COMPARISON OF INVASIVE AND NON-INVASIVE MEASUREMENT OF CONTINUOUS ARTERIAL PRESSURE USING THE FINAPRES

D. N. STOKES, T. CLUTTON-BROCK, C. PATIL, J. M. THOMPSON AND P. HUTTON

SUMMARY
A comparison was made of arterial pressures measured invasively from a radial arterial cannula and non-invasively from the middle finger using the 2300 Finapres (Ohmeda) during induction and maintenance of anaesthesia. Digital outputs of both pressures were captured directly onto computer hard disk; data recorded during flushing of the arterial line were excluded from analysis. We studied 53 patients undergoing cardiac, major vascular and neurosurgical procedures; 17705 comparisons of systolic, diastolic and mean pressure were analysed. Overall correlations between Finapres and invasive pressures were poor ($r = 0.82$, 0.68 and 0.78 for systolic, diastolic and mean pressures, respectively). The Finapres exhibited a high level of accuracy and precision in some recordings. However, patient data sets showed marked variability in average pressure differences (invasive minus Finapres) when examined individually or grouped by operation type. Unexplained variations in pressure difference with time and absolute pressure were observed also. Whilst providing useful beat-to-beat information on arterial pressure trends, the Finapres cannot be recommended as a universal substitute for invasive arterial pressure monitoring.

KEY WORDS

Invasive beat-to-beat arterial pressure monitoring is practised widely in anaesthesia and intensive care. Although it is considered generally to be a low-risk, high-benefit monitoring technique [1], serious complications may develop after radial artery cannulation [2]. In 1973, Penaz described a method whereby a continuous non-invasive arterial pressure waveform could be obtained from a finger cuff [3]. This idea was developed by the Dutch Biomedical Instrumentation Group of TNO [4] and the first prototype finger arterial pressure monitor (Finapres; Ohmeda) emerged in 1982 [5].

The finger cuff incorporates a photo-plethysmograph with an infra-red light emitter and detector. The wavelength detected is characteristic of that absorbed by haemoglobin, allowing arterial pulsations to be sensed. The principle of operation involves "volume-clamping" of the finger whereby cuff pressure is adjusted rapidly under feedback control to keep the infra-red signal at constant amplitude and hence the finger at constant blood volume over the arterial pressure cycle. Initially, the cuff pressure is inflated in steps until the maximum amplitude pulsation is recorded (open-loop mode), which is taken to be equivalent to mean arterial pressure. Thereafter a servo control loop with a delay time of 10 ms rapidly adjusts finger cuff pressure to keep the intensity of the infra-red signal constant (closed-loop mode). In order to do this, cuff pressure must balance digital intra-arterial pressure over the whole pressure cycle, hence keeping the transmural pressure across the arterial wall at zero. Fluctuations in cuff pressure are transduced...
and displayed as a continuous waveform. The servo control system is adjusted automatically every 1 min during operation to compensate for changes in finger interstitial fluid and blood volume and changes in arterial smooth muscle tone. The digital display of pressure may be updated “beat-by-beat” or averaged over 6 s.

A clinical evaluation of the 2300 Finapres (FINger Arterial PRESSure; Ohmeda) Blood Pressure Monitor is described using a computer-based system during induction and maintenance of anaesthesia. The aim of this study was to establish if the data obtained by the Finapres are sufficiently reliable to form a basis on which clinical management decisions can be made.

PATIENTS AND METHODS

Patients undergoing induction of anaesthesia for cardiac, major vascular and neurosurgery were studied. These subjects were chosen primarily because they routinely undergo arterial cannulation before the induction of anaesthesia. Furthermore, an opportunity was afforded to compare the performance of the Finapres in healthy (neurosurgical) and diseased (cardiac and vascular) cardiovascular systems at a time of hemodynamic instability. Further recordings during maintenance of anaesthesia were undertaken in neurosurgical patients over a period of up to 3 h. No patient received vasoactive drugs during the study. Anaesthetic techniques were not standardized.

Measurement of pressures

Direct intra-arterial pressure was measured from the radial artery of the non-dominant hand after insertion of a 20-gauge Teflon catheter (Abbocath or Viggo) connected via a 1.2-m long, 1.5-mm diameter extension to a disposable transducer (CR Medicals, Bordon). Before each case, the transducer was fixed at the level of the Finapres electropneumatic transducer then zeroed and calibrated to 200 mm Hg using a mercury column. The arterial waveform was displayed on a Hewlett-Packard 78353B monitor. Calibration was checked also after each set of recordings. The frequency response of the system was flat to 12 Hz.

Non-invasive pressure was measured with a pre-calibrated 2300 Finapres Blood Pressure Monitor (Ohmeda). The Finapres cuff was applied to the middle phalanx of the middle finger on the same side or side opposite to the arterial line after measurement of finger circumference. A medium sized cuff was applied unless an unsatisfactory fit was obtained, in which case a more appropriately sized cuff was used. The box containing the Finapres electropneumatic transducer was strapped to the back of the hand, which rested by the patient’s side during recordings. Both transducers were secured throughout the study period. The Finapres digitized output was set to “beat-to-beat”. Recordings were commenced after a stable Finapres signal had been obtained and discontinued at the time when the patient was transferred to the operating theatre. Maintenance recordings were commenced after positioning the patient for surgery and discontinued after 3 h or at completion of surgery.

Data collection

Simultaneous digitized outputs from the Hewlett-Packard 78353B monitor and Finapres RS232C interface were stored as ASCII files on the hard disk of a Hermes 100 IBM-compatible PC (fig. 1) using a program developed in this department by one of the authors (C.P.). This program captured simultaneously systolic, mean and diastolic pressures from both sources, together with other variables such as heart rate. A sampling interval of 3 s was selected for induction recordings and 30 s for maintenance recordings.

Data handling

Data files for each patient were re-formatted for statistical analysis using statistical software packages (Statgraphics: Statistical Graphics Corporation; Minitab: Minitab Inc.; Complete Statistical System: Statsoft). Artefactual values recorded during flushing or sampling from the arterial line were edited out of each recording. Readings during the Finapres “lock-out” routine which occurs once every 70 beats were not edited—the Finapres displays the values for the preceding beat during this procedure.

Various aspects of the performance of the Finapres were investigated by analysis of the resulting data:

1. To assess if the Finapres gave a good overall estimate of radial arterial pressure, linear regression was performed on all systolic, diastolic and mean pressure comparisons and 95% confidence intervals were calculated for the line. In view of the considerable inter-individual variability, further analysis was undertaken in order to
establish how accurate, precise and reproducible Finapres readings were in individual patients.

(2) Systolic, diastolic and mean pressure differences (invasive minus Finapres readings) were calculated for each individual patient record. The average of this difference for each record was plotted against its SD in order to display the scatter of the data. Further analyses examined the influence of cuff size, finger circumference, cuff position and type of surgery on between-patient variability.

(3) The pressure differences were plotted against their averages [6] and the "limits of agreement" (mean (2 SD)) were calculated to assess variability with changing pressure.

(4) Time series plots of paired invasive and non-invasive pressures (systolic, diastolic and mean) were displayed from each recording. Time series analysis of the differences between each pair of pressures (invasive minus Finapres) was undertaken to investigate temporal variability.

(5) Simultaneous first order differential pressures were calculated at 30-s intervals for each pressure and displayed as scatterplots of invasive vs Finapres differential pressure (systolic, diastolic and mean) for each record. The frequency with which changes in Finapres readings occurred in phase with changes in invasive readings (i.e. an increase in Finapres pressure accompanied by a simultaneous increase in invasive pressure and vice versa) was calculated for each record. This analysis established how often Finapres and invasive pressures moved in the same direction simultaneously.

Data were analysed using Spearman's rank correlation coefficient and Fisher's exact, chi-square, Mann–Whitney and unpaired Student's t test where appropriate.

**RESULTS**

We studied 53 patients (age range 18–75 yr) (table I). The Finapres displayed a waveform which resembled an arterial pressure trace in all cases. Finapres and invasive pressures were measured from the same arm in 24 patients (45.3%). Finger circumference was in the range 38–73 mm, but did not differ significantly between patients grouped by operation type (P > 0.05). A total of 17705 comparative pressure readings was available for statistical analysis.

**Linear regressions**

Linear regression analysis between the Finapres and invasive pressure measurements of all paired systolic, diastolic and mean pressures demonstrated correlation coefficients of r = 0.82, 0.68 and 0.78, respectively (fig. 2). Clearly, the Finapres does not always reflect invasive arterial pressure faithfully in all patients.
Table I. Details of patients studied. Numbers in parentheses denote the number of patients within each group in whom Finapres data and invasive pressure were measured from the same arm. *S* = Small; *M* = medium; *L* = large

<table>
<thead>
<tr>
<th>Operation</th>
<th>No. patients (M/F)</th>
<th>Mean age (yr)</th>
<th>Induction</th>
<th>Maintenance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neurosurgical</td>
<td>11/9</td>
<td>49.6</td>
<td>15 (7)</td>
<td>19 (6)</td>
</tr>
<tr>
<td>Cardiac (CABG)</td>
<td>13/3</td>
<td>60.3</td>
<td>16 (5)</td>
<td>—</td>
</tr>
<tr>
<td>Cardiac (valve)</td>
<td>8/4</td>
<td>53.7</td>
<td>12 (8)</td>
<td>—</td>
</tr>
<tr>
<td>Major vascular</td>
<td>4/1</td>
<td>62.8</td>
<td>5 (4)</td>
<td>—</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Finapres cuff size</th>
<th>S</th>
<th>M</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>18</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>—</td>
<td>—</td>
<td>5</td>
</tr>
</tbody>
</table>

**Fig. 2.** Linear regression lines (with 95% confidence limits (CL) about the mean) for all comparisons (*n* = 17705) of Finapres and invasive monitoring of systolic, diastolic and mean arterial pressures in the study population. Systolic: *r* = 0.82; *y* = 0.92x - 2.37; 95% CL = ±34.1 mm Hg. Diastolic: *r* = 0.68; *y* = 0.95x + 2.75; 95% CL = ±28.3 mm Hg. Mean: *r* = 0.78; *y* = 0.96x - 1.43; 95% CL = ±27.5 mm Hg.

**Between-patient variability**

In order to examine the variability between individual patients, the average pressure difference (invasive minus Finapres) for each patient was plotted against its sd. Separate scatterplots were obtained for systolic, diastolic and mean pressures (figs 3–5). They show considerable...
scatter in the accuracy (average difference) and precision (SD) of the Finapres. The American National Standards Institute (ANSI) has recommended limits for the accuracy of automated non-invasive arterial pressure devices when compared with invasive pressure [7] and these were superimposed onto the scatterplots. Only 11.9, 29.9 and 28.4% of patient records fulfilled the ANSI recommendations for systolic, diastolic and mean pressure differences, respectively. Diastolic pressure differences showed less variability than systolic or mean differences. The predominance of positive systolic average pressure differences demonstrates that the Finapres under-reads systolic pressure in many cases.

Finapres cuff size, cuff position and type of surgery (with the exception of major vascular procedures) had no effect on the proportion of patient recordings which conformed to ANSI standards (Fisher's exact and chi-square tests). However, these factors undoubtedly accounted for some of the observed variability. Under-reading of systolic pressure was significantly greater when large finger cuffs were used (unpaired Student's t test). There was no relationship between finger circumference and the magnitude of the average pressure difference (correlation coefficients r = 0.25, 0.1 and 0.14 between finger circumference and systolic, diastolic and mean pressure differences, respectively). Positioning of the Finapres cuff in relation to the radial arterial cannula (contralateral or ipsilateral) was responsible for variability between patients undergoing the same type of operative procedure. When contralateral and ipsilateral cuff placements were compared, averaged pressure differences (Finapres minus invasive) differed significantly within each group of operative procedures except systolic and diastolic pressures during induction for neuro-
surgical procedures (unpaired Student's t test; Mann-Whitney test). There was no consistent pattern to the observed differences.

There were significant between-group differences for all comparisons made of pressure differences grouped by operation type (fig. 6). Recordings from neurosurgical cases during induction of anaesthesia showed the greatest scatter of readings. Scatter was least marked for recordings from major vascular cases, probably because of the small number of patients in this group.

Variability with pressure

To investigate the accuracy and precision of the Finapres over a range of pressures, the pressure differences were plotted against simultaneous average pressure for individual patient records using the method recommended by Bland and Altman [6]. Considerable bias was observed in many of the resulting plots. In more than 50% of the individual plots for systolic, diastolic and mean pressures there was no relationship between pressure difference and average pressure. The remaining plots displayed a variety of relationships. The pressure difference decreased with increasing average pressure in 25% of cardiac (CABG) patient records (fig. 7) and showed increased scatter with increasing average pressure in 47% of records from patients undergoing major vascular surgery (fig. 8).

Variability with time

Time series plots of systolic, diastolic or mean absolute comparative pressures and pressure differences during maintenance recordings demonstrated marked variability in pressure difference with time. Baseline drift characterized by a decreasing pressure difference was identified in 53% of recordings when the trend was not obscured by fluctuations attributable to variations in absolute pressure. Baseline drift averaged 7.8 mm Hg h⁻¹ (range 2.5 to 15 mm Hg h⁻¹) affecting systolic, diastolic and mean pressure differences to a similar extent (fig. 9) in all but one recording. No baseline drift was identified in the calibration of the invasive pressure measurement system, suggesting that Finapres readings increased in magnitude relative to invasive measurements over time.

Reliability of trend information

To establish if trend information from the Finapres was reliable, 6467 comparative Finapres
and invasive first order pressure differentials were analysed from all patient records. Finapres and invasive comparisons of systolic, diastolic and mean differential pressure were in phase for 81.1, 84.4 and 85.6% of readings, respectively. Conversely, this analysis implies that Finapres pressure was increasing whilst invasive pressure was decreasing (or vice versa) for 18.9, 15.6 and 14.4% of readings of systolic, diastolic and mean pressure, respectively. Finapres systolic pressure was less likely to follow invasive pressure than mean or diastolic pressures in all patient groups (table II), but differences were not significant (chi-square).

**TABLE II. Number (%) of first order differentials of Finapres pressures moving in the direction opposite to the simultaneous differentials of invasive pressure readings (no significant differences; chi-square test)**

<table>
<thead>
<tr>
<th>Operation</th>
<th>Total</th>
<th>Systolic (%)</th>
<th>Diastolic (%)</th>
<th>Mean (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiac Valves</td>
<td>785</td>
<td>126 (16.1)</td>
<td>132 (16.8)</td>
<td>98 (12.5)</td>
</tr>
<tr>
<td>CABG</td>
<td>1106</td>
<td>206 (18.6)</td>
<td>153 (13.8)</td>
<td>158 (14.3)</td>
</tr>
<tr>
<td>All</td>
<td>1891</td>
<td>332 (17.6)</td>
<td>285 (15.1)</td>
<td>256 (14.3)</td>
</tr>
<tr>
<td>Major vascular</td>
<td>378</td>
<td>56 (14.8)</td>
<td>32 (8.5)</td>
<td>40 (10.6)</td>
</tr>
<tr>
<td>Neurosurgical</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Induction</td>
<td>337</td>
<td>58 (17.2)</td>
<td>47 (14.0)</td>
<td>41 (12.2)</td>
</tr>
<tr>
<td>Maintenance</td>
<td>3861</td>
<td>74 (20.1)</td>
<td>645 (16.7)</td>
<td>592 (15.3)</td>
</tr>
<tr>
<td>All</td>
<td>4198</td>
<td>832 (19.8)</td>
<td>692 (16.5)</td>
<td>633 (15.1)</td>
</tr>
<tr>
<td>Totals</td>
<td>6467</td>
<td>1220 (18.9)</td>
<td>1009 (15.6)</td>
<td>929 (14.4)</td>
</tr>
</tbody>
</table>
Examination of time series plots did not demonstrate any consistent phase lag between Finapres and invasive pressure changes to account for these discrepancies.

**DISCUSSION**

Clearly, digital arterial pressure differs from that measured in the radial or brachial arteries and this difference has not been characterized in man. In order to be accepted as a basis for making clinical decisions, the Finapres must be shown to display values which are identical or approximate closely to readings obtained from either an indwelling catheter or a brachial cuff. It is therefore logical to compare Finapres and intra-arterial readings.

Since Wesseling developed the first Finapres device in 1982, studies comparing its accuracy with directly measured arterial pressure have been published by several groups [8–11]. Whilst being informative, these studies have shortcomings and are of limited relevance to the clinical application of the Finapres. All used analog signals for data collection and output was sampled either at predetermined points [8-10] or over a limited period of time [11]. Smith, Wesseling and de Wit [8] analysed mean pressure comparisons only during stable anaesthesia. In the present study, digitized outputs from Finapres and invasive monitors were captured directly onto computer hard disk (fig. 1). Little attempt was made to edit our data, other than rejecting artefactual values recorded by the Hewlett-Packard monitor during flushing of the arterial cannula. All the remaining pressure recordings were included for analysis. The resulting comparisons constitute a true reflection of the performance of the Finapres in anaesthetic practice. Furthermore, no previous studies have assessed the Finapres during induction of anaesthesia, when large changes in arterial pressure occur rapidly.

Statistical analysis in previous studies [8–10] has centred on linear regression and correlation, which have been shown to be inappropriate when comparing two measurement techniques which are subject to variability [6].

Several fundamental requirements of a non-invasive continuous monitoring system merit further discussion in relation to the Finapres.

**Quality of signal, accuracy and precision**

Assessment was made of the ease with which a reliable signal could be obtained in different patients, including groups with low cardiac outputs and abnormal peripheral vasculature. In all patients studied, a recognizable waveform was obtainable, within 1 min of activating the Finapres when an appropriately sized finger cuff had been applied. Under-reading of systolic pressure by the Finapres was apparent in cardiac patients and those with arteriopathies, compared with neurosurgical patients ($P < 0.05$).

The morphology of the systemic arterial waveform depends on the site of measurement in the arterial tree. More distal readings should be characterized by a smaller mean pressure, a change in shape caused by pulse wave reflections, increased damping and a wider pulse pressure [8]. Paradoxically, narrower pulse pressures were obtained using the Finapres compared with invasive measurements in cardiac patients and arteriopathies. Low cardiac output associated with compensatory increases in peripheral vascular resistance could explain these findings, although diastolic pressures did not differ as greatly as systolic pressures. Vasocostriction induced by the infusion of phenylephrine has been shown to reduce mean arterial pressure measured by the Finapres without affecting invasive pressure [9].

Significant within-group differences were observed between readings obtained from contralateral and ipsilateral cuff placement in cardiac and major vascular patients ($P < 0.05$). Possible explanations include between-arm differences in systemic arterial pressure and reductions in blood flow distal to a cannulated radial artery. Finapres readings usually returned to pre-cannulation values within 4 min of radial artery cannulation [12], so the effects of insertion of an arterial cannula do not explain these differences. Furthermore, averaged Finapres readings of systolic, diastolic and mean pressure were greater than invasive pressures when measured in the cannulated arm of cardiac patients.

There are no internationally recognized standards for assessing the performance of automated non-invasive arterial pressure devices. The American National Standards Institute [7] have suggested that a mean difference of no greater than ±5 mm Hg with an SD of 8 mm Hg should exist between readings obtained from the device under test and the standard device. The standard makes allowances for the true mean errors inherent in both standard and test devices and it is accepted that performance cannot be guaranteed
at any particular pressure in any particular patient. In the present study, fewer than 33% of mean and diastolic, and only 10% of systolic recordings obtained with the Finapres conformed to these standards (figs 3–5). These proportions were not influenced by site of cuff placement (ipsilateral or contralateral), size of cuff (small, normal or large) or type of surgery. Whether or not ANSI standards formulated to evaluate devices using a cuff on the upper arm are applicable to a finger cuff non-invasive system, is open to question.

It is also interesting to contrast the performance of the Finapres with other non-invasive methods which have been tested against intra-arterial readings. From studies on the Korotkoff sounds [13], the oscillotonometer [14], and the Dinamap [15], it is apparent that the population regression equations produced by the Finapres (fig. 2) are superior in both intercept and slope, but have wider 95% confidence limits. Furthermore, the Finapres has less tendency to under-read high and over-read low arterial pressures. The oscillotonometer and Korotkoff sounds are subject to observer bias and results obtained from the studies undertaken probably are unlikely to be bettered. It is therefore difficult to deduce the true comparative performance in everyday practice. The Dinamap is an automated device and its 95% confidence limits on the population readings of ±16.4, ±16.1 and ±15.3 mm Hg for systolic, mean and diastolic pressures, respectively are considerably narrower than those obtained from the Finapres (fig. 2).

Consistency of performance of the Finapres was assessed during rapid changes in arterial pressure associated with induction of anaesthesia. Accurate continuous measurement of acute fluctuations in arterial pressure is the prime indication for invasive arterial monitoring in clinical practice. The Finapres did reflect accurately the rapid changes in intra-arterial pressure in most neurosurgical and major vascular surgery patients, but results were less satisfactory for cardiac patients. The pressure differences (systolic, diastolic and mean) between Finapres and invasive values showed matching fluctuations when the absolute pressure changed acutely (fig. 9). No consistent relationship could be demonstrated between absolute pressure and the magnitude of the pressure difference, although various patterns were identifiable. Occasionally, marked discrepancies in pressure difference occurred for no apparent reason.

Baseline drift

Finapres trend performance was assessed by comparison with intra-arterial pressure readings over several hours in patients undergoing neurosurgery. Systolic, diastolic and mean pressure differences exhibited matching baseline drift away from zero in just under 50% of recordings (fig. 9).

Trend analysis

Data were analysed to indicate the probability that a change in pressure recorded by the Finapres was accompanied by a change in invasive pressure in the same direction (but not necessarily of the same magnitude). This analysis suggested that diastolic and mean Finapres pressures were more likely than systolic pressure to change in phase with invasive pressure, for all patient groups (table II). The Finapres did follow changes in invasive pressure in 83% of all the comparisons made.

In conclusion, the 2300 Finapres non-invasive arterial pressure monitor displayed changes in intra-arterial pressure with a performance comparable to other non-invasive methods, but with considerable inter-individual variability in absolute pressure readings. Although the present study failed to identify clear relationships between patient or technical factors and the observed variability in performance of the Finapres, between- and within-patient differences in cardiac output and peripheral resistance may be important. Further investigation of the patient–cuff interface is also warranted. In view of these findings, the Finapres cannot be recommended at present as an alternative to invasive arterial pressure monitoring in clinical practice or clinical research. However, the Finapres does provide valuable information regarding trends in arterial pressure in patients in whom conventional non-invasive monitoring would be the method of choice, and has the advantage of displaying beat-to-beat recordings.

REFERENCES


