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## A Comparison of Two Automated Indirect Arterial Blood Pressure Meters: With Recordings from a Radial Arterial Catheter in Anesthetized Surgical Patients

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Most clinical measurements of arterial blood pressure are made by sphygmomanometry. Recently, automated sphygmomanometric blood pressure meters have been developed as substitutes for the manual sphygmomanometer. We evaluated two such devices: the Dinamap 845®\*\* and the Infrasonde 4000®.†† Both devices automatically inflate a cuff to above systolic arterial pressure and determine arterial pressure by incremental deflations of the cuff. They differ in the physical measure used: the Dinamap 845® analyses pressure fluctuations sensed by the occluding cuff,‡‡ while the Infrasonde

4000® uses a microphone to detect infrasound (20-30 Hz) waves associated with motion of the arterial wall.§§ Both devices display heart rate, and systolic, diastolic, and mean blood pressures.

### MATERIALS AND METHODS

Forty male patients, who required arterial cannulation for medical reasons, participated in this study. All patients meeting this criterion, and given general anesthesia in the supine position, were included in succession until the study was complete. The experimental protocol was reviewed and approved by the Veterans Administration Research and Development (Human Studies) Committee. We compared the Dinamap 845® (N = 20) and the Infrasonde 4000® (N = 20) with a common direct measure, obtained from a radial artery catheter.

For the direct measurements, a radial artery was cannulated with a Criticon Catholon-IV® 20 G 1-1/4 catheter. A Gould/Statham® P23 pressure transducer was connected to the patient via a Sorensen Research® monitoring kit, which contained pressure tubing, an Intra-flo® automatic flushing device, and a stopcock. The total length of tubing in the system was 161 cm.

Direct arterial pressure measurements may be seriously

§§ Operations Manual, Infrasonde D4000® Automatic Digital Blood Pressure Monitor. Puritan-Bennett, 1983.

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\*\* Dinamap® Adult/Pediatric Vital Signs Monitor, model 845. Criticon Inc., Northwest Shore Blvd, Tampa, Florida 33607.

†† Infrasonde D4000® Automatic Digital Blood Pressure Monitor, Puritan-Bennett, 12655 Beatrice St., Los Angeles, California 90066.

‡‡ Operations Manual, Dinamap® Adult/Pediatric Vital Signs Monitor, model 845. Criticon, Inc., 1981.

TABLE 1. Pooled Data Comparison of Direct and Indirect Measures of Arterial Pressure

	Arterial Catheter		Dinamap®		Mean Diff.	Correlation	Arterial Catheter		Infrasonde®		Mean Diff.	Correlation
	Mean	SD	Mean	SD			Mean	SD	Mean	SD		
Systolic	120.88	15.89	121.56	16.26	-0.68	0.83	126.58	21.15	113.25	18.03	13.33*	0.83
Diastolic	65.48	10.22	79.03	12.28	-13.55*	0.82	67.65	13.70	75.36	13.83	-7.71*	0.84

Mean pressures by method, using all data. Mean diff. = direct-indirect. All values are in mmHg.

in error if the resonant frequency of the system is lowered by air bubbles anywhere in the measuring system.<sup>1,2</sup> The dynamic characteristics of the system were checked by the "fast flush" method of Gardner,<sup>1</sup> and the system was reflushed until the resonant frequency exceeded 15 Hz and the damping factor was in the range 0.22-1. Inadequate dynamic response was almost always due to trapped air; clotting was rarely a problem. The dynamic response was rechecked after each drawing of blood for analysis of arterial blood gases and at the end of the procedure. Static accuracy and absence of leakage was evaluated by calibration against a column of mercury prior to each surgical operation. The transducer was positioned at the level of the right atrium, as was the occluding cuff for the indirect measurement.

Indirect measurements were made according to the instructions provided by the manufacturers of the devices tested. Direct and indirect measurements were made from the same arm; the direct measurement always was made first. The cuff was placed over the brachial artery. Cuff width was selected to be about 40% of arm circumference.

For each comparison, systolic pressure, diastolic pressure, and heart rate were recorded from direct and indirect readings. Groups of three direct-indirect pairs of readings ("triplets") were made, in rapid succession, every 15-30 min during the surgical procedure. Repeat readings were made as soon as the shape of the arterial pressure was returned to normal after deflation of the cuff. Each patient yielded from 6 to 30 pairs of readings (mean 18). A total of 357 comparisons were obtained in the Infrasonde® study and 318 in the Dinamap® study.

Pairs of readings were plotted and fitted with a straight line by least-squares fit. The computer program used also provided means, standard deviations, and a Pearson correlation coefficient for each set of data. The differences between the means for direct and indirect methods were evaluated by independent *t* tests. Starred differences in tables 1-3 differ from zero with *P* < 0.005.

### RESULTS

Figures 1-4 summarize the comparisons for systolic and diastolic blood pressure, while table 1 summarizes and compares all three methods. Correlation coefficients are 0.82 to 0.84, clearly significant, but also evidence for considerable scatter. Except for the systolic pressure as measured by the Dinamap®, differences in mean value are large enough (8-14 mmHg) to be of clinical concern. Starred differences between means are significant at *P* < 0.005. To see if the same result occurred within the data from one patient, a single patient from each group, with mean closest to the group mean, was evaluated separately. Table 2 summarizes this data; the same pattern of systematic error is present.

Since arterial blood pressure often changed markedly during surgery, and the direct/indirect measurements could not be made at the same time, there was a possibility that the time (about 1 min) between direct and indirect readings might have biased the results. To check on this possibility, one "triplet" of readings, in which the direct reading varied the least, was taken from the data of each patient and the readings compared as above. These results are shown in table 3.

There was no significant difference between these

TABLE 2. One Patient from Each Group Comparison of Direct and Indirect Measures of Arterial Pressure

	Arterial Catheter		Dinamap®		Mean Diff.	Correlation	Arterial Catheter		Infrasonde®		Mean Diff.	Correl
	Mean	SD	Mean	SD			Mean	SD	Mean	SD		
Systolic	131.30	13.22	129.60	11.24	1.70	0.76	120.28	15.83	106.77	13.07	13.51*	0.75
Diastolic	73.53	5.24	88.06	6.60	-14.53*	0.88	66.55	6.09	74.77	5.52	-8.22*	0.78

Mean pressures by method, using one representative patient from

each group. Mean diff. = direct-indirect. All values in mmHg. Number of comparisons: Dinamap® 15, Infrasonde® 18.

TABLE 3. One Triplet/Patient Comparison of Direct and Indirect Measures of Arterial Pressure

	Arterial Catheter		Dinamap <sup>®</sup>		Mean Diff.	Correlation	Arterial Catheter		Infrasonde <sup>®</sup>		Mean Diff.	Correlation
	Mean	SD	Mean	SD			Mean	SD	Mean	SD		
Systolic	120.50	14.01	122.00	16.33	-1.50	0.86	123.98	18.59	111.45	12.91	12.53*	0.84
Diastolic	66.30	7.89	79.05	12.28	-12.75*	0.81	66.01	11.35	73.48	11.30	-7.47*	0.83

Mean pressures by method, using one set of three successive comparisons (triplet) from each patient. The set was chosen to show a minimum change in arterial pressure over the three pairs of readings,

as judged from the direct readings. Mean diff. = direct-indirect. All values are in mmHg.

findings and those obtained using all the data. Systolic pressures from this subset of the Infrasonde<sup>®</sup> group are shown in figure 5. The least-squares fit line for these data is not statistically distinguishable from that of figure 1.

### DISCUSSION

The results of this study are generally consistent with those from earlier studies in which direct and sphygmomanometric measures of arterial blood pressure have been compared. The major difference is that this study indicates that current automated sphygmomanometers have improved to the point where they compete on equal terms with manual sphygmomanometry.

Earlier studies have reported less favorable results.

Reder *et al.*<sup>3</sup> compared three methods in children: Doppler flow, infrasonde, and direct. Their best result ( $r = 0.99$ ) was with a Doppler method that could measure only systolic pressure. A rival Doppler system yielded  $r = 0.83$ , with a systematic underestimation of systolic pressure. Performance on diastolic pressure was worse:  $r = 0.71$ , with some readings differing by more than 50%. Their infrasonde device yielded a correlation of  $r = 0.00$ . Chastonay *et al.* (1982) evaluated a more recent Korotkoff sound device.<sup>4</sup> Correlations with direct measurements ranged from 0.58 to 0.70, and they concluded that the device was useless for monitoring patients in an intensive care unit.

The limitations of manual sphygmomanometry carefully were explored by van Bergen *et al.* in 1954.<sup>5</sup> In

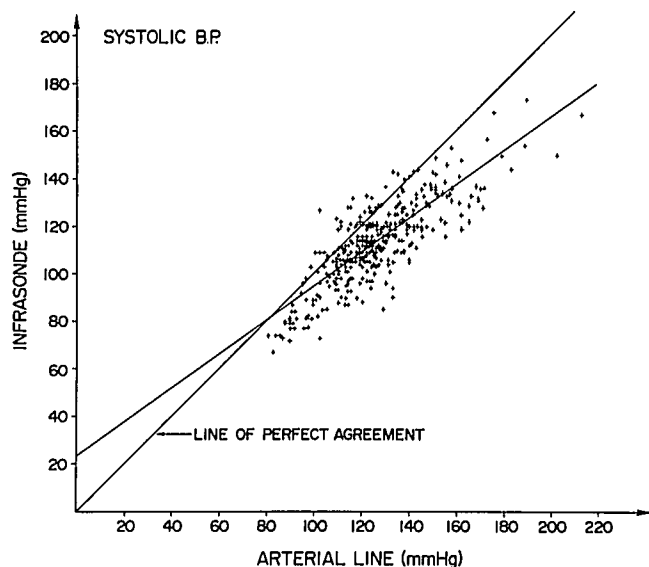


FIG. 1. Relationship between direct and indirect (Infrasonde 4000<sup>®</sup>) measurements of systolic pressure in 20 patients. All 357 pairs of measurements are plotted (many overlap). The least-squares fit line is as follows: Systolic, Infrasonde<sup>®</sup> =  $23.29 + 0.7106 \times$  (systolic, direct). The correlation coefficient is 0.83. The pressure range (direct method) is 81–214 mmHg.

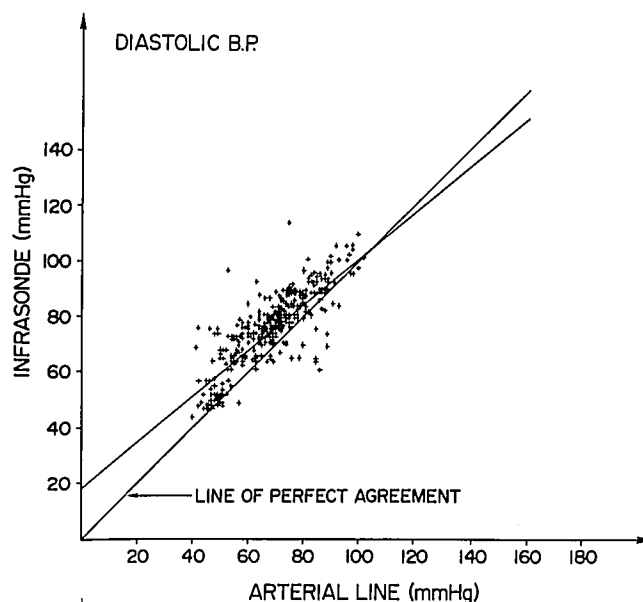


FIG. 2. Relationship between direct and indirect (Infrasonde 4000<sup>®</sup>) measurements of diastolic pressure in 20 patients. All 357 pairs of measurements are plotted (many overlap). The least-squares fit line is as follows: Diastolic, Infrasonde<sup>®</sup> =  $18.66 + 0.8302 \times$  (diastolic, direct). The correlation coefficient is 0.84. The pressure range (direct method) is 42–110 mmHg.

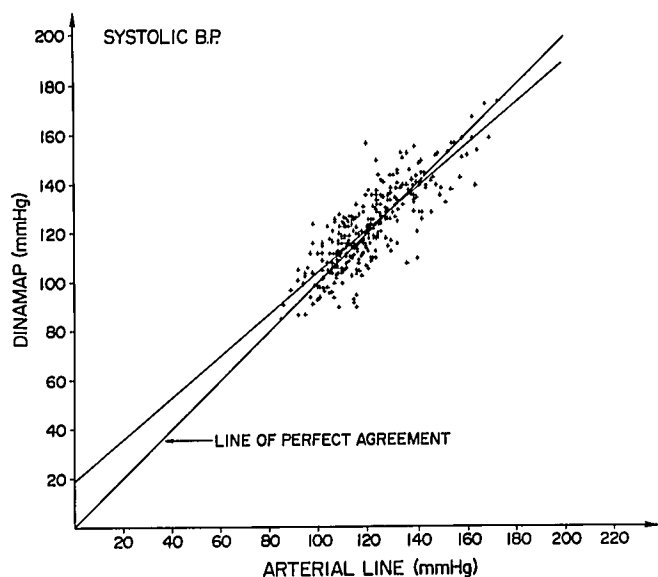


FIG. 3. Relationship between direct and indirect (Dinamap 845<sup>®</sup>) measurements of systolic pressure in 20 patients. All 318 pairs of measurements are plotted (many overlap). The least-squares fit line is as follows: Systolic, Dinamap<sup>®</sup> = 18.31 + 0.8540 × (systolic, direct). The correlation coefficient is 0.83. The pressure range (direct method) is 86–174 mmHg.

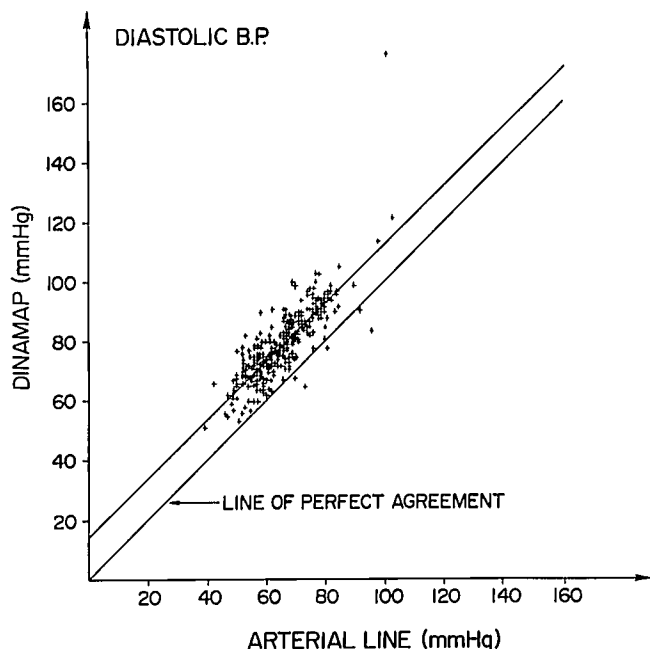


FIG. 4. Relationship between direct and indirect (Dinamap 845<sup>®</sup>) measurements of diastolic pressure in 20 patients. All 318 pairs of measurements are plotted (many overlap). The least-squares fit line is as follows: Diastolic, Dinamap<sup>®</sup> = 14.75 + 0.9820 × (diastolic, direct). The correlation coefficient is 0.82. The pressure range (direct method) is 39–103 mmHg.

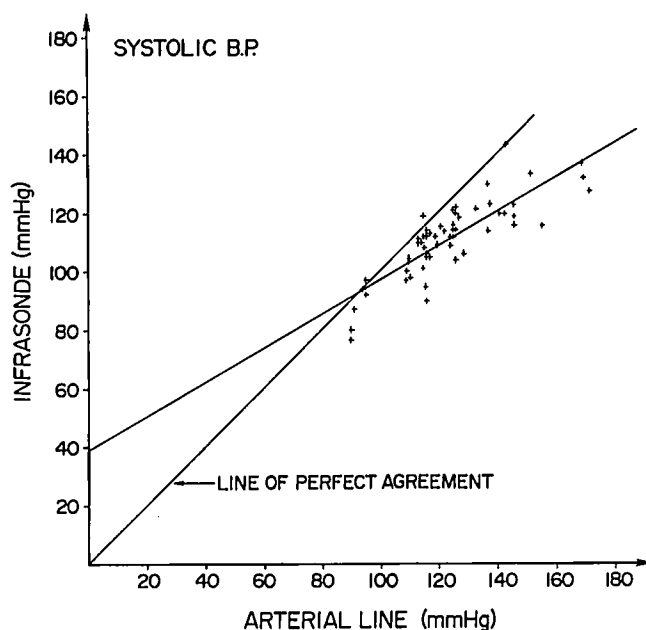


FIG. 5. Relationship between direct and indirect (Infrasonde 4000<sup>®</sup>) measurements of systolic pressure in 20 patients, using "best" triplets of comparisons (see text). Sixty pairs of comparisons are plotted (many overlap). The least-squares fit line is as follows: Systolic, Infrasonde<sup>®</sup> = 32.43 + 0.7485 × (systolic, direct). The correlation coefficient is 0.84. The pressure range, from arterial line measurements, is 90–172 mmHg.

comparison with direct readings from an arterial cannula, the error in estimation (scatter width) for systolic pressure was about 20%, while estimates of diastolic pressure were even worse.

The direct method itself is not without problems. Bruner *et al.*<sup>2</sup> reviewed both direct and indirect methods. Systolic pressure is higher in the peripheral artery than at the aorta, due to the amplification of the pressure pulse by the elasticity of the artery. This effect is most marked in the young; our subjects were largely over 50 years of age.

Compression of the peripheral artery, a necessity for the indirect method, can raise direct systolic pressure by 20–30 mmHg.<sup>2</sup> This effect, due to reflection of the pressure pulse, prevented us from measuring direct and indirect pressures at the same time. The similarity of our overall results with those from selected periods when arterial pressure was nearly constant suggests that this limitation did not noticeably change our results.

The characteristics of the recording system used for direct measurement of arterial blood pressure have been a subject of much concern. The "best" frequency band for clinical measurement of blood pressure by cannulation has yet to be defined.<sup>2</sup> A band width of at least 20

Hz has been advocated.<sup>1,5</sup> Most direct arterial pressure recording systems have underdamped responses, with resonances between 20 and 40 Hz. However even a small air bubble can lower the resonant frequency to 10, or even 5 Hz, and the frequencies defining the pressure pulse are typically from 3 to 5 Hz. Systolic pressure may be overestimated grossly if there are resonances below 10 Hz, so we exercised extreme care to eliminate all air bubbles from the system and checked dynamic response regularly during each measurement period. Nevertheless, we cannot exclude the possibility that the consistently low slopes observed may be due in part to an overestimation of high blood pressures and an underestimation of low blood pressures by the direct method.

In comparing the two indirect techniques, we favor the Dinamap<sup>®</sup> over the Infrasonde<sup>®</sup>. The Dinamap<sup>®</sup> gave a better measure of systolic pressure, and no worse a measure of diastolic pressure, than did the Infrasonde<sup>®</sup>. The latter also was more difficult to use; unless the microphone was placed precisely over the artery, the results were poor. The Dinamap<sup>®</sup> appears as good as a manual sphygmomanometric measurement and may be better under operating room conditions.

The residual differences between direct and indirect measures, which are nontrivial, relate to inherent limitations of both. Clinicians may have to recognize that direct and indirect "blood pressures" are inherently different measures, both related only indirectly to the physiologic phenomena of interest.

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### Inability to Titrate PEEP in Patients with Acute Respiratory Failure Using End-tidal Carbon Dioxide Measurements

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Positive end-expiratory pressure (PEEP) increases functional residual capacity,<sup>1</sup> decreases venous admixture in the lungs ( $\dot{Q}_S/\dot{Q}_T$ ),<sup>2</sup> and improves oxygenation in patients with acute respiratory failure (ARF). How much PEEP should be applied in each case has been a matter of controversy. Suter *et al.*<sup>1</sup> advocated the improvement obtained by PEEP in total compliance (CT) and used

this measurement to determine the "best PEEP." Conversely, Downs *et al.*<sup>3</sup> advocated an "optimum PEEP" as producing the lowest  $\dot{Q}_S/\dot{Q}_T$  without any consideration about lung mechanics. "Optimum PEEP" requires aggressive hemodynamic support because this high level of PEEP causes major circulatory impairment.<sup>4</sup> Recently, Murray *et al.*<sup>5</sup> recommended titration of PEEP by monitoring of arterial ( $P_{aCO_2}$ ) minus end-tidal carbon dioxide ( $P_{etCO_2}$ ) gradient. The  $P_{aCO_2}$ – $P_{etCO_2}$  gradient can be measured by determining the  $P_{CO_2}$  in exhaled gas and in arterial blood. When some degree of alveolar dead space is present, the  $P_{CO_2}$  of end-expiratory gas will be less than that of "ideal" alveolar gas, since it is diluted with alveolar dead space gas, which is practically free of  $CO_2$ . To measure alveolar dead space,  $P_{aCO_2}$  can be substituted for "ideal" alveolar  $P_{CO_2}$  because there is

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