Feasibility of Ambulatory, Continuous 24-Hour Finger Arterial Pressure Recording

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We tested Portapres, an innovative portable, battery-operated device for the continuous, noninvasive, 24-hour ambulatory measurement of blood pressure in the finger. Portapres is based on Finapres, a stationary device for the measurement of finger arterial pressure. Systems were added to record signals on tape, to alternate measurements between fingers automatically each 30 minutes, and to correct for the hydrostatic height of the hand. We compared the pressure as measured by Portapres with contralateral intrabrachial pressure measured with an Oxford device. Results were obtained in eight volunteers and 16 hypertensive patients. Time lost due to artifact was about 10% for each device. In two patients a full 24-hour Oxford profile was not obtained. In the remaining 22 subjects finger systolic, diastolic, and mean pressures differed +1 (SD 9), —8 (6), and —10 (6) mm Hg, respectively, from intrabrachial pressure. These diastolic and mean pressure underestimations are similar to what was found earlier for Finapres, are typical for the technique, and are systematic. Avoiding brisk hand movements resulted in fewer waveform artifacts. The hand had to be kept covered to continue recording at low outside temperatures. Sleep was not disturbed by Portapres, and arterial pressure showed a marked fall during siesta and nighttime. There were no major limitations in behavior, and no discomfort that originated from continuous monitoring was reported. Measurements continued normally during physical exercise. Portapres provides for the first time continuous 24-hour, noninvasive ambulatory blood pressure waveform monitoring and offers real and obvious advantages over current noninvasive and invasive devices. (Hypertension 1993;21:65–73)

KEY WORDS • blood pressure determination • exercise • blood pressure monitors • monitoring, physiological • feasibility studies • hydrostatic pressure

In clinical practice ambulatory blood pressure monitoring is usually performed by commercial, noninvasive devices that read blood pressure only infrequently, such as every 10–30 minutes. These devices thus record only a fraction of the blood pressures occurring. To avoid artificial recordings the subject has to be (nearly) immobile during the measurement, which means that readings during episodes of motion and exercise cannot be obtained. Furthermore, intermittent blood pressure readings cannot properly assess blood pressure variability. Finally, these devices often disturb the sleep of patients.

Since 1982 finger arterial pressure measurements by Finapres have allowed blood pressure to be measured noninvasively on a beat-to-beat basis, and the pressures obtained correspond closely to intra-arterial measurements. Finapres is a stationary device, but we were impressed by its insensitivity to motion artifact during exercise and orthostatic and Valsalva maneuvers. This and clinical interest have stimulated the further development of Finapres to a portable, battery-operated version for 24-hour ambulatory blood pressure measurement, named Portapres.

For 24-hour ambulatory recording, the addition of three new systems was required: 1) a system to switch blood pressure monitoring between fingers at short intervals since continuous monitoring on a single finger may cause transient painful or numbing sensations in the finger, usually occurring at intervals from 30 minutes to 3 hours in awake subjects; 2) a system to monitor the hydrostatic height of the measured finger with respect to heart level; and 3) a system to record signal waveforms and device diagnostics information on tape.

Our goal was to investigate the performance of this new device: for artifacts by measuring monitoring time lost per 24 hours, for blood pressure accuracy by comparing with simultaneous intrabrachial blood pressure, for finger switching by assessing the pressure differences between fingers, and finally, for effects of changing hydrostatic height by observing subsequent changes in finger pressure levels and pulse pressure.

Methods

Subjects

The study included eight male, normotensive volunteers, aged 19–32 years, and 16 patients (three women,
Blood pressure is measured at a finger using an Ambulatory Finger Blood Pressure method within 5 mm Hg when measured simultaneously on the left and right upper arm by two observers reading a single mercury column.

Intra-arterial pressure was measured through a Teflon cannula with a length of 11 cm and an internal diameter of 1 mm. After local anesthesia with 1% lidocaine, the cannula was inserted into the brachial artery of varying degree. Two patients received antihypertensive combination therapy; the remaining patients received monotherapy. Treatment was discontinued in all cases at least 2 weeks before the measurements began. The volunteers and eight hypertensive patients were investigated in the Academic Medical Centre of the University of Amsterdam. Another eight hypertensive patients were investigated with the same equipment in the University Hospital (Ospedale Maggiore) of Milan. Because we applied intra-arterial and finger devices on contralateral arms, each subject was required to have an average of six auscultatory systolic and diastolic pressures agree to within 5 mm Hg when measured simultaneously on the left and right upper arm by two observers reading a single mercury column.

Each participant gave his or her informed consent to the study. The study protocol was approved by the ethics committees of the institutions involved.

**Ambulatory Finger Blood Pressure**

Portapres provides an indirect measurement of blood pressure in a finger based on the arterial volume–clamp method and the physiocal (physiological calibration) criteria for the full unloading of the arteries in a manner identical to Finapres. As shown in Figure 1, the model 1 prototype consisted of a small patient front end unit connected to a larger main unit. The front end box, which is worn on the back of the hand or on the wrist, measures 30×50×70 mm and weighs 200 g. It contains preamplifiers, a pressure sensor, a cuff pressure control valve, and a pneumatic switch to pressurize one of two permanently mounted cuffs on the annular and middle fingers, alternating every 30 minutes. This schema avoids the discomfort associated with long-term blood pressure measurement in a single finger and thereby allows measurement to continue for 24 hours. At each alternation, the temperature-compensated pressure transducer is rezeroed, avoiding any appreciable zero drift in the Portapres measurements.

The larger main box measures 250×210×60 mm, weighs approximately 3 kg, and is worn on the abdomen secured by two belts, or hung from a shoulder with one belt. This box contains a lithium battery pack, a highly efficient air pump, a cassette tape recorder, a microcomputer, and various analog electronic components. The front panel comprises a 32-character liquid crystal display, a marker button, and a small number of recessed buttons to interact with device operation. The battery pack provides the power necessary to record pressure for 24 hours. The pump, which is powered from the battery pack, supplies air pressure to the patient front end unit.

A separate recording system measures the hydrostatic height of the hand, continuously tracking pressure changes induced by moving the hand. A liquid-filled tube is connected to a pressure transducer at one end and a compliant bag at the other. The bag is attached to the finger, and the transducer is fixed at the level of the intra-arterial transducer. Its output is separately recorded but is also automatically added to the finger pressure signal. Addition is based on previous observations that changes in finger height appear negated in mean finger pressure, although with a delay. In the height recording system, therefore, a low pass filter is used, with a similar time constant (2 seconds) as the physiological delay time constant. Thus, ambulatory finger arterial pressure is corrected continuously for any height changes occurring between the finger and the intra-arterial reference transducer at heart level. Given the time constant, however, the system cannot correct for shocks and abrupt movements.

A built-in four-channel instrumentation cassette recorder (TEAC HR-101, Teac Corporation, Japan) is used for storage of the height-corrected finger arterial pressure signal (Portap), the hydrostatic height signal with superimposed amplitude-coded marker signals (Height), and the simultaneous intra-arterial pressure signal (IAP). The fourth channel of the recorder is used for the compensation of tape flutter.

The microcomputer controls and monitors the entire system. It includes an algorithm to start the finger measurement; clock timers; and algorithms to digitize signal waveforms, to recognize and measure heartbeats, to implement physiocal, to perform adaptive cuff pressure control, to recognize artifacts, to switch between fingers, and to display, record, and output data, device diagnostics information, and markers.

The analog system includes a modern battery power management system and an automatic, patient-adaptive servocontroller. A monitor cable can be connected to the main unit for visual inspection of the recorded signals on an external oscilloscope or strip chart recorder during the 24-hour run.

**Intra-arterial Pressure**

Intra-arterial pressure was measured through a Teflon cannula with a length of 11 cm and an internal diameter of 1 mm. After local anesthesia with 1% lidocaine, the cannula was inserted into the brachial
artery of the nondominant arm by the Seldinger techni-
que. The cannula was connected via a 70-cm-long polyethylene tube to the transducer of a commercial Oxford Medilog Mark II system (Romulus Technology Ltd, Brunel University, Uxbridge, UK). To obtain improved zero stability, power to the Oxford/Akers B22 transducer was supplied from Portapres via a special bridge amplifier. For storage of the intrabrachial signal we used one channel of the Portapres built-in TEAC recorder.

After mounting a cassette tape, all recorder channels were calibrated by a 0–2 V (0–200 mm Hg) square wave. After a warm-up period of at least 30 minutes, the Oxford transducer was calibrated by an accurate, servo-stabilized pneumatic pressure staircase of 0–100–200–100–0 mm Hg of 5 minutes duration generated by Portapres. The zero offset could thus be nulled and the sensitivity adjusted to make the calibrations of both pressure signals exactly identical. The zero offset was checked and recorded at approximately 4 and 20 hours into the 24-hour measurement period. The calibration sequence was repeated at the end of the 24-hour period. No changes in transducer sensitivity were seen. The zero offset usually showed an upward drift during the measurements. The zero offset observed at the end stage ranged from −5.2 to +13.4 mm Hg with an average value for the group of 1.4 mm Hg and standard deviation of 3.6 mm Hg. To correct intra-arterial pressures for zero drift, we used half the end-stage zero offset for each subject throughout the entire 24-hour recording. Assuming linear drift, the 24-hour means are thus correct.

The dynamic performance of the invasive system was measured by applying stepwise pressure changes of 100–mm Hg amplitude and 10-msec rise time to the Oxford transducer and recording the responses on a high speed electronic strip chart recorder (model TA4000, Gould Inc., Cleveland, Ohio). The average overall resonance frequency of the combined system was 19 Hz (range 14–30 Hz). This represents an improvement over the frequency response of an unmodified Oxford Medilog Mark II system, which is near 10 Hz, but is still insufficient to guarantee a correct measurement of intrabrachial systolic pressure levels at all times.

Protocol

All hypertensive patients but not the volunteers were hospitalized at least 1 day before the 24-hour protocol began. The cannulation of the brachial artery was performed between 9 and 10 AM in the morning of the first day. After the completion of another experimental protocol, to be reported elsewhere, Portapres was installed on the hand contralateral to the intrabrachial site. Properly sized finger cuffs according to the Portapres manual were carefully wrapped around the annular and middle fingers of the subject. Beginning on the annular finger, measurements started at 1 PM and continued until 1 PM the next day. During the recording period the subjects were free to move within the hospital and to engage in the usual activities of inpatients not confined to bed. In addition, a number of activities were scheduled for all subjects in the following sequence: from 2 to 3:30 PM, siesta; from 4:45 to 5:15 PM, cycling at 50 W, 50–60 rpm; from 10 PM to 6 AM, sleep; from 10 to 10:30 AM, first walk outside hospital; from 11 to 11:30 AM, second walk outside hospital. The subjects were instructed not to bend or compress the cuffed fingers. The first six subjects (all normotensive volunteers) were given no instructions with respect to the movement of the instrumented hand during the recording. The remaining subjects, however, were asked to keep the hand more stable near heart level, also during physical activity.

Data Analysis

Off-line analysis of the 24-hour recordings was done on an IBM-compatible personal computer system. Before A/D conversion, the signals were zero- and gain-adjusted using the tape-recorded calibration. The tape was then replayed at eight times real-time and A/D converted with 0.25 mm Hg resolution at 100 Hz real-time equivalent rate by means of DIGIFAST, a program of the FAST software package.

From the IAP and then the Portap signals beat-to-beat results were obtained by BEATFST. This program identified for each heartbeat the time of the systolic upstroke, the levels of systolic, true integrated mean, and arterial end-diastolic pressure and height. Instantaneous pulse rate was computed from the time interval between upstrokes. In addition, the presence of physio-
cal periods was identified and appropriately marked. Markers were detected in the Height signal and sepa-
ately stored.

The comparison of Portap and IAP was performed on a beat-to-beat basis. During visual inspection of the Portap and IAP signals, periods of evident signal dis-
turbances were removed. The conditions for rejection are listed in Table 1. The remaining files were fed through a computer program that matched beats in Portap and IAP having the corresponding begin upstroke instant.

For each matched beat the Portap systolic, mean, and dia-
stolic difference with the corresponding IAP beat

<table>
<thead>
<tr>
<th>Type of artifact</th>
<th>IAP Minutes</th>
<th>%</th>
<th>Portap Minutes</th>
<th>%</th>
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<tr>
<td>Device-related</td>
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<td></td>
<td></td>
<td></td>
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<td>fluxing and zeroing</td>
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<tr>
<td>Faulty connection</td>
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<td>1.2</td>
<td>...</td>
<td>...</td>
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<td>...</td>
</tr>
<tr>
<td>Empty battery pack</td>
<td>...</td>
<td>...</td>
<td>164</td>
<td>0.5</td>
</tr>
<tr>
<td>Fall of Portapres</td>
<td>...</td>
<td>...</td>
<td>262</td>
<td>0.8</td>
</tr>
<tr>
<td>Loose air tube</td>
<td>...</td>
<td>...</td>
<td>29</td>
<td>0.1</td>
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<td>Other technical</td>
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<td>600</td>
<td>1.7</td>
</tr>
<tr>
<td>Total</td>
<td>3,330</td>
<td>9.6</td>
<td>2,945</td>
<td>8.5</td>
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</table>

Portap, hydrostatic height-corrected finger pressure recorded with Portapres; IAP, zero drift corrected intrabrachial pressure obtained with the Oxford device. Percentage of time lost is with respect to the total registration time in the 24 subjects of 34,556 minutes.
was calculated (Portap—IAP) and corrected for Oxford zero drift. Thus, an overestimation of intra-arterial pressure by Portapres is shown as a positive number. This formed the primary data for statistical comparison. Blood pressures and blood pressure differences were then averaged by calculating mean and standard deviation each half hour in synchrony with finger alternation. These averages were used to present 24-hour blood pressure profiles and to assess differences between the annular and middle fingers. Separate averages for each subject were also computed over the entire 24-hour period, and over daytime (nonsleep period), nighttime (sleep), siesta, cycling, and walking, and were pooled for the group.

**Effects of Hydrostatic Height**

To assess whether hydrostatic height, mean pressure level, and pulse rate affect differences between finger and intrabrachial pressures, the multiple regression of the mean pressure differences (Portap—IAP) on these variables was calculated. This was done only for the first six subjects (normotensive volunteers) in which the movement of the hand was not restricted. In addition, the extent of relative pulse pressure changes (pulse wave amplification) was studied by computing the multiple regression of the pulse pressure ratio (Portap/IAP) on height, pressure, and rate. In each of the six subjects a 10–20-minute period with marked movements of the hand was selected, comprising at least 600 heartbeats.

**Statistical Evaluation**

Means and standard deviations were computed and reported as required by the Association for the Advancement of Medical Instrumentation (AAMI), and parametric tests, in particular the t test, were used to test differences in mean values for significance. The 95% confidence intervals (CI) and the limits of agreement are also based on the t distribution. Multiple linear regressions were computed to verify the effects of hydrostatic height and tested for significance with Pearson’s product-moment correlation.

**Results**

Figure 2 shows a typical continuous intrabrachial and finger pressure registration in subject 9 of Table 2. The Portap signal obtained during the 24 hours was visually similar to the intra-arterial pressure recorded simultaneously from the contralateral side. The expected fall in blood pressure during the night was evident in both tracings and so was the blood pressure rise occurring during the exercise periods and the blood pressure fall occurring during the afternoon siesta.

No subject complained of any disturbance related to the wearing or the alternate half-hourly inflation of the finger cuffs during either the day or night.

**Artifact Rejection**

After visual inspection of the recordings, 9.6% of the total intrabrachial and 8.5% of the total finger recording times were rejected for the various reasons mentioned in Table 1. Pump artifacts accounted for nearly two-thirds (59.9%) of the rejections in the intrabrachial Oxford recording. In fact, due to Oxford problems in the arm (3.6%) and to ambient cold. This causes repeated automatic start-ups of Portapres devices are −16.7 to +18.1 for systolic, −19.6 to +3.6

![Image](https://example.com/image.png)

**FIGURE 2. Representative tracings of a continuous 24-hour intrabrachial (IAP) and finger (Portap) pressure measured in patient 9 of Table 2. The registration runs from 1 PM on the first day until 1 PM on the next. The height signal is the bottom trace. The event marks in this track each 30 minutes indicate switching between the finger cuffs. Coded error messages and manual diary markers are also superimposed on the height signal.**

24-hour profile could be obtained. The largest loss of monitoring time on the finger with Portapres was due to reduced circulation during pinch off of the arterial system in the arm (3.6%) and to ambient cold. This causes repeated automatic start-ups of Portapres (1.1%), recognized by the typical cuff pressure search staircase generated by the computer at start-up and broken off if finger circulation is detected as insufficient. A “marching artifact” was seen in two of the first six subjects during walking, probably caused by swinging of the arm. Walking produced oscillations in finger pressure of amplitudes that did not exceed one-third of the pulse pressure. Since intrabrachial and finger artifacts did not always occur at the same time, of the total recording period simultaneous IAP and Portap signals were available for comparison during 86.7% of the time.

**Portap—IAP Differences**

Table 2 lists the intrabrachial pressures and the deviations of Portapres values from intrabrachial, averaged per subject, over all the matched beats in the 24-hour period. Note that within a subject all finger pressure levels usually deviated in the same direction from the intrabrachial levels. For example, subject 2 had rather positive systolic, diastolic, and mean pressure differences, whereas subject 9 had the opposite. It appears that differences within a subject tend to be systematic.

Group averages are summarized in the bottom lines of Table 2 and exclude the partial results of subjects 13 and 22. Systolic offset is essentially zero (CI, −3.2 to +4.6) but with high scatter (standard deviation) at 8.7 mm Hg. Mean and diastolic pressures show offsets of −8.0 (CI, −10.6 to −5.4) and −10.3 mm Hg (CI, −13.1 to −7.5), respectively, but with scatter less than 7 mm Hg. The computed limits of agreement between devices are −16.7 to +18.1 for systolic, −19.6 to +3.6
Table 2. Pressures and Pressure Differences

<table>
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<tr>
<th>Patient</th>
<th>IAP</th>
<th>ΔSBP Mean</th>
<th>ΔSBP SD</th>
<th>ΔDBP Mean</th>
<th>ΔDBP SD</th>
<th>ΔMAP Mean</th>
<th>ΔMAP SD</th>
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<td>1</td>
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</tr>
</tbody>
</table>

Group: 134 | 80 | 102 | 0.7 | 12.9 | -8.0 | 7.9 | -10.3 | 7.7
SD: 16 | 10 | 13 | 8.7 | 2.4 | 5.8 | 2.0 | 6.4 | 2.4

IAP, intrabrachial pressure; SBP, systolic blood pressure; DBP, diastolic blood pressure; MAP, mean arterial pressure; SD, standard deviation. Pressures and pressure differences are in millimeters of mercury. IAP are averaged over 24 hours per patient and again averaged for the group. The differences between finger and intrabrachial pressure are for systolic (ΔSBP), diastolic (ΔDBP), and mean (ΔMAP) levels. Both mean and standard deviation are given.

*Subjects excluded from group average IAP. For these subjects no 24-hour profile was obtained due to device malfunction.

for mean, and -23.1 to +2.5 mm Hg for diastolic pressure, and are larger than observed.

Figure 3 shows one subject's individual and the group average pressure responses and finger-to-brachial pressure differences. The top panel represents subject 9 in Table 2 as an example of a finger and intrabrachial 24-hour blood pressure profile based on half-hour averages. Differences (Portap-IAP) are separately plotted. The siesta and nighttime periods show drops in all pressure levels, whereas the walking periods show increased pressures. The pressure differences, though quite steady, do show apparently systematic variations. Differences are more negative during siesta and sleep, less negative during physical exercise. The group average 24-hour profiles are shown in Figure 3 bottom panel, excluding subjects 13 and 22. Systematic pressure differences between the middle and annular fingers can be seen as a repeating triangle with hourly periodicity. Trends in pressure difference during 24 hours follow the pattern seen in the top panel registration in subject 9.

Figure 4 shows the pressure differences averaged over the 24-hour period and also separately group averaged for a number of specific activities. Most activity-grouped differences were quite similar. However, walking was associated with an overestimation of systolic intrabrachial pressures in the finger and reductions in the underestimation of mean and diastolic levels. Artifact levels were higher, leading to a smaller number of included subjects. For cycling, the upward movement of finger pressure with respect to intrabrachial pressure was not as clear, partially because the timing of this exercise was such that the first quarter hour fell in one half hour average and the second quarter in the following half hour period and thus were averaged in with normal resting values, and partially because the effect on blood pressure of cycling at 50 W is small.

Two-Finger Agreement

Pressure measured in the annular finger was higher than in the middle finger. Group average differences for systolic, diastolic, and mean pressure were 1.1 (SD 8.0), 3.3 (5.4), and 2.4 (6.0) mm Hg, respectively. The average differences are small compared with total differences, and only the diastolic difference is significant (p=0.01; paired per subject t test since compared with common reference). However, the large standard devi-
FIGURE 3. Panel A: An individual 24-hour intrabrachial (lap) and finger (Portap) blood pressure profile in patient 9 of Table 2, composed of 30-minute average values of systolic and diastolic pressures. Intrabrachial traces are the continuous lines, and the finger traces are the dashed lines. Traces, continuous for systolic and dashed for diastolic, at the bottom represent the differences. Panel B: The 22-patient group average 24-hour blood pressure profiles presented in the same manner. Both panels show a substantial dip in pressure in the inactive siesta and sleep periods beginning at 2 PM and 10 PM. Blood pressure differences also dip in these periods and clearly rise in the highest activity periods of outside walking at 10 AM and 11 AM.

 FIGURE 4. Bar graphs show average differences and standard deviations for systolic, mean (M.A.P.), and diastolic pressures for the 24-hour period as a whole and subdivided for the specific conditions labeled. Total number of subjects included in the different activities is indicated. These numbers are not always 24 because of the artifact rejection explained in Table 1. For example, one entire night's intrabrachial blood pressure recording had to be rejected because of pump artifact, another because of a broken pressure transducer. Initially, outside walking often disturbed Portapres registrations due to repeated start-ups and movements until measures were taken to protect the hand from cold by placing it under the overcoat.

Effects of Hydrostatic Height

The regression of the differences in mean pressure between finger and brachial pressures and of the pulse pressure ratio on the height of the finger in the first six subjects are given in Table 3. The regression slopes differ widely between subjects; however, they are statistically significant except in one subject each for mean pressure difference and pulse pressure ratio. Even so, the explained variance is only small. Regression of mean pressure difference on the level of mean pressure and regression of pulse pressure ratio on heart rate were also significant in most subjects but explained even smaller fractions of the variance.

Discussion

The present study was performed to validate Portapres, a device designed to measure ambulatory blood pressure noninvasively on a beat-to-beat basis. The results provide information on the device feasibility. They also allow examination of problem points of the device components and a discussion of advantages for clinical and basic research in the field of ambulatory intra-arterial blood pressure monitoring.

Feasibility of Ambulatory Blood Pressure Monitoring by Portapres

In our subjects the blood pressure signal provided by Portapres could be used for evaluation of the subject's blood pressure more than 90% of the total recording time. Thus, monitoring time lost, at less than 10%, is a...
The absence of re-peated inflations of an arm cuff as with ordinary, 24-hour blood pressure recorders probably facilitated the subjects’ acceptance of Portapres. This is further enhanced by the low and uninterrupted noise of the Portapres pump.

**Differences in Ambulatory Blood Pressures From Portapres and Medilog**

We evaluated differences between blood pressure in the finger measured by Portapres and in the brachial artery measured invasively by an Oxford Medilog Mark II. Since these measurement sites are separated by approximately 45 cm, with finger pressure being arterial pressure at an end point of the arterial system, we cannot expect to measure identical pressures. A pressure gradient exists in the arterial system, causing distal mean pressure to be at most equal but usually below more proximally measured pressures. In addition, a wave pulse amplification effect exists that increases the pulse amplitude along the arterial system, and thereby systolic pressure in particular. Such differences, which are by no means stable or constant but depend on age, flow, blood pressure, and heart rate, can be called physiological. Further, technical systems such as Portapres or Oxford Medilog can add measurement differences due to incorrect calibration, unstable baseline, incorrect flush rate, insufficient dynamic response, or in the case of Portapres, an erroneous arterial unloading set point. Such differences can be called instrumental or error. In most cases, it has been impossible to differentiate the source of an observed difference as physiological difference or instrumental error. We therefore used the word difference throughout.

Comparison with intrabrachial pressure on a paired beat basis showed that Portapres underestimated diastolic and mean blood pressure to a degree that is regarded as too large by the AAMI criteria, i.e., larger than ±5 (8) mm Hg. Systolic blood pressure levels were estimated more closely but with larger scatter. The differences within any one subject are rather constant and only show a small and slow, systematic fluctuation. It would appear that the systematic offsets could be compensated for in an average sense by correcting for group average offsets. The within-subject standard deviation, although too large in all subjects for systolic pressures, is within AAMI limits for mean and diastolic pressures in 16 of the 22 subjects in whom a full 24-hour profile was obtained.

Finally, although systolic blood pressure showed a tendency to be overestimated at the highest heart rate values seen during the 24-hour period, the differences in the estimation of diastolic and mean blood pressure actually decreased in ambulant conditions. This is in sharp contrast with the performance of intermittent noninvasive blood pressure monitoring devices, which may be accurate at rest but are often inaccurate to the point of utmost unreliability during exercise and ambulant conditions. Thus, the ambulatory blood pressure values provided by Portapres compare favorably for accuracy and insensitivity to motion artifact with those from other intermittent noninvasive systems, having over them the real advantage of continuous assessment of the changing blood pressure.

**Table 3. Effect of Finger Height on Mean Pressure Difference and Pulse Pressure Ratio**

<table>
<thead>
<tr>
<th>Patient</th>
<th>Slope</th>
<th>%XP</th>
<th>p</th>
<th>Slope</th>
<th>%XP</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.147</td>
<td>16</td>
<td>0.12</td>
<td>2</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-0.010</td>
<td>0</td>
<td>NS</td>
<td>-0.65</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.053</td>
<td>8</td>
<td>-0.57</td>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.094</td>
<td>22</td>
<td>-0.28</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.115</td>
<td>12</td>
<td>-0.45</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.268</td>
<td>45</td>
<td>-0.40</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>0.111</td>
<td>17</td>
<td>-0.37</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>-0.010</td>
<td>0</td>
<td>-0.65</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum</td>
<td>0.268</td>
<td>45</td>
<td>0.12</td>
<td>26</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Δ Mean, regression of the difference between finger and intrabrachial mean pressure; PPR, regression of finger to brachial pulse pressure ratio on height signal; %XP, percentage of Δ mean and PPR variance explained by the height signal. Regression slopes are in millimeters of mercury/millimeters of mercury and percent/millimeters of mercury, respectively.

*Except for two not significant measurements at p=0.05 (NS), all slopes are significant at p<0.01 (t test), taking into account that in the time span considered only approximately 100 independent samples on the height signal are available.

- Imholz et al. Phasic Ambulatory Finger Blood Pressure

- British Hypertension Society

- AAMI

- Oxford Medilog Mark II

- Portapres

- Pulse Pressure Ratio (PPR)

- Percentage of A mean and Pulse Pressure Ratio

- Comparison with intrabrachial pressure on a paired beat basis showed that Portapres underestimated diastolic and mean blood pressure to a degree that is regarded as too large by the AAMI criteria, i.e., larger than ±5 (8) mm Hg. Systolic blood pressure levels were estimated more closely but with larger scatter. The differences within any one subject are rather constant and only show a small and slow, systematic fluctuation. It would appear that the systematic offsets could be compensated for in an average sense by correcting for group average offsets. The within-subject standard deviation, although too large in all subjects for systolic pressures, is within AAMI limits for mean and diastolic pressures in 16 of the 22 subjects in whom a full 24-hour profile was obtained.

- Finally, although systolic blood pressure showed a tendency to be overestimated at the highest heart rate values seen during the 24-hour period, the differences in the estimation of diastolic and mean blood pressure actually decreased in ambulant conditions. This is in sharp contrast with the performance of intermittent noninvasive blood pressure monitoring devices, which may be accurate at rest but are often inaccurate to the point of utmost unreliability during exercise and ambulant conditions. Thus, the ambulatory blood pressure values provided by Portapres compare favorably for accuracy and insensitivity to motion artifact with those from other intermittent noninvasive systems, having over them the real advantage of continuous assessment of the changing blood pressure.
Portapres Components

Finger switching altered the recorded blood pressure values for undetected reasons, but the changes were too small as to fail to offer the 24-hour blood pressure profile when group data were considered. Importantly, differences between fingers did not introduce any substantial differences in the estimates of 24-hour blood pressure standard deviations. The larger differences observed between fingers in some subjects can be removed almost completely by taking half-hour averages (fifty-fifty) of pressures from each finger.

The system to measure hydrostatic height of the finger showed a slight but statistically significant positive correlation between mean pressure differences and measured height (Table 3). Although at first sight this might suggest a less than perfect functioning of the compensation device, the large differences in the regression slopes between subjects, although recorded with the same device, indicate that the phenomenon is physiological and not instrumental. We were aware that raising the hand reduces pulse pressure, which is why we included this computation, but we were surprised to see this positive effect on mean pressure. A possible explanation may be that raising the hand reduces flow, as observed recently by Joyner. The reduced flow results in a reduced pressure gradient along the arteries and increased peripheral mean pressure. Since this effect causes an increase in mean finger pressure of approximately 1 mm Hg by raising the hand 10 cm and a decrease in pulse pressure of 3% and since subjects moved their hands 70–100 cm in height, this effect alone causes a peak-to-peak deviation of 7–10 mm Hg in mean pressure difference and a pulse pressure ratio scatter of 6%. After the first six subjects, therefore, we instructed the remaining 18 subjects to keep the hand being measured near heart level. To reach maximal recording accuracy and smallest rejection of artifact beats, it seems important to limit the degree of the hand excursion above and below the heart and to perform physical activity without sudden changes in hand level.

Since Portapres is essentially a Finapres device, Portapres results can be compared with those of Finapres. In a previous study in 40 patients we have seen that Finapres systolic, diastolic, and mean blood pressure differed by an average of −3.5, −4.4, and −8.0 mm Hg, respectively, from intrabrachial pressure, although in other studies, the systolic and diastolic offsets were larger (for review, see Reference 28). In the present study, the Portapres blood pressure levels differed from intrabrachial levels by an average of +0.7, −8.0, and −10.3 mm Hg, i.e., less for systolic, more for diastolic and mean pressures. However, none of the differences with the Finapres data from the previous study were statistically significant (p = 0.05). Thus, Portapres ambulatory blood pressure levels show deviations similar to stationary Finapres.

Portapres in Cardiovascular Research

The availability of a device for the noninvasive measurement of ambulatory blood pressure on a continuous basis carries obvious advantages for cardiovascular research. With current noninvasive methods, ambulatory blood pressure can be assessed in an intermittent basis only. The overall number of values that can be collected in 24 hours (usually less than 100) represents just about 1/1,000 of the values that occur over this period. This prevents the investigation and knowledge of 24-hour blood pressure phenomena of great basic and clinical interest such as acute changes in blood pressure induced by behavior, spectral blood pressure events, drug-induced blood pressure falls, or overall blood pressure variability.

Also, conventional intra-arterial blood pressure monitoring by the Oxford Medilog method, although providing a large and accurate body of registrations, is confined to a few specialized centers worldwide and is not devoid of risks for the patient. Obtaining the same large body of registrations by a noninvasive and reasonably accurate device, such as Portapres, would greatly advance the potential for studying blood pressure control mechanisms operating in daily life, in health and disease. It may also offer a tool to accurately assess the antihypertensive efficacy of new drugs.

References

16. van Montfrans GA: Continuous ambulatory blood pressure registration in uncomplicated hypertension: Cuff responders and blood pressure variability. (thesis) Amsterdam, University of Amsterdam, 1984, pp 1-138
Feasibility of ambulatory, continuous 24-hour finger arterial pressure recording.
B P Imholz, G J Langewouters, G A van Montfrans, G Parati, J van Goudoever, K H Wesseling, W Wieling and G Mancia

Hypertension. 1993;21:65-73
doi: 10.1161/01.HYP.21.1.65

Hypertension is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0194-911X. Online ISSN: 1524-4563

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