Comparison of Finger and Intra-arterial Blood Pressure Monitoring at Rest and During Laboratory Testing

Gianfranco Parati, Roberto Casadei, Antonella Groppelli, Marco Di Rienzo, and Giuseppe Mancia

The accuracy of blood pressure values obtained by continuous noninvasive finger blood pressure recording via the FINAPRES device was evaluated by comparison with simultaneous intra-arterial monitoring both at rest and during performance of tests known to induce fast and often marked changes in blood pressure. The comparison was performed in 24 normotensive or essential hypertensive subjects. The average discrepancy between finger and intra-arterial blood pressure recorded over a 30-minute rest period was 6.5±2.6 mm Hg and 5.4±2.9 mm Hg for systolic and diastolic blood pressure, respectively; a close between-method correspondence was also demonstrated by linear regression analysis. The beat-to-beat changes in finger systolic and diastolic blood pressure were on average similar to those measured intra-arterially during tests that induced a pressor or depressor response (hand-grip, cold pressor test, diving test, Valsalva maneuver, intravenous injections of phenylephrine and trinitroglycerine) as well as during tests that caused vasomotor changes without major variations in blood pressure (application of lower body negative pressure, passive leg raising). The average between-method discrepancy in the evaluation of blood pressure changes was never greater than 4.3 and 2.0 mm Hg for systolic and diastolic blood pressure, respectively; the corresponding standard deviations ranged between 4.6 and 1.6 mm Hg. Beat-to-beat computer analysis of blood pressure variability over the 30-minute rest period provided standard deviations almost identical when calculated by separate consideration of intra-arterial and finger blood pressure tracings (3.7 and 3.8 mm Hg, respectively). The two methods of blood pressure recording also allowed similar assessments of the sensitivity of baroreceptor control of heart rate (vasoactive drug injections) and blood pressure (neck chamber technique) to be obtained. Thus, beat-to-beat blood pressure recording via FINAPRES provides an accurate estimate of means and variability of radial blood pressure in groups of subjects and represents in most cases an acceptable alternative to invasive blood pressure monitoring during laboratory studies. (Hypertension 1989; 13:647-655)

In the early 1970s a Czech physiologist, Ian Peñaz, described a new approach to continuous noninvasive recording of blood pressure at the finger level, based on a volume-clamp method. This device was improved in its technical aspects (finger plethysmograph of reduced dimension, feedback system for finger volume control, and automatic calibration) by Wesseling and coworkers, resulting in an instrument called “FINAPRES” (from FINger Arterial PresSure). In preliminary studies performed in patients undergoing surgery, FINAPRES was shown to provide blood pressure values close to those simultaneously recorded intra-arterially.

Our study was undertaken to evaluate the accuracy of FINAPRES in reproducing intra-arterial blood pressure values in a large number of subjects. Because the potential importance of this method resides in its ability to provide noninvasively a beat-to-beat estimate of rapid blood pressure changes, we compared FINAPRES and intra-arterial blood pressures not only in resting conditions but also during a number of laboratory maneuvers that caused rapid and pronounced blood pressure rises and falls. The comparison included the standard deviation of relatively prolonged blood pressure tracings to assess the ability of FINAPRES to measure an important feature of blood pressure, variability.
Subjects and Methods

Subjects

The study was performed 1 week after admission to hospital in 17 subjects with uncomplicated essential hypertension and in 8 normotensive subjects affected by noncardiovascular diseases. In each subject blood pressure was recorded with the FINAPRES device, and the data were compared with those simultaneously recorded from the radial artery of the same or the contralateral side. However, because the quality of the finger pressure recording was unsatisfactory in one hypertensive patient, only data collected in 24 subjects (19 men, five women; mean age 48.2 years, range 25–64 years) were processed. The subjects were given no cardiovascular drugs at the time of the study, and hypertensive patients had discontinued their therapy at least 15 days before the study period. The protocol of the study was approved by the ethical committee of our institute, and each subject entered the study only after giving informed consent.

Hemodynamic Recordings

The intra-arterial blood pressure signal was obtained by a catheter (11 cm length, 1.3 mm i.d.) that was introduced percutaneously into a radial artery after local anesthesia with 2% lidocaine. The catheter was connected by a rigid polyethylene tube to a Statham transducer (P23ID, Oxnard, California), and signal was recorded on a Grass polygraph (Grass Equipment, Quincy, Massachusetts) to allow calculation of beat-to-beat systolic blood pressure, diastolic blood pressure, and mean blood pressure (which was obtained by electronic damping of the pulsatile tracing). The intra-arterial signal was also sent to a Racal recorder (Racal Recorders Limited, Hythe, Southampton, UK) and stored on magnetic tape.

The finger pressure recording was obtained by the Model n.5 prototype of the FINAPRES device (TNO, Academic Medical Centre, Amsterdam, The Netherlands), a version of which is commercially available as Ohmeda 2300 FINAPRES blood pressure monitor (Ohmeda Monitoring Systems, Englewood, Colorado).

The FINAPRES method has been described in detail elsewhere. Briefly, the instrument operates through a small finger cuff equipped with an infrared photoplethysmograph to measure the arterial blood volume under the inflatable cuff. The cuff is connected with a front-end box wrapped to the patient’s hand. The box contains a fast proportional pneumatic valve, connected with a source of compressed air, an electropneumatic transducer, and the electronics for the photoplethysmograph. The arterial blood volume, as assessed by the photoplethysmograph, is clamped at a set point value corresponding to two-thirds of the maximum arterial volume by adjustment of the cuff pressure in parallel with the intra-arterial pressure through a fast-reacting electropneumatic servo system, with a bandwidth of at least 40 Hz. The volume-clamp set point is periodically adjusted to keep the finger arteries fully unloaded at zero transmural pressure and to allow the cuff pressure to continuously reflect intra-arterial pressure. In 19 subjects the cuff was wrapped around the middle or ring finger of the hand ipsilateral to that from which the intra-arterial signal was derived. In the remaining five subjects it was wrapped on the hand opposite to that instrumented with the intra-arterial catheter because ipsilateral measurements were technically unfeasable. In these subjects the between-arm difference in sphygomanometric blood pressure, as assessed three times by two observers who switched both arms and cuffs, was always less than 5 mm Hg.

Throughout the study, the finger equipped with the FINAPRES cuff was kept at the same level as the transducer to which the intra-arterial blood pressure signal was directed.

Protocol

The study started 15 minutes after insertion of the radial artery catheter and proper positioning of the finger cuff. First, during a 30-minute period when the subjects were lying quietly, blood pressure was measured by the two methods (resting conditions); then it was measured before and during performance of tests that raised blood pressure either by directly induced vasoconstriction (intravenous bolus of 100 μg phenylephrine) or by an increase in sympathetic drive induced by 1) stimulation of skeletal muscle receptors by a hand-grip exercise performed at 40% of subject’s maximal strength for 90 seconds with the hand contralateral to the one instrumented with the blood pressure monitoring devices, 2) stimulation of skin receptors by immersion of the noninstrumented hand in ice water for 60 seconds, and 3) trigeminal and chemoreceptor stimulation by immersion of subject’s face into ice water for 15–20 seconds. The blood pressure signal obtained by the two methods was further assessed during 1) the mechanical and reflex changes in blood pressure that accompanied a Valsalva maneuver that was performed by blowing into a plastic tube connected to a mercury manometer to raise the mercury column by 40 mm Hg for 20 seconds, 2) the fall in blood pressure accompanying the vasodilatation induced by an intravenous bolus of 100 μg nitroglycerine, and 3) the rise and fall in blood pressure induced by deactivating or stimulating carotid baroreceptors through 2-minute applications of three positive and three negative pressures in a neck chamber within the range of ±40 mm Hg. These tests were complemented by the assessment performed before and during a 20-minute deactivation of cardiopulmonary receptors (application of −40 mm Hg pressure to the lower body) and a 20-minute stimulation of cardiopulmonary receptors (passive elevation of the legs to 60°) that caused peripheral vasoconstriction and vasodilatation.
respectively, in the absence of marked blood pressure changes.

All tests were applied randomly; each was performed twice and spaced from the preceding one by at least 15 minutes. Except for diving, all tests were given to at least 9-10 subjects to have a sufficiently large data base for comparison.

Data Analysis

Resting conditions. The intra-arterial blood pressure tracing obtained in the resting condition was analyzed by manual calculation of the average systolic and diastolic values of 20-second periods, which were regularly taken at 3-minute intervals to obtain mean values for the 30-minute recording. Furthermore, the blood pressure tracing stored on magnetic tape was digitized on 12 bits by a computer (Digital PDP 11/23), which sampled the signal at 165 Hz. The digitized signal was stored on a magnetic disk and edited by means of an interactive program to eliminate possible morphological artifacts (e.g., arrhythmias or reduced amplitude of the

intra-arterial tracing). Average mean blood pressure values of each minute recording were calculated, and the corresponding standard deviations were further averaged to obtain a measure of the tendency of blood pressure to vary within very short time intervals. The finger blood pressure signal was edited and analyzed in an identical fashion.

Responses to laboratory tests. The changes in intra-arterial blood pressure induced by the various tests were calculated by averaging systolic and diastolic blood pressure values during a 20-second period taken 1 minute before the test and comparing them with the average blood pressure values measured in the final 10 seconds of the test (hand-grip, cold pressor test, diving) or at regular 3-minute intervals during the test (lower body negative pressure and passive leg raising). Likewise, the intraarterial blood pressure changes induced by the Valsalva maneuver were calculated by comparison of the baseline 20-second values with the peak increase, decrease, and increase in blood pressure observed after the beginning, before the end, and in

![Graph showing systolic and diastolic blood pressure values](image-url)
the rebound phase, respectively, after the termination of the Valsalva maneuver (phase 1, 2, and 3). Finally, the changes in intra-arterial blood pressure induced by intravenous injections of phenylephrine and nitroglycerine were calculated by comparison of the average systolic and diastolic blood pressure of the five beats before injection and the peak blood pressure change induced by the injection. The finger blood pressure signal was analyzed in an identical fashion. Data obtained during two performances of each test were averaged.

The intra-arterial blood pressure increases and reductions induced by phenylephrine and nitroglycerine were also used to stimulate and deactivate arterial baroreceptors and to evoke reflex bradycardia and tachycardia, respectively. Heart rate was
TABLE 1. Average Discrepancies Between Finger and Intra-arterial Blood Pressure Responses to Laboratory Tests

<table>
<thead>
<tr>
<th>Laboratory tests</th>
<th>Δ (mm Hg) Regardless the sign</th>
<th>Δ (mm Hg) Considering the sign</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SBP</td>
<td>DBP</td>
</tr>
<tr>
<td>Hand grip</td>
<td>3.5±3.6</td>
<td>1.3±1.5</td>
</tr>
<tr>
<td>Cold pressor (n=14)</td>
<td>4.6±4.1</td>
<td>2.1±1.2</td>
</tr>
<tr>
<td>Lower body negative pressure (−40 mm Hg, n=11)</td>
<td>4.1±3.7</td>
<td>3.5±3.2</td>
</tr>
<tr>
<td>Leg raising (n=12)</td>
<td>4.1±3.0</td>
<td>2.4±1.8</td>
</tr>
<tr>
<td>Phenylephrine (100 µg i.v., n=14)</td>
<td>3.4±2.0</td>
<td>2.3±2.1</td>
</tr>
<tr>
<td>Trinitroglycerine (100 µg i.v., n=14)</td>
<td>3.8±1.1</td>
<td>2.5±1.8</td>
</tr>
</tbody>
</table>

Values are mean±SD. A, discrepancies in responses; SBP, systolic blood pressure; DBP, diastolic blood pressure.

*p<0.05; †p<0.01 between finger and intra-arterial blood pressure changes induced by various laboratory maneuvers.

Comparison Between Finger and Intra-arterial Blood Pressure Data

Means and variabilities obtained in the resting condition by intra-arterial and finger blood pressure recording were compared with use of linear regression analysis between the two sets of data; a perfect correspondence was indicated by an intercept equal to zero and a regression coefficient equal to one. In addition, the average discrepancies (mean±SD) between finger and intra-arterial values were calculated for individual subjects and for the group as a whole.

Linear regression analysis was also used to compare baroreceptor reflex sensitivities, whereas average discrepancies (±SD) were employed to evaluate the correspondence between the responses to the laboratory tests obtained intra-arterially and those obtained by the finger pressure method. The statistical significance of the differences was estimated by Student's paired t test.

Throughout the study a p<0.05 was taken as the minimal level of statistical significance.

Results

Resting Condition

As shown in Figure 1, the average systolic and diastolic blood pressure obtained at rest by the FINAPRES device and the intra-arterial catheter showed a relatively narrow scattering around the identity line; the linear regression analysis between the two sets of data showed correlation and regression coefficients close to optimal values. The individual average paired differences between finger and intra-arterial blood pressures ranged from −13.4 to +6.7 mm Hg for systolic and from −14.6 to +8.7 mm Hg for diastolic blood pressure; the mean group discrepancies (±SD) were +1.2±5.4 mm Hg and +2.9±5.0 mm Hg, respectively (Figure 2).

Responses to Laboratory Tests

As exemplified in Figure 3, the marked beat-to-beat changes in intra-arterial blood pressure induced by laboratory tests were reproduced by the FINAPRES device in a qualitatively similar fashion. The systolic and diastolic blood pressures measured intra-arterially before and during each test were on average similar to those measured noninvasively by finger pressure recording for the tests that induced a pressor or a depressor response as well as for those that caused vasomotor changes without major variations in blood pressure (Figure 4). The average between-method discrepancy in the evaluation of the blood pressure changes was never greater than 4.3 mm Hg or 1.9 mm Hg for systolic and diastolic pressure, respectively. The corresponding standard deviations were always less than ±4.6 mm Hg and ±4.5 mm Hg (Table 1) indicating that the discrepancies were also small in individual subjects. The differences were only slightly higher when individual data were averaged regardless the sign to avoid negative errors to compensate for the positive ones (Table 1).

The fast and marked intra-arterial blood pressure rises that characterized the diving test were also closely reproduced by the FINAPRES method, both with regard to their time course (Figure 5) and to their absolute changes. The average difference measured by an electrocardiogram (ECG), and the baroreceptor reflex sensitivity was estimated as the slope of the linear regression relating changes in RR interval with rises and falls in systolic blood pressure. Another measure of baroreceptor reflex sensitivity was obtained by the ratio between the changes in tissue pressure outside the carotid sinuses, induced by neck chamber pressure changes, and the resulting alterations in mean arterial pressure. Data from the three positive or the three negative neck pressures were averaged. The same analysis was performed for the finger blood pressure tracing.
DIVING REFLEX

FIN • A • PRES

TABLE 2. Blood Pressure Response to Diving Test

<table>
<thead>
<tr>
<th>Change in intra-arterial pressure (mm Hg)</th>
<th>Change in finger pressure (mm Hg)</th>
<th>Δ (mm Hg) Regardless of the sign</th>
<th>Δ (mm Hg) Considering the sign</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBP +56.9±9.1</td>
<td>-57.5±11.0</td>
<td>5.4±1.3</td>
<td>0.6±2.7</td>
</tr>
<tr>
<td>DBP +27.3±4.9</td>
<td>+25.3±4.6</td>
<td>3.3±0.9</td>
<td>-2.0±1.5</td>
</tr>
<tr>
<td>MAP +33.0±6.7</td>
<td>+36.5±7.9</td>
<td>4.7±1.7</td>
<td>3.5±2.2</td>
</tr>
</tbody>
</table>

Values are mean±SEM. Δ, mean difference between finger and intra-arterial blood pressure changes induced by diving test; SBP, systolic blood pressure; DBP, diastolic blood pressure; MAP, mean arterial blood pressure. n=6 subjects.

measured intra-arterially and by the FINAPRES method (3.7 mm Hg and 3.8 mm Hg). Even when averaged regardless of the sign, the difference between the two methods amounted to only 0.29 mm Hg, and the corresponding standard deviation was only 0.28 mm Hg. This close correspondence was confirmed by the high correlation and regression coefficients between the two sets of values (Figure 7).

As shown in Figure 8, the sensitivity of the baroreceptor–heart rate reflex, as assessed by nitroglycerine injection, was very similar when the hypotension induced by the drug was estimated by intra-arterial or by finger pressure recording. The two methods also provided good estimates of the sensitivity of the baroreceptor reflex, as assessed by phenylephrine injection and positive neck chamber pressure application, although in both instances the between-method differences were greater than those observed for nitroglycerine injection. On the other hand, when the baroreceptor reflex sensitivity was measured by negative neck chamber pressure application, the estimate provided by finger pressure recording was less accurate.

Discussion

Our study confirms that measurements of finger blood pressure by the FINAPRES method provide resting systolic and diastolic blood pressures similar to those existing in the radial artery. It also demonstrates, in a large number of subjects, that this similarity extends to the measurements of the fast and marked blood pressure increases and decreases that can be induced by laboratory maneuvers.

The similarity of the blood pressure values obtained by finger pressure and by intra-arterial recording in resting condition is documented by the strict linear relation between the systolic and diastolic blood pressures that were measured by the two methods. It is also documented by the fact that, in the group as a whole, finger and intra-arterial blood pressures differed by no more than 2 or 3 mm Hg and the standard deviations of the average differences were approximately 5 mm Hg. These figures are largely within the requirements for new blood pressure–measuring devices of the Association for the Advancement of Medical Instrumentation, which consider the difference between non-

Blood Pressure Variability and Baroreceptor Reflex Sensitivity

The standard deviation of mean arterial pressure obtained by the beat-to-beat analysis of the 30-minute resting period was almost identical when (computed with or without the sign) was never greater than 5.4 mm Hg with a standard deviation never greater than ±2.7 mm Hg (Table 2). This was usually the case also for the fast and marked blood pressure increases and decreases that occurred during the Valsalva maneuver (Figure 6).
VALSALVA MANOEUVRE (n=17)

[Graph showing intra-arterial and finger systolic (SBP) and diastolic (DBP) blood pressure values recorded in control condition and during phase 1, 2, and 3 of Valsalva maneuver (see Methods). Data are shown as mean±SEM from 17 subjects. Left panel, absolute values and right panel, average discrepancies computed considering or not considering the sign.]

Invasive and intra-arterial measurements to be acceptable when less than or equal to 5±8 mm Hg (mean±SD). However, the most important result of our study is that, in agreement with recent observations made during the Valsalva maneuver, the correspondence between finger and intra-arterial blood pressure recording is good not only in the resting condition but also when blood pressure undergoes fast, marked, and variable changes. This correspondence makes this approach superior to manual or automatic sphygmomanometric measurements, which lose accuracy when not performed at

MAP VARIABILITY
(SD, n=14)

[Graph showing mean arterial pressure (MAP) standard deviation (SD) as assessed by separate beat-to-beat analysis of finger and intra-arterial blood pressure tracings over a 30-minute resting period. Data from 14 subjects. n, number of subjects; r is correlation coefficient of regression.]

FINGER PRESSURE

INTRA-ARTERIAL PRESSURE

r=0.95

[Graph showing baroreceptor reflex sensitivity as estimated by considering finger pressure and intra-arterial blood pressure. Sensitivity of arterial baroreceptor control of heart rate was assessed by slope of regression line between changes in systolic blood pressure induced by injection of phenylephrine (PHE) or trinitroglycerine (TNG) and corresponding lengthening or shortening in pulse interval (PI). Sensitivity of carotid baroreceptor control of blood pressure was assessed by ratio between changes in neck tissue pressure (NTP) and resulting changes in mean arterial pressure (MAP). Thin lines represent identity lines between paired values obtained by two methods. Thick lines represent regression lines between same values. n, number of subjects included in each analysis; r is correlation coefficient of various regressions.]
rest.19-21 This superiority is further emphasized by the fact that finger pressure recording can also follow, on a beat-to-beat basis, fast blood pressure changes, thereby providing a description of the time course of these changes; this is the case for blood pressure rises and systemic vasodilatations and for blood pressure falls and systemic vasoconstrictions, which indicates that alterations in blood pressure gradient and peripheral artery tone do not impair the ability of this peripheral instrument to sense intra-arterial blood pressure.

Although similar, the blood pressures obtained by finger pressure and intra-arterial recording were not superimposable. For example, the resting blood pressure values were often slightly greater when measured by finger pressure recording than by the intra-arterial catheter at the radial artery level. Furthermore, the overall small discrepancies between the two sets of values showed an appreciable between-subject variability. Finally, in rare instances, an acceptable finger blood pressure recording could not be obtained (see Subjects and Methods). These problems probably originate from the fact that both intra-arterial blood pressure measurements and the measurements provided by the FINAPRES device may not necessarily be 100% accurate in all subjects.3,4,17,22-24 It is possible, however, that the somewhat variable discrepancy between the data provided by the two methods also depended on the different site of their blood pressure detection (i.e., on the fact that noninvasive blood pressure was sensed at a more distal site than invasive blood pressure). This means that the loss of energy occurring in the arterial tree and the pulse wave reflection phenomenon may have affected the two pressures to a different degree, their influence varying as a function of the arterial structural and functional status.2,23,25-27 This raises the possibility that blood pressures provided by the FINAPRES method may be even more accurate than they appear in this study. Two other results of our study deserve to be mentioned. First, in virtue of its ability to accurately measure beat-to-beat resting blood pressure, finger pressure recording can provide a precise measure of the standard deviation of all blood pressure values occurring over a prolonged monitoring period, thereby offering a reliable index of blood pressure variability, particularly when changes in mean arterial pressure are considered. This is important for basic and clinical studies because blood pressure variability may reflect cardiovascular regulation in daily life.8,9,28-33 It may also be a factor contributing to the adverse consequences of hypertension on its target organs.34,35

Second, the ability of the finger pressure device to accurately measure blood pressure changes induced by vasoactive drug injection and the neck chamber device allows proper evaluation of the sensitivity of the baroreceptor control of the heart and peripheral circulation. This makes baroreceptor reflex functions testable in subjects in whom intra-arterial blood pressure measurements cannot be easily carried out (children, pregnant women, or severely ill patients), greatly enhancing the possibility to obtain information on reflex modulation of the cardiovascular system in health and disease.

In conclusion, our data demonstrate that finger blood pressure recording by the FINAPRES method provides an accurate estimate of the average radial blood pressure of a population and that it also allows a reasonably good estimate of intra-arterial blood pressure in individual subjects. The time course and the magnitude of the blood pressure changes brought about by a variety of stimuli, the tendency of blood pressure to vary within a prolonged time interval, and the relation between blood pressure and baroreceptor control of circulation are also reliably assessed by noninvasive finger pressure recording.

This reliability makes the finger blood pressure recording approach valuable for laboratory studies, which can then collect the extensive information provided by continuous blood pressure monitoring without the risks and the inconveniences of intra-arterial catheters.36

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