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Continuous Noninvasive Finger Blood Pressure during Controlled Hypotension

A Comparison with Intraarterial Pressure

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The Finapres® is a noninvasive monitor that continuously displays the arterial waveform, pulse rate, and systolic, mean, and diastolic blood pressure. We determined its bias (mean prediction error) and precision (mean absolute error), relative to directly measured radial arterial blood pressure, in 16 otherwise healthy patients undergoing spinal fusion surgery under hypotensive anesthetic techniques. Data were recorded during three contiguous epochs: 20 min of normotension; 30 min following the initiation of hypotension; 20 min of hypotension. The Finapres demonstrated a systolic, mean, and diastolic bias (±standard deviation) of 3.6 ± 12.3, 5.2 ± 10.8, and 8.3 ± 9.4 mmHg, respectively. There were no significant differences in systolic bias among the epochs, whereas mean and diastolic bias were both greater during the hypotensive epoch, compared to the normotensive epoch. In 2 of the 16 patients, systolic and mean arterial pressure bias exceeded 20 mmHg. Finapres precisions of systolic, mean, and diastolic blood pressures were 9.8 ± 9.0, 8.7 ± 7.6, and 10.4 ± 8.2 mmHg, respectively. Precisions among the epochs were not significantly different. When Finapres pressures were "corrected" by subtracting the baseline difference between Finapres and oscillometrically determined mean pressure, bias decreased significantly. The correction process did not improve precision. The Finapres closely tracked changes in blood pressure, even in the presence of a large bias. In most patients, the Finapres is a useful continuous noninvasive blood pressure monitor. Periodic calibration of the Finapres by the difference between Finapres and oscillometrically determined mean arterial pressure is recommended. (Key words: Anesthesia: general. Equipment: monitors; blood pressure; Finapres. Hypotension: controlled. Measurement techniques: blood pressure. Monitoring: blood pressure.)

THE Finapres® (Ohmeda, Englewood, CO) is a noninvasive monitor that uses the methodology of Peňaz§ to display continuously the arterial waveform, pulse rate, and systolic, mean, and diastolic blood pressures. The physics upon which this method is based can be summarized as follows:[1] the external pressure, applied by a circumferential finger cuff, required to maintain constant digital arterial diameter, is equal to the internal digital arterial pressure. By rapidly varying the intracuff pressure so as to keep light transmission through the finger constant (measured with a photoplethysmograph built into the cuff), zero transmural pressure is maintained. Thus, the time-dependent cuff pressure reflects, in real time, intraarterial pressure. The Finapres displays this waveform, along with the rate and pressure variables derived from the cuff pressure trace.

Such a monitor could be useful in situations where blood pressure can change rapidly but where direct intraarterial monitoring is not justified. It also might prove useful in cases where unanticipated hypotension occurs and arterial cannulation is technically difficult. Finally, since it can be applied quickly, it may also be useful as a temporary measure when a delay in surgery to establish invasive arterial monitoring might be inadvisable.

Before such use can be considered, it is necessary to verify the accuracy of the device compared to invasively determined arterial pressure. Furthermore, such evaluations need to be carried out not only during relatively steady-state conditions but also under demanding clinical circumstances, such as when the rate of change of blood pressure is great and when significant hypotension is present. We therefore designed the current investigation to study the accuracy of the Finapres in patients in whom the anesthetic plan included the establishment of controlled hypotension.

In our previous studies, we noted that in 20% of patients, the Finapres demonstrated a clinically unacceptable bias (> 20 mmHg higher than concurrently determined oscillometric[2] and arterial pressure[3]). This offset, in individual patients, was similar for systolic, mean, and diastolic pressure, relative to arterial values. Because average mean oscillometric pressure in our study agreed within 1 mmHg of mean arterial pressure,[3] it occurred to us that it might be possible to improve the performance of the Finapres by "correcting" the Finapres pressures by the Finapres − oscillometric mean pressure difference. We therefore set out to determine the validity of this hypothesis as well.

Materials and Methods

After obtaining informed patient consent and the approval of our Institutional Review Board, we studied 16

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

patients undergoing spinal fusion with metal instrumentation under general anesthesia. Hypotension was induced using a variety of agents (*e.g.*, sodium nitroprusside, propranolol, labetalol, and isoflurane) at the discretion of the attending anesthesiologist; a reduction of mean pressure by 20–25% from the lowest preoperative pressure recorded on the chart was targeted.

A 20-G nontapered plastic cannula was inserted into a radial artery, and arterial pressure was measured using a model HP 78205D pressure module (Hewlett-Packard, Waltham, MA) and a disposable transducer (Cobe, Inc., Lakewood, CO). A 15-cm length of rigid plastic tubing connected the catheter to the transducer, and all bubbles were removed from the system, which was flushed with heparinized saline at 3 ml/h. Waveforms were continuously examined for evidence of damping or ringing. Damping coefficients and undamped resonance frequencies of pressure transducer systems were determined *in vivo* using a fast-flush test.[4] Accuracy and linearity of the pressure module used was verified with a mercury manometer at pressures between 0 and 200 mmHg following internal electronic calibration.

A correctly sized Finapres finger cuff was placed around the middle phalanx of the middle finger of the hand ipsilateral to the radial arterial catheter. If initial cuff placement resulted in a damped waveform, the cuff was adjusted so that the displayed pressure trace resembled a typical arterial waveform. No attempts were made to "tune" the Finapres once a reasonable waveform was displayed. If a satisfactory trace could not be obtained from the middle finger, the thumb was selected as an alternate site. No patients had to be excluded from the study because of failure to obtain an acceptable trace. During the study, the arm with the monitoring devices was pronated in extension on a padded board. The arterial transducer was zeroed at the same level as the Finapres cuff, eliminating any hydrostatic differences between the two devices. The transducers were approximately at the height of the right atrium.

Oscillometric blood pressures from the arm contralateral to the arterial cannula were determined by a Dinamap 1846SX monitor (Critikon, Tampa, FL). To ensure the absence of a significant pressure difference between the arms, three oscillometric pressures were recorded bilaterally over a 3–4-min interval prior to induction of anesthesia. No medications were administered and patients were not stimulated during this time.

Values of Finapres pressure variables were recorded by computer from the serial communication port of this monitor. Arterial systolic, mean, and diastolic pressures were output as a voltage on three separate channels of the Hewlett-Packard module and were read by a DASH-8 analog-to-digital converter (Metrobyte, Inc., Taunton, MA), housed in the computer. Following each pulse, the Finapres transmitted values averaged over the preceding 2 s; approximately every other set of data was stored. Direct arterial pressure variables from the last pressure wave were recorded simultaneously with each stored Finapres serial output. Dinamap pressures, along with the time interval over which the measurement took place, were also recorded by computer from the serial port of this monitor. Clocks from all monitoring devices were synchronized, and recorded numbers time stamped to allow for subsequent analysis of the data.

Comparison of the Finapres and arterial pressure variables were made for each patient during three contiguous epochs: a 20-min period of normotension; a 30-min period during the induction of hypotension; and a 20-min period of hypotension. We considered invasive arterial pressure as the reference value and determined the accuracy of the Finapres by measuring its bias (mean prediction error) and precision (mean absolute error) according to the following formulas:[5–7]

$$\text{Bias} = \frac{\sum_{i=1}^{n} (FP_i - AP_i)}{n}$$

and

$$\text{Precision} = \frac{\sum_{i=1}^{n} |FP_i - AP_i|}{n}$$

where i = pressure determination; n = number of pressures compared; FP = Finapres pressure variable; and AP = arterial pressure variable.

The bias and precision for the pressure variables during each epoch for each patient were averaged to give the mean bias and precision for the Finapres. Thus, each patient contributed equally to measurement of the performance of this device.

The utility of a simple procedure to improve the performance of the Finapres was evaluated as follows. The differences between the first three Dinamap mean pressures during the epoch of normotension and the average Finapres mean pressure during the corresponding Dinamap pressure determination cycle were averaged; this number was then subtracted from all Finapres pressures to "correct" the tendency of the Finapres to read higher than the arterial pressure monitor.[2,3] Corrected bias and precision values were then calculated as described above.

Plots of Finapres − arterial pressure differences (bias) *versus* the average of the two measurements for systolic, mean, and diastolic pressure (uncorrected and corrected) were made according to the method of Altman and Bland.[8,9] The first 250 comparisons from each of the study epochs were selected from each patient to provide equal weighting of the data.

TABLE 1. Clinical Details of Study Patients

Age	Sex	Weight (kg)	Agent for Hypotention	Primary Anesthetic*	MAP Bias (±SD) (Normotension)
45	F	100	SNP, esmolol	Fentanyl	−11.2 ± 3.3
50	M	80	Isoflurane	Isoflurane	−7.4 ± 3.1
43	F	59	Labetolol	Isoflurane	−2.8 ± 2.8
47	F	62	SNP, labetolol	Sufentanil	−1.8 ± 3.5
59	F	80	Labetolol	Isoflurane	−1.4 ± 9.1
72	M	77	Labetolol	Isoflurane	0.1 ± 4.1
32	M	82	Labetolol	MSO_4, midazolam	1.5 ± 3.4
38	M	91	Isoflurane	Isoflurane	1.5 ± 2.7
35	M	82	SNP, esmolol	Isoflurane	2.0 ± 3.9
13	F	59	SNP, propranolol	Sufentanil	2.2 ± 4.3
17	M	55	Enflurane	Enflurane	6.0 ± 3.5
57	F	53	SNP, labetolol	Fentanyl	10.4 ± 3.2
34	F	84	SNP, propranolol	Sufentanil	11.6 ± 3.7
26	M	54	SNP, propranolol	Fentanyl	11.9 ± 2.6
26	M	85	Isoflurane	Isoflurane	21.6 ± 13.0
44	F	60	Isoflurane	Isoflurane	30.8 ± 5.9

MAP = mean arterial pressure; SNP = sodium nitroprusside; MSO_4 = morphine sulfate.

* In addition, all patients received nitrous oxide.

Differences between bias and precision for each pressure variable among the three epochs were compared using one-way analysis of variance for repeated measures, with $P < 0.05$ required to claim statistical significance. Where a significant F value was found for a given pressure variable, a two-tailed paired Student *t* test was calculated between the various recording intervals. Differences between bias and corrected bias, and precision and corrected precision were analyzed by a paired *t* test using a Bonferroni correction for the *post hoc* analysis. Data are presented as mean ± standard deviation.

Results

Patients studied included eight men or boys and eight women or girls; they ranged in age from 13–72 (mean 40 ± 15.0 years), and all were ASA physical status 1 or 2. Demographic information about the patients, details of their anesthetic management, and Finapres MAP bias during the normotensive epoch are presented in table 1. A total of 8,546 pressure comparisons were made in the first study epoch (normotension), 12,756 in the second epoch (initiation of hypotension), and 9,218 in the third epoch (hypotension). There were no significant differences in any patient in oscillometric blood pressure between the two extremities.

The damping coefficient of the pressure transducer system was 0.26 ± 0.10 (range 0.18–0.48), and the undamped resonance frequency was 17.0 ± 3.4 Hz (range 12.8–20.4). No arterial or Finapres waveforms showed any evidence of ringing during visual examination of the pressure traces.

When data from all three recording epochs were combined, the Finapres had a positive systolic, mean, and diastolic bias of 3.6 ± 12.3, 5.2 ± 10.8, and 8.3 ± 9.4 mmHg, respectively. There were no significant differences in systolic bias among the three recording intervals. Mean pressure bias was greater during the period of hypotension than during normotension ($P < 0.05$); mean pressure bias during the induction of hypotension was not different from either of the other time intervals (table 2). Diastolic pressure bias also was greater during the hypotensive period compared to the normotensive period ($P = .01$); diastolic pressure bias during the induction of hypotension was not significantly different from the other two times (table 2).

Results of the "correction" procedure for bias are also presented in table 2. The improvement in systolic, mean, and diastolic bias for each the three study epochs was highly significant. Notably, by making the correction, the MAP bias was reduced from 5.2 to −0.6 mmHg ($P < 0.01$). The correction process led to a small negative systolic bias (−2.2) and a small positive diastolic bias (2.8).

TABLE 2. Bias and Corrected Bias (Relative to Radial Arterial Pressure) in Finapres Systolic, Mean, and Diastolic Pressures

Epoch	Systolic Bias	MAP Bias	Distaolic Bias
Normotension	2.5 ± 13.8	4.1 ± 10.6	6.5 ± 10.0
Normotension, corrected	−3.3 ± 8.0	−1.7 ± 7.1	1.7 ± 8.0
Induction of Hypotension			
Induction of Hypotension, corrected	3.5 ± 12.7	4.5 ± 10.4	8.9 ± 9.1
	−2.2 ± 8.5	−1.3 ± 6.3	3.1 ± 6.9
Hypotension	4.8 ± 10.8	7.0 ± 9.6*	9.4 ± 9.3*
Hypotension, corrected	−1.0 ± 9.8	1.2 ± 9.0	3.6 ± 8.9
All epochs	3.6 ± 12.3†	5.2 ± 10.1†	8.2 ± 9.4†
All epochs, corrected	−2.2 ± 8.7	−0.6 ± 7.5	2.8 ± 7.8

MAP = mean arterial pressure; "corrected" = Finapres values "corrected" by the initial Finapres-Dinamap MAP difference (see text for details).

* $P < 0.05$ *versus* corresponding normotension value.

† $P < 0.01$ *versus* corresponding "corrected" value.

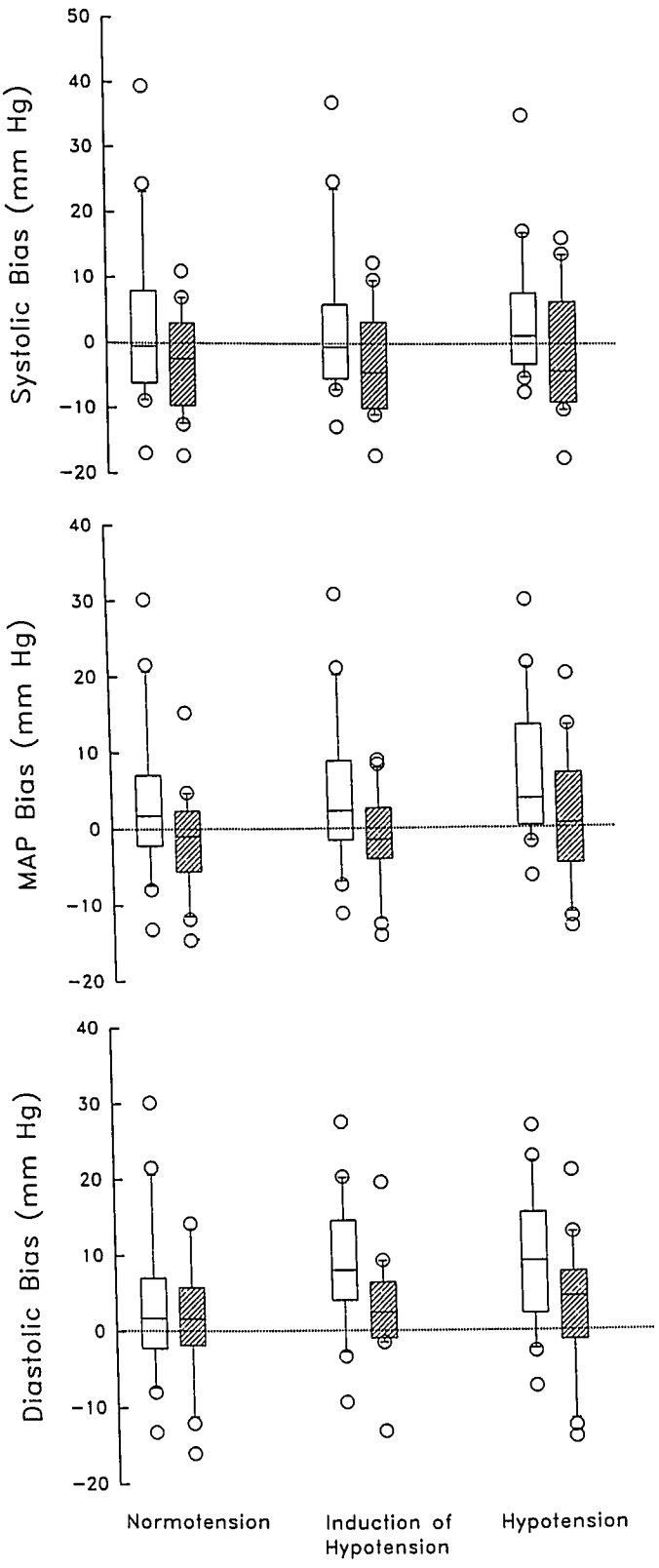


FIG. 1. Box plots of bias (open bars) and "corrected" bias (hashed bars) in Finapres systolic, mean, and diastolic blood pressure relative to directly measured radial arterial pressures during normotension, induction of hypotension, and hypotension. The 10th and 90th percentiles are delimited by the bars, and the 25th and 90th percentiles by the ends of the boxes. The median is marked by the solid horizontal line within the box. Data points outside the 5th and 95th percentiles are displayed as open circles.

When data from all three recording epochs were combined, the precisions for systolic, mean, and diastolic pressure were 9.8 ± 9.0, 8.7 ± 7.6, and 10.4 ± 7.2 mmHg. There were no statistically significant differences for the precision of any pressure variable among the three recording intervals (table 2). In contrast to bias, "correction" of the Finapres pressures did not lead to a statistically significant improvement in precision (table 3).

Despite the low mean bias between Finapres and directly measured radial arterial pressures, there were several patients in whom Finapres pressures showed a marked positive bias between 20–40 mmHg (fig. 1). When the Finapres pressures were "corrected" by the initial Finapres − Dinamap mean pressure difference, these outlying pressures were brought into a more clinically acceptable range (<20 mmHg) (fig. 1). Even after correcting the Finapres pressures, the bias in mean and diastolic pressure was significantly greater during the hypotension period than during the normal blood pressure interval, as was seen using the uncorrected values. The outliers in precision data were from the same patients as were the bias outliers, and their values also decreased to a clinically acceptable range with correction (data not shown).

The distributions of systolic, MAP, and diastolic Finapres − arterial differences *versus* the average of the pressure variable measured by the two devices are displayed in figure 2. Similar plots are presented in figure 3 following "correction" of the Finapres values, as described above. The mean bias in uncorrected *versus* corrected systolic pressure was 3.0 ± 13.5 *versus* −1.7 ± 10.8; for MAP, 5.1 ± 10.9 *versus* 0.2 ± 9.5; and for diastolic pressure, 7.4 ± 10.4 *versus* 2.5 ± 9.5 mmHg. There was no relationship between arterial pressure and systolic, MAP, or diastolic bias.

In figure 3, Finapres and arterial mean pressures are plotted over the three study epochs for a representative patient who demonstrated a relatively large bias. Note the close tracking of arterial pressure by the Finapres, even when pressure was rapidly increasing or decreasing. Although the mean bias for each epoch was similar, the variance increased during the induction and hypotension periods, as demonstrated by the plot of the Finapres − arterial MAP difference. Plots for patients with greater or smaller bias show similar features (data not shown).

Discussion

According to accuracy standards proposed by he Association for the Advancement of Medical Instrumenta-

TABLE 3. Precision and Corrected Precision (Relative to Radial Arterial Pressure) in Finapres Systolic, Mean, and Diastolic Pressures

Epoch	Systolic Precision	MAP Precision	Diastolic Precision
Normotension	10.4 ± 9.8	8.6 ± 8.0	9.7 ± 7.5
Normotension, corrected	8.9 ± 3.7	7.3 ± 4.9	7.1 ± 5.2
Induction of hypotension	9.8 ± 9.3	8.8 ± 6.9	10.5 ± 7.1
Induction of hypotension, corrected	8.4 ± 3.5	6.9 ± 4.6	7.3 ± 4.8
Hypotension	9.3 ± 85	8.6 ± 7.4	10.9 ± 7.5
Hypotension, corrected	10.1 ± 4.1	8.3 ± 5.1	9.0 ± 5.6
All epochs	9.8 ± 9.0	8.7 ± 7.6	10.4 ± 7.2
All epochs, corrected	8.9 ± 3.6	7.3 ± 4.8	5.0 ± 1.9

MAP = mean arterial pressure; "corrected" = Finapres values "corrected" by the initial Finapres-Dinamap MAP difference (see text for details).

No corrected precision was statistically different from uncorrected precision. No statistical differences between precision or corrected precsion for any pressure variable between epochs.

tion (AAMI), for a noninvasive blood pressure device to be considered equivalent to invasively determined arterial pressure, the average bias should be within ± 5 mmHg, and the standard deviation of the bias 8 mm or less.¶ Using uncorrected data, the Finapres satisfied the bias criterion for systolic and mean pressure but exceeded the threshold for diastolic pressure. When corrected data are considered, bias for all three pressure variables are well within the limits. Precision for all pressure variables were outside the acceptable standard for either corrected or uncorrected data. It should be emphasized, however, that the AAMI standards were derived from studies in healthy volunteers under steady-state conditions. The circumstances of our testing procedure were considerably more rigorous, and thus, the AAMI criteria may be unrealistic.

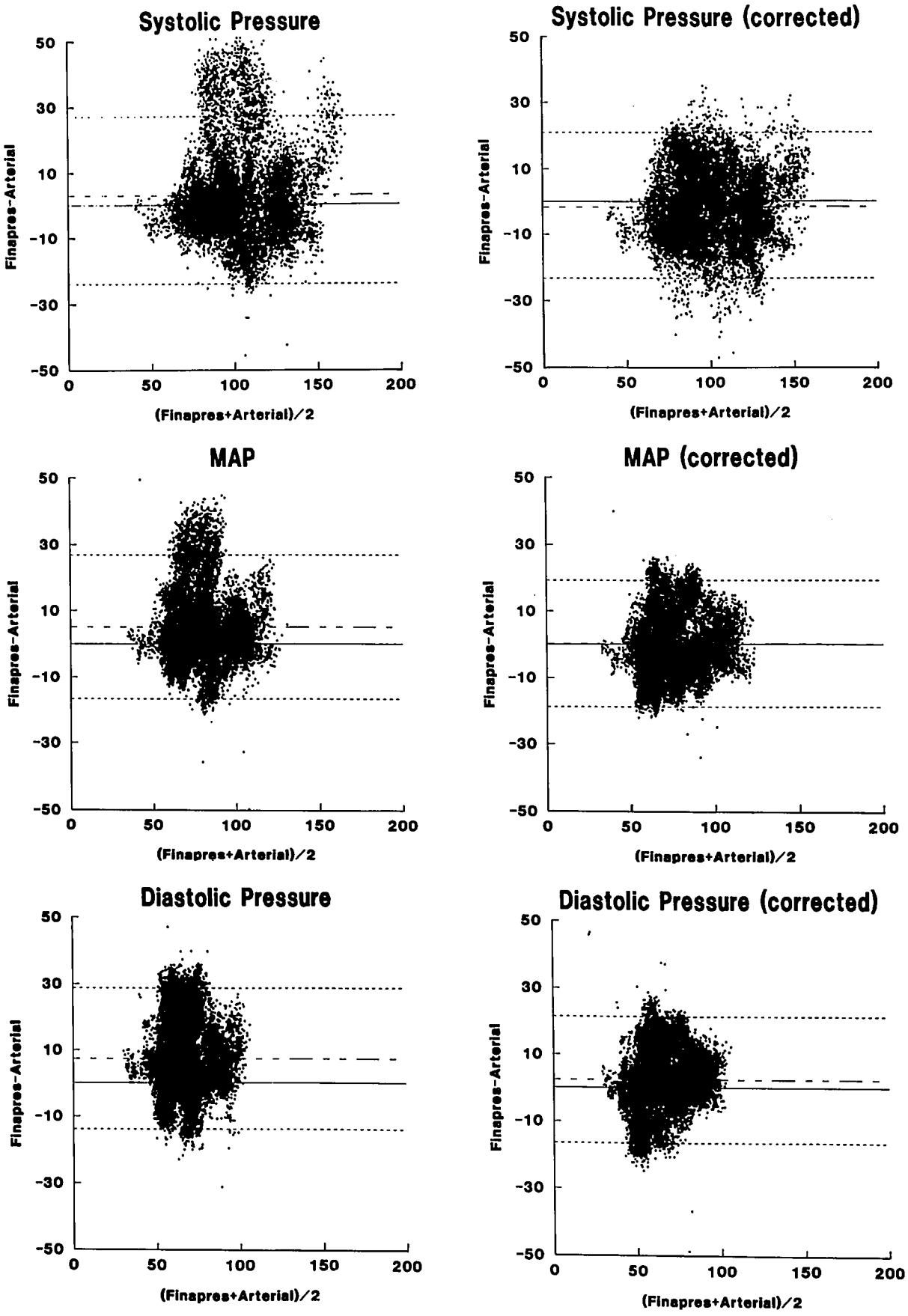
Our data agree with those of Parati *et al.*,[10] who noted a positive bias of similar magnitude in 24 patients at rest. They contradict the data of Molhoek *et al.*,[11] who recorded lower systolic and diastolic finger pressures with a prototype Finapres than brachial artery pressure in 21 hypertensive patients. Gorbeck *et al.*,[12] in a more recent study of 32 patients, using the same statistical methods as we used, found a precision similar to what we determined but noted an overall negative bias of approximately − 5 mmHg. The reason for this difference is not clear, but their patient population was older, had more significant underlying disease, were studied at higher blood pressures, and were not studied during periods in which blood pressure was as labile as in our study. The Finapres, its algorithms, and the finger cuff itself all have undergone improvement over the years; thus, it may not be possible to compare more recent results with those of earlier investigators.

In determining radial arterial pressure, we took great care to minimize catheter-, tubing-, and transducer-related factors that might have lead to distortion of the arterial waveform and consequent inaccurate measurements. The electronic circuits used to measure pressure variables of the module we used (HP 78205D) are identical to those in the HP 78205C (Hewlett-Packard), a module that has been extensively studied *in vitro* and *in vivo*.[4] Even though it incorporates a 12-Hz low-pass filter (which causes electronic damping of the pressure wave and a relatively low frequency response), the HP 78205C demonstrated reduction of errors and reduced variability of systolic pressure measurement. Mean and diastolic pressures, which are much less influenced by changes in damping and frequency response, were also accurately recorded by this module. Therefore, we trust the accuracy of our invasive pressure determinations and believe that the radial arterial pressures we recorded as the reference for this investigation are valid.

That the Finapres had a positive bias cannot be explained by the presence of a catheter in the ipsilateral radial artery. If anything, this should have resulted in decreased flow to the hand and decreased rather than increased the Finapres pressures.[13] One might explain the higher systolic pressures recorded by the Finapres in the finger as a consequence of increasing systolic pressures that are noted as one makes such determinations further down the arterial tree. This phenomenon probably is the

¶ Association for the Advancement of Medical Instrumentation: Appendix C: American national standard for electronic or automated sphygmomanometers. Arlington, Association for the Advancement of Medical Instrumentation, 1987, p 22

FIG. 2. Plots of the difference between Finapres and arterial systolic, mean, and diastolic pressure (bias) *versus* the average of the Finapres and arterial value. In the right-hand column, Finapres values were "corrected" by subtracting the baseline difference between Finapres and arterial MAP at the start of the normotension epoch. The zero-bias line is marked by the solid line, and the mean bias is indicated by the long dashed line. The 2-SD limits of the bias are given by the dotted lines. Seven hundred fifty comparisons for each patient, taken equally from the normotension, induction of hypotension, and hypotension epochs are plotted, for a total of 12,000 points per graph.



result of marked impedance mismatching between larger proximal and smaller distal arteries, which causes wave reflection and systolic pressure augmentation.[14] However, there is no theoretical basis upon which to predict a positive Finapres bias for mean and diastolic pressure, which, in fact, was greater than that demonstrated for systolic pressure.

All Finapres cuffs in this study were carefully applied by the senior investigator (R.H.E.) according to instructions provided in the Finapres manual. Therefore, we do not attribute our findings to operator variability or inexperience.

Despite the generally satisfactory performance by the Finapres, the statistics obscure what we believe is an important concern: in a clinically significant number of patients (2 of 16), there were large (20–40-mmHg) differences between the Finapres and radial arterial pressures. In our previous investigations, we demonstrated a similar incidence (20%) of large differences between the Finapres and oscillometric blood pressure.[2,3] This problem limits the usefulness of the Finapres as a stand-alone pressure monitor. However, even in the outliers in this study, the Finapres very closely tracked changes in pressure. By "correcting" all Finapres values by the difference between baseline oscillometric MAP and Finapres MAP, bias was reduced to less than 20 mmHg in all patients, and average bias for each pressure variable was reduced to less than 3 mmHg.

Examination of the plots in figure 3 reveals the presence of the outlier data, clustered above the line for mean bias + 2 standard deviations. The improvement in the distribution of bias values as a result of the correction process is also clearly evident.

For clinical use, we suggest comparison of several oscillometric mean blood pressure measurements to Finapres mean pressure during a stable period at the onset of monitoring to identify those patients in whom a large Finapres bias is present, and adjustment of displayed Finapres values by this difference. Periodic examination of this oscillometric − Finapres mean blood pressure difference may be even more useful in improving the accuracy of the finger pressure monitor. Since oscillometric blood pressure can be accurately measured from the thumb,[6] it is possible that periodic, automated autocorrelation could be designed into subsequent releases of the Finapres and that this might improve the accuracy of the device. As another strategy, in patients in whom a large Finapres − oscillometric MAP difference exists, one may choose to simply use the Finapres qualitatively as a trend monitor and base clinical judgments on quantitative blood pressure values reported by an oscillometric device. Alternatively, one may elect to place an arterial catheter.

We previously postulated that a problem with Finapres cuff design is the cause for the large pressure biases noted in some patients.[2,3] It may be that in certain individuals, the intracuff pressure is incompletely transmitted to the digital arteries, requiring a pressure higher than that within the arteries to keep their size constant. By way of analogy, falsely elevated values are also noted when too small a cuff is applied to the arm and pressure determined by Korotkoff sounds or by oscillometric devices.

We believe that the Finapres is a potentially useful continuous noninvasive blood pressure monitor because of its ability to closely track arterial pressure, even in patients with extremely large biases. In the great majority of patients, it demonstrates acceptable clinical accuracy during

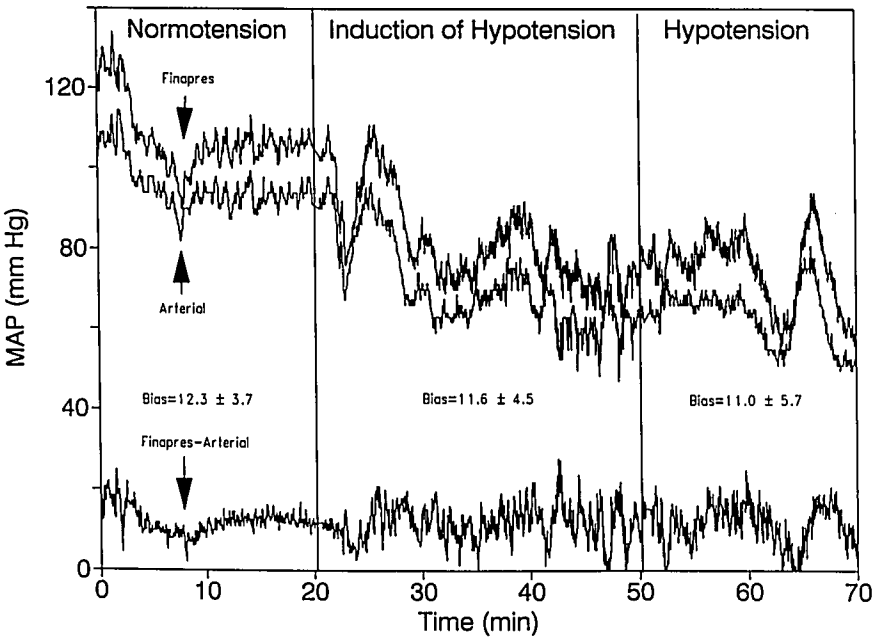


FIG. 3. Finapres MAP (upper line) and arterial MAP (middle line) from a typical patient with a relatively large bias over the three study epochs. In the lower line, the difference between Finapres and arterial MAP is plotted. The mean bias ± SD for each study period is also displayed. Despite the relatively large positive Finapres bias, the Finapres accurately tracked sudden changes in blood pressure.

periods of normotension and controlled hypotension. Its performance during hemorrhagic shock requires further study. Engineering enhancements of cuff design and perhaps an internal correction method similar to that which we have presented may lead to even better accuracy, and should be pursued.

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