values by the built-in cuff method when unexpected sudden increases or decreases in blood pressure are observed. Confirmation of pressure values by oscillometry before medical intervention is recommended, because sudden changes in blood pressure may be related to drifting or the improper positioning of the sensor elements on the wrist. Although we did not have such problems during TBP measurements in our study, a small shift in sensor position (due to patient movement, for example) can cause a large but inaccurate change in the pressure measurement. It is also true that there are still technical problems to overcome (*e.g.*, positioning, sensor size) in children, particularly small (<8 kg) children.

In conclusion, when pulse contour is sufficient for analysis, our results indicate that TBP monitoring provides an apparently safe and accurate method for the continuous measurement of arterial blood pressure during anesthesia in children aged 1–6 yr.

Appendix

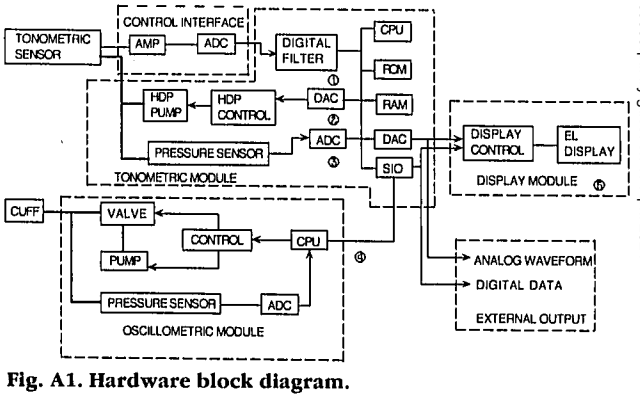

Fig. A1. Hardware block diagram.

1. **The pressure pulse wave is obtained by each element of the tonometer sensor, and the analog wave signals are converted to digital values by the ADC. The digital data are passed through the digital filter.**
2. **The HDP pump and values are controlled by the analog signal converted from digital data that is calculated by the CPU.**

3. The HDP requirement for applying the proper pressure to the artery is monitored by the pressure sensor. Then it is digitized by the ADC.
4. Pulse rate and systolic, mean, and diastolic blood pressure values are measured by the oscillometric module and sent to the CPU.
5. Blood pressure values and waveforms are displayed on the screen.

At the beginning of the measurement and thereafter on demand, the CPU will determine the proper HDP value by monitoring the signals as described in steps 1, 2, and 3. The CPU will maintain the proper HDP (step 3) during the tonometric measurement. The CPU will calculate the tonometric blood pressure values using the cuff blood pressure (step 4) and display these results on the screen (step 5). ADC = analog-to-digital converter; AMP = amplifier; CPU = central processing unit; DAC = digital-to-analog converter; EL = electroluminescent; HDP = hold-down pressure; RAM = random access memory; ROM = read only memory; SIO = serial communication.

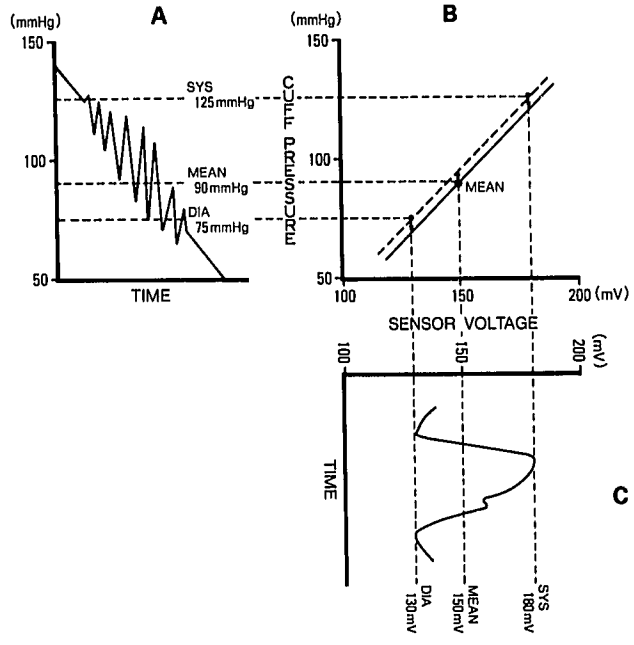

Fig. A2. As shown in *C*, the tonometer sensor measures the pressure changes during a pulse and provides an output in voltage. The highest voltage corresponds to the systolic blood pressure and the lowest voltage to the diastolic blood pressure. The computer in the unit also calculates the mean voltage over the span of the pulse by integrating the signal. The oscillometric cuff measures the systolic, mean, and diastolic pressures (*A*). The relationship between sensor voltage and blood pressure is calculated by assigning the highest voltage value read by the tonometer sensor to the systolic measurements obtained from the oscillometric cuff and plotting it on a graph. The lowest voltage reading from the sensor is assigned to the diastolic pressure, the mean voltage reading from the sensor is assigned to the mean pressure, and they are plotted on the graph (*B*). A straight line is drawn through the points representing systolic and diastolic pressures to obtain the slope for a line that represents the blood pressure/voltage relationship. Because a plot of the sensor-voltage/cuff-pressure for the mean often does not lie on the same line as the sensor-voltage/cuff-pressure for the systolic and diastolic, the tonometer calibration algorithm offsets the line somewhat toward the mean so that the sensor will provide the most accurate mean measurement.

The line that describes the relationship between sensor voltage and pressure is calculated as follows: sensor pressure = A × sensor voltage + B, where A = (systolic cuff pressure − diastolic cuff pressure)/(systolic sensor voltage − diastolic sensor voltage), and B = mean cuff pressure − A × mean sensor voltage.

A Calibration Example. **Suppose that, during a sensor calibration, the oscillometric cuff measured the following pressures: systolic 125 mmHg, mean 90 mmHg, and diastolic 75 mmHg; and that, during the same calibration, sensor voltages were as follows: systolic 180 mV, mean 150 mV, and diastolic 130 mV. Then A = (125 mmHg − 75 mmHg)/(180 mV − 130 mV) = 1 mmHg/mV, and B = 90 mmHg − 1 mmHg/mV × 150 mV = −60 mmHg. Accordingly, the sensor pressure in this case would be as follows: sensor pressure = 1 mmHg/mV × sensor voltage − 60 mmHg.**

If the calibration sensor voltage values are inserted into the above formula, the resulting pressures would be: systolic sensor pressure = 1 mmHg/mV × 180 mV − 60 mmHg = 120 mmHg, mean sensor pressure = 1 mmHg/mV × 150 mV − 60 mmHg = 90 mmHg, and diastolic sensor pressure = 1 mmHg/mV × 130 mmHg − 60 mmHg = 70 mmHg.

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