Estimation of Blood Pressure Variability From 24-Hour Ambulatory Finger Blood Pressure

Stefano Omboni, Gianfranco Parati, Paolo Castiglioni, Marco Di Rienzo, Ben P.M. Imholz, Gerard J. Langewouters, Karel H. Wesseling, Giuseppe Mancia

Abstract—Portapres is a noninvasive, beat-to-beat finger blood pressure (BP) monitor that has been shown to accurately estimate 24-hour intra-arterial BP at normal and high BPs. However, no information is available on the ability of this device to accurately track ambulatory BP variability. In 20 ambulatory normotensive and hypertensive subjects, we measured 24-hour BP by Portapres and through a brachial artery catheter. BP and pulse interval variabilities were quantified by (1) the SDs of the mean values (overall variability) and (2) spectral power, computed either by fast Fourier transform and autoregressive modeling of segments of 120-second duration for spectral components from 0.025 to 0.50 Hz or in a very low frequency range (between 0.00003 and 0.01 Hz) by broadband spectral analysis. The 24-hour SD of systolic BP obtained from Portapres (24±2 mm Hg) was greater than that obtained intra-arterially (17±1 mm Hg, P<0.01), but the overestimation was less evident for diastolic (3±1 mm Hg, P<0.01) and mean (3±1 mm Hg, P<0.01) BP. The BP spectral power <0.15 Hz was also overestimated by Portapres more for systolic than for diastolic and mean BPs; similar findings were obtained by the fast Fourier transform, the autoregressive approach, and focusing on the broadband spectral analysis. BP spectral power >0.15 Hz obtained by the Portapres was similar during the day but lower during the night when compared with those obtained by intra-arterial recordings (P<0.01). No differences were observed between Portapres and intra-arterial recordings for any estimation of pulse interval variabilities. The overestimation of BP variability by Portapres remained constant over virtually the entire 24-hour recording period. Thus, although clinical studies are still needed to demonstrate the clinical relevance of finger BP variability, our study shows that Portapres can be used with little error to estimate 24-hour BP variabilities if diastolic and mean BPs are used. For systolic BP, the greater error can be minimized by using correction factors. (Hypertension. 1998;32:52-58.)

Key Words: blood pressure ■ blood pressure monitoring, ambulatory ■ power spectral analysis ■ Portapres ■ blood pressure variability

We have previously shown that a portable version of the Finapres device, called Portapres, allows monitoring of mean 24-hour and hourly BP values similar to those simultaneously recorded from a contralateral arterial catheter, thereby validating a tool that permits ambulatory BP to be obtained noninvasively on a beat-to-beat basis. However, no information is available on the ability of the Portapres device to accurately assess ambulatory BP variability. This is of considerable importance because (1) BP variability has been ascribed a prognostic value and (2) the actual magnitude of BP variability escapes the intermittent BP readings typical of automatic BP monitoring and that can only be determined by continuous BP measurement.

In the present study we have addressed this issue by comparing different estimates of the 24-hour BP variability derived from the respective recordings obtained from Portapres and from a contralateral arterial catheter.

Methods

Subjects
Our study was performed in 8 male normotensive volunteers (mean±SD age, 25±5 years) and in 16 patients (13 men and 3 women) with mild to moderate essential hypertension (mean±SD age, 46±10 years). In all hypertensive patients, antihypertensive treatment was withdrawn 2 weeks before the study. All subjects gave their oral consent to the study after being informed of its nature and purpose. The study protocol was approved by the Ethics Committees of the institutions involved.

Ambulatory Finger BP Recording
Beat-to-beat noninvasive finger BP was monitored through the Portapres model 1 device (TNO-TPD, BioMedical Instrumentation), which has been described in detail previously. In brief, the Portapres device (as is the Finapres device) is based on the arterial volume clamp method of Péna. This device measures BP through two small finger cuffs wrapped around the middle and ring fingers of the hand of the dominant arm, which are alternately used every 30 minutes to avoid the discomfort associated with prolonged measurements from...
Selected Abbreviations and Acronyms

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>D/S BP</td>
<td>diastolic/systolic blood pressure</td>
</tr>
<tr>
<td>FFT</td>
<td>fast Fourier transform</td>
</tr>
<tr>
<td>HF</td>
<td>high frequency</td>
</tr>
<tr>
<td>LF</td>
<td>low frequency</td>
</tr>
<tr>
<td>MAP</td>
<td>mean arterial pressure</td>
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<tr>
<td>MF</td>
<td>mid frequency</td>
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<tr>
<td>PI</td>
<td>pulse interval</td>
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one finger only. The device also includes a system capable of automatically correcting for changes in finger pressure induced by changes in the hydrostatic level between the heart and the instrumented finger due to hand displacements during daily life activities. These changes are further minimized by instructing the subjects to refrain from unnecessary movements of the equipped arm and hand. The height-corrected finger arterial pressure, the hydrostatic height signal, the intra-arterial pressure signal (see below), and a synchronization signal employed for tape flutter compensation were all stored on a four-channel, analog cassette tape recorder (TEAC-HR 10J, TEAC Corp).

Ambulatory Intra-arterial BP Recording

Intra-arterial BP (brachial artery catheter) was measured by the Oxford method described in detail elsewhere. A box containing a transducing-perfusing unit was placed at the level of the heart and connected to the cassette tape recorder (see above), where the transduced BP signal was conditioned by an amplifier and stored on the same tape as the noninvasive BP signal. The overall mean resonance frequency of the transducing-recording system was 19 Hz (range, 14 to 30 Hz). Before and after a warm-up period of 30 minutes, the signal was calibrated by a 0- to 2-V (0 to 200 mm Hg) tape calibration signal employed for tape flutter compensation were all stored. The height-corrected finger arterial pressure, the hydrostatic height signal, the intra-arterial pressure signal (see below), and a synchronization signal employed for tape flutter compensation were all stored on a four-channel, analog cassette tape recorder (TEAC-HR 10J, TEAC Corp).

Protocol

All subjects were hospitalized for the duration of the study. The Portapres and intra-arterial 24-hour BP recordings were started simultaneously at ~1 PM. During the recording period, the subjects were free to move within the hospital area and to engage in the usual activities of inpatients not confined to bed. They were also asked to abide by the following standardized activities: (1) a 1.5-hour afternoon siesta (from 2 to 3:30 PM), (2) a half hour of cycling at 50 W and 50 to 60 rpm (from 4:45 to 5:15 PM), and (3) 1 hour of walking in the morning (from 10 to 10:30 AM and from 11 to 11:30 AM). Each subject had to stay in bed for the night sleep from 10 PM to 6 AM.

Data Analysis

Twenty-four-hour noninvasive and invasive recordings were analyzed off-line. Analog signals were A/D converted with a 0.25- mm Hg resolution at 100 Hz real time by dedicated software (FAST package, TNO-TPD, BioMedical Instrumentation). SBP, DBP, MAP, and PI were derived from each single pulse wave by the FAST software. PI was computed by measuring the time interval between consecutive pulse wave upstrokes, a procedure that enabled us to quantify heart rate variability with an accuracy comparable to that provided by analysis of electrocardiographic recordings in all daily life activities except strenuous physical exercise.8

BP and PI values were stored in separate time series for further analysis. Each series was visually scanned and edited from artifacts by an interactive procedure. The recording segments containing the automatic calibration signal were also removed from the Portapres tracings. After being edited, the Portapres and intra-arterial signals were compared by matching corresponding valid beats. After the editing procedure, data for 20 of the initial 24 subjects were considered suitable for further analysis. Recordings from 4 subjects were discarded owing to the failure of either the Oxford or the Portapres device to provide a full 24-hour BP profile. Although the number of beats available for these 4 subjects sufficed for a previous analysis based on a calculation of average BP values, it was not regarded as optimal for the more complex analyses of BP variability performed in the present study. However, as shown below (see “Results”), mean BP values and discrepancies between Portapres and intra-arterial signals in the 20 subjects were similar to those observed in the larger group of 24 subjects previously considered. Mean SBP, DBP, MAP, and PI values were computed for the entire 24-hour period and for the day (6 AM to 10 PM) and night (10 PM to 6 AM) periods together with their corresponding SDs. Mean and SD values were also computed for the time periods corresponding to the specific behaviors listed above. Because the Portapres device was programmed to be switched between fingers every 30 minutes, calculations of half-hour mean values and SDs were also made.

After high-pass filtering8-9 of fluctuations with a period >90 seconds and after linear interpolation of missing data, each series was split into segments of 120 seconds’ duration with a 10% overlap. Segments containing >10% interpolated signal were discarded. The power spectra were estimated by a nonparametric approach. First, the segments were “windowed” by a 10% cosine taper to reduce side lobes, and FFT spectra were estimated and integrated over three frequency bands, defined as low (0.025 to 0.04 Hz), mid (0.04 to 0.15 Hz), and high (0.15 to 0.50 Hz).8-11 All of the different power spectra were averaged over the periods for which mean BP had been computed (see above). Power spectra were also estimated on the same segments by means of autoregressive modeling. The autoregressive modeling spectra were computed by the Burg method12 after selection of a model order not <20 to satisfy the Akaike information criterion. With this approach, LF and HF powers were defined for a frequency range between 0.04 and 0.15 Hz and between 0.15 and 0.50 Hz, respectively, on the basis of recent recommendations.11

Power spectral analysis was also performed for frequencies below the range included in the aforementioned sequential spectral analysis by broadband spectral analysis.13 To this aim, each beat-to-beat series was interpolated by cubic splines, low-pass filtered at 1 Hz, and sampled at 2.2 Hz. For each 24-hour evenly sampled series, a single FFT spectrum was computed. Frequency and spectral powers were logarithmically transformed, and linear regression was computed over a frequency range of 0.00003 to 0.01 Hz for the whole 24-hour spectrum. The slopes of the regression lines represent the exponents (a) of the 1/fα model, which describes in a simple fashion the greater or smaller tendency of BP oscillations to become progressively more pronounced as the oscillation frequency decreases.13

Statistical Analysis

For each analyzed variable, individual data were averaged for the group as a whole. The agreement between the 24-hour spectral powers obtained from the Portapres and the intra-arterial recordings was assessed by the Bland and Altman14 approach; ie, the mean of Portapres and intra-arterial spectral powers was plotted versus the between-method difference for each variable and for each subject. Comparison of the results obtained by the Portapres and the intra-arterial method was carried out by a two-tailed Student’s t test for paired observations. Spectral powers were expressed in absolute values after logarithmic transformation to account for their nonnormal distribution. Comparison between the α exponents of the 1/fα model derived from the analysis of intra-arterial and finger BP recordings was carried out by the nonparametric sign test. A value of P<0.05 was taken as the level of statistical significance. Unless otherwise indicated, data are shown as mean±SEM.

Results

Mean Values and SDs

Figure 1 (left) shows mean intra-arterial and Portapres SBP, MAP, DBP, and PI values for the whole 24 hours, for daytime and nighttime separately, and for the standardized activities

<table>
<thead>
<tr>
<th>Time Period</th>
<th>SBP Mean (mm Hg)</th>
<th>SBP SD (mm Hg)</th>
<th>DBP Mean (mm Hg)</th>
<th>DBP SD (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Daytime</td>
<td>120 (±20)</td>
<td>15 (±5)</td>
<td>70 (±10)</td>
<td>8 (±2)</td>
</tr>
<tr>
<td>Nighttime</td>
<td>105 (±15)</td>
<td>12 (±4)</td>
<td>60 (±8)</td>
<td>7 (±3)</td>
</tr>
</tbody>
</table>
required by the study protocol (see “Methods”). Intra-arterial and Portapres mean values were usually similar for SBP and PI, but Portapres values were, in most instances, lower than intra-arterial ones for mean and DBP. These results were superimposable on those obtained in the entire group of 24 subjects studied and reported in a previous article. The SDs of SBP, MAP, and DBP were greater when computed from Portapres values than when derived from the intra-arterial tracing. This trend was particularly evident for SBP. The SDs of PI derived from the invasive and noninvasive signals were superimposable (Figure 1, right).

As shown in Figure 2 the nocturnal fall in intra-arterial BPs and BP SDs were greater when assessed by Portapres, whereas no difference was observed for the nocturnal increase in PI mean value and nocturnal reduction in PI SD (Figure 2).

**BP Spectral Powers**

Figure 3 illustrates the mean values of LF, MF, and HF BP powers obtained by the FFT approach for each half hour of the 24 hours separately for the Portapres and intra-arterial recordings, whereas Figure 4 shows the between-method differences in FFT-obtained powers for the entire 24 hours, day and night periods separately, and the standardized activities prescribed by the study protocol. LF BP powers were systematically higher when derived from Portapres than from intra-arterial recordings for the entire 24 hours. MF powers of SBP obtained by Portapres recordings were also greater than those obtained by intra-arterial recordings. In contrast, MF powers of mean and DBP were similarly assessed by intra-arterial and Portapres recordings except for data obtained during physical activity, for which MF powers of MAP and DBP of the Portapres were lower and MF powers of SBP similar as estimated by the two signals. HF spectra obtained by Portapres and intra-arterial recording were also similar, except for lower values of all HF BP powers during the night when Portapres signal was considered. As shown in Figure 5, there was no relation between the Portapres–intra-arterial discrepancies in spectral powers and the absolute power value. Similar findings were obtained when LF and HF powers were obtained by the autoregressive modeling approach. This is shown for the powers throughout the 24 hours in Table 1. No differences were observed between Portapres and intra-arterial recordings for any estimation of PI powers.

Intra-arterial and Portapres powers as obtained by broadband spectral analysis from a representative subject are shown in Figure 6, together with the corresponding regression lines of the 1/ƒα model. It is clear that owing to an overestimation of the lowest-frequency powers, the α value of SBP power was less steep for Portapres than for intra-arterial data.
(Table 2), whereas $\alpha$ values for MAP and DBP were similar for the two signals. This was also the case for $\alpha$ values of PI.

**Discussion**

In our study an overall measure of ambulatory BP variability, such as the 24-hour SD, was greater when quantified by Portapres than when quantified by the intra-arterial signal at the brachial artery level. Furthermore, ambulatory BP monitoring by Portapres also led to greater BP SD values when different subperiods or specific behaviors within the 24 hours were considered. Finally, use of the Portapres device was associated with greater day-night BP differences than those simultaneously quantified by intra-brachial recording, not only for mean values but also for SDs. Thus, the Portapres estimation of BP variability in daily life is greater than that obtained intra-arterially from the brachial artery, which is the common standard reference value that has been found to be clinically significant because of its relationship to end-organ damage of hypertension.

Does this overestimation of BP variability by the Portapres prevent this device from meaningfully quantifying this phenomenon? We believe that this is not the case for a number of reasons. First, as discussed below, some difference between BP variability measured by Portapres in the finger and...
intra-arterially from the brachial artery might be expected because the arterial signal differs throughout the arterial tree. Second, the overestimation of 24-hour SD was \(\approx 40\%\) for SBP but consistently less (\(\approx 20\%\)) for MAP and DBP. Furthermore, the difference between intra-arterially and Portapres-derived SD values tended to be similar, regardless of the time window or the activities during which the SDs were computed. This finding suggests that although the accuracy of the device is far from perfect, the error associated with the Portapres estimate of BP variability is not large, at least for MAP and DBP. It further suggests that because this error is relatively stable throughout the 24 hours, changes in BP variability over time may be reliably tracked by Portapres, which can thus be used to determine alterations in BP variability induced in a given subject by interventions of any nature. Obviously, it may also be used to study alterations in BP variability due to antihypertensive treatment by taking advantage of the evidence that overestimation of brachial BP variability by the Portapres is not related to the subject’s BP.

Our study also provides evidence on the ability of the Portapres device to reliably estimate BP powers at different frequencies throughout the 24 hours. The very low frequency fluctuations quantified by broadband spectral analysis were overestimated by Portapres compared with those obtained by brachial recording. This was also the case for the LF powers sequentially estimated by the FFT approach over contiguous segments of 120 seconds. However, the overestimation was again greater for systolic than for diastolic and mean BPs. Furthermore, MF powers of SBP as quantified by the FFT approach from Portapres and intra-arterial catheter data were less different, and MF powers for diastolic and mean BPs provided by the two methods were almost superimposable.

The Portapres overestimates several components of brachial artery BP variability, particularly in the very low and LF range, which is in line with the major contributions of these frequencies to overall BP variance. The Portapres more accurately reflects BP variability components in the MF range, which is important in the light of evidence that this range may reflect, to some degree, sympathetic BP influences. The accuracy of such a noninvasive estimate of this BP variability component can be made even greater if diastolic or mean rather than SBP is considered.

Few additional points should be made. One, the similarities and differences between the quantification of BP powers by Portapres and intra-arterial recording were similar when power spectral analysis was performed by FFT and the autoregressive modeling approach. Thus, the method used to compute powers does not affect the results obtained by the noninvasive, beat-to-beat, 24-hour BP monitoring device. Second, the HF brachial BP powers were accurately estimated by Portapres during the day but underestimated during the night. Third, the reason for this phenomenon, as well as for the different accurate estimates of intra-brachial BP variability components by the Portapres, cannot be explained by our study. It is possible, however, that (1) the greater amplitude of the LF BP oscillations in the Portapres recordings reflects more active vasomotor phenomena in peripheral compared with larger arteries and (2) the underestimation of HF BP oscillations by Portapres during sleep only depends on a sleep-induced synchronization of respiratory activity that

### Table 1. Mean Portapres–Intra-arterial Discrepancies

<table>
<thead>
<tr>
<th></th>
<th>LF (\log_{10})</th>
<th>(P_{\text{vs MF}_{\text{FFT}}})</th>
<th>HF (\log_{10})</th>
<th>(P_{\text{vs HF}_{\text{FFT}}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBP</td>
<td>0.13 ± 0.03</td>
<td>NS</td>
<td>0.03 ± 0.03</td>
<td>NS</td>
</tr>
<tr>
<td>MAP</td>
<td>−0.001 ± 0.01</td>
<td>NS</td>
<td>−0.02 ± 0.02</td>
<td>NS</td>
</tr>
<tr>
<td>DBP</td>
<td>0.08 ± 0.02</td>
<td>NS</td>
<td>0.05 ± 0.03</td>
<td>NS</td>
</tr>
</tbody>
</table>

AR indicates autoregressive modeling. Values are mean Portapres–intra-arterial discrepancies in SBP, MAP, and DBP LF (0.04 to 0.15 Hz) and HF (0.15 to 0.50 Hz) powers computed over the 24 hours in 20 subjects by the AR approach. Data are shown as mean ± SE. Statistics \((P)\) refer to comparison with FFT, MF, and HF data.
increases the HF BP oscillations, with a downward gradient from the large to the peripheral arteries. Finally, the importance of the overestimation of all SBP variability components by Portapres should not be minimized because (1) methods that allow baroreflex sensitivity to be assessed in daily life are based on SBP variations and (2) the error in estimating some components of SBP variability differs according to different activities, which may lead to a between-behavior bias that is difficult to correct.

In conclusion, the Portapres overestimates daily life overall BP variability and its components compared with the quantification provided by intra-arterial recording from a brachial artery. This overestimation may depend on differences related to the noninvasive versus the invasive approach, although phenomena related to the different measuring sites cannot be excluded. The important points, however, are that (1) the overestimation is not a major one, particularly if mean and DBPs are used; (2) for overall BP variability and for some of its frequency components, a similar overestimation occurs throughout the 24 hours; and (3) PI variability and its various components are accurately quantified by this noninvasive method compared with the values derived from the intra-arterial signal. This finding is clinically relevant because joint analysis of BP and PI variability can provide significant information on reflex cardiovascular regulation that may be of prognostic value in cardiovascular disease. The actual clinical importance of BP variability estimates provided by the Portapres, however, needs to be specifically addressed by studies relating these parameters to organ damage.

## References

## Table 2. Mean $\alpha$ Coefficients for the 1/$f^{\alpha}$ Distribution

<table>
<thead>
<tr>
<th></th>
<th>SBP</th>
<th>MAP</th>
<th>DBP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intra-arterial</td>
<td>1.47±0.03</td>
<td>1.38±0.05</td>
<td>1.43±0.04</td>
</tr>
<tr>
<td>Portapres</td>
<td>1.29±0.03*</td>
<td>1.37±0.03 NS</td>
<td>1.39±0.03 NS</td>
</tr>
</tbody>
</table>

Values are mean±SEM $\alpha$ coefficients for SBP, MAP, and DBP in the 20 study subjects. Asterisk refers to statistical significance of the between-methods differences. *$P<0.01$. 

## Figure 6. 1/$f^{\alpha}$ Distribution of intra-arterial (dotted line) and Portapres (solid line) SBP, MAP, and DBP powers (upper) and corresponding regression lines of the 1/$f^{\alpha}$ model (lower) in a representative subject.
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