Spectral and Sequence Analysis of Finger Blood Pressure Variability
Comparison With Analysis of Intra-arterial Recordings

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The aim of our study was to assess whether the Finapres device is able to accurately monitor not only average blood pressure values but also blood pressure variability. To examine this issue, we analyzed 30-minute recordings of finger and intra-arterial pressure simultaneously obtained at rest in 14 patients. We compared systolic blood pressure, diastolic blood pressure, mean arterial pressure, pulse interval (the reciprocal of heart rate), overall variability (standard deviation), and specific time-domain and frequency-domain components. Systolic blood pressure, diastolic blood pressure, mean arterial pressure, and pulse interval spectral powers were computed by fast Fourier transform over three frequency bands: low frequency (0.025 to 0.07 Hz), midfrequency (0.07 to 0.14 Hz), and high frequency (0.14 to 0.35 Hz). The coherence, ie, the degree of association between blood pressure and pulse interval powers obtained by the two techniques, was also assessed. Standard deviations of diastolic blood pressure, mean arterial pressure, and pulse interval were similar when assessed from the two recordings, whereas standard deviation of systolic blood pressure was overestimated by analysis of finger pressure recordings. All powers of diastolic blood pressure and mean arterial pressure and high-frequency powers of systolic blood pressure estimated from analysis of finger blood pressure tracings were superimposable to those obtained by analyzing invasive recordings. Low-frequency and midfrequency powers of intra-arterial systolic blood pressure were significantly overestimated by the analysis of finger blood pressure tracings (±13.7±4.4 mm Hg², P<.01, and ±2.3±0.9 mm Hg², P<.05). Finger and intra-arterial systolic blood pressure, diastolic blood pressure, mean arterial pressure, and pulse interval powers showed a high coherence in the frequency range considered (0.025 to 0.35 Hz). The coherence of all blood pressure powers became smaller for frequencies greater than 0.35 Hz and lower than 0.025 Hz. The number and slope of hypertension-bradycardia (+pulse interval/+systolic blood pressure) and hypotension-tachycardia (−pulse interval/−systolic blood pressure) sequences assessed by time-domain analysis of both recordings were similar. Thus, specific frequency-domain and time-domain components of blood pressure and pulse interval variability seem to be properly assessed by finger blood pressure recordings in most cases, although low-frequency oscillations of systolic blood pressure appear to be magnified by finger blood pressure tracings. (Hypertension 1993;22:26-33)

KEY WORDS • blood pressure monitors • spectrum analysis • pressoreceptors • blood pressure determination

Computer analysis of blood pressure variability provides information on the mechanisms regulating blood pressure in humans. This analysis relies on the standard deviation or the variation coefficient calculated from prolonged monitoring periods.1 It also makes use of complex methods to identify blood pressure variations in the time and frequency domains, which have been shown to reflect neural and nonneural mechanisms modulating the cardiovascular system.2-8

The above analyses require a beat-by-beat blood pressure signal of adequate quality, a problem that has limited their application to intra-arterial recordings. In recent years, however, a method based on continuous monitoring of blood pressure through a finger cuff has offered a noninvasive, beat-by-beat alternative to the intra-arterial approach.9-12 To date, this method has been shown to provide reliable blood pressure values at rest and during laboratory maneuvers causing a pressor or depressor response.13,14 Little or no information exists as to whether beat-by-beat finger pressure recording is also suitable for more complex time- and frequency-domain analysis of the blood pressure signal, making it available on a larger scale. We have set out to examine this issue.

Methods
Subjects and Measurements
Our study included 14 mild or moderate untreated essential hypertensive inpatients (12 men, 2 women;
mean age ± SEM, 47.4 ± 10.2 years; range, 29 to 64 years). In each patient, between-arm difference in mean blood pressure was assessed by two trained operators making use of two arm cuffs connected via Y tubing to a single mercury column and always found to be less than 5 mm Hg. Blood pressure was then recorded for approximately the noninvasive arm (mean ± SD, 27.1 ± 0.3 minutes) with patients in a supine resting condition by both the Finapres device (Ohmeda 2300, Finapres, Englwood, Colo) and an intra-arterial catheter (11-cm length, 1.3-mm internal diameter) percutaneously introduced into the radial artery of the nondominant arm (Seldinger technique) after local anesthesia with 2% lidocaine. The catheter was periodically flushed with a saline solution containing 0.3% heparin and was connected via a rigid polyethylene tube to a P23 ID pressure transducer (Statham, Oxnard, Calif). The frequency response of the catheter-tubing-transducer system was optimal up to 35 Hz (−3 dB level). The transduced signal was displayed on a strip-chart recorder (model 7, Grass Instruments, Quincy, Mass) and stored on magnetic tape (Racal Recorders Ltd, Hythe, Southampton, UK). The Finapres device has been described in detail elsewhere. Briefly, this instrument operates through an inflatable finger cuff equipped with an infrared photoplethysmograph devised to measure the finger artery blood volume under the cuff. The cuff is plugged to a front-end box wrapped to the subject’s hand. The box contains a fast proportional pneumatic valve connected to a source of compressed air, an electropneumatic transducer, and the electronics for the plethysmograph. The finger artery blood volume, as assessed by the plethysmograph, is clamped at a predetermined set-point value (corresponding to two thirds of the maximal artery blood volume) at which the arterial wall is considered as unloaded, ie, the external pressure equals the internal pressure. This set point is thereafter maintained by continuous adjustments of the finger cuff pressure in parallel with intra-arterial pressure changes through a fast electropneumatic servo system having a bandwidth of at least 40 Hz. The clamped volume set point is periodically adjusted to keep the finger arteries unloaded (ie, at zero transmural pressure) also in case of changes in vasomotor tone, thus allowing cuff pressure to continuously reflect intra-arterial pressure. For each 30-minute recording period, the automatic Finapres calibration was performed only at the beginning, after 15 minutes, and at the end. It was switched off over the remaining time periods. This was done to obtain a continuous undisturbed recording. This procedure should be considered safe because (1) no shift in the zero level occurred over the 30-minute recordings obtained in controlled conditions, as shown by the absence of significant differences in the finger pressure values obtained before the last calibration preceding the recording period and after the final calibration performed at the end of the recording period; and (2) our group previously compared finger and intra-arterial tracings in different experimental conditions and observed that over the same time no worsening of the difference between the noninvasive and intra-arterial signals occurs with time, over a similar 30-minute recording period at rest, even with the automatic calibration of the Finapres switched off.

In nine patients, the cuff was wrapped around the middle or ring finger of the hand ipsilateral to the arm in which the arterial catheter was inserted. In five patients, the middle and ring fingers of the contralateral arm had to be used because the ipsilateral finger blood pressure signal was unsatisfactory, presumably because it was disturbed by the proximal location of the catheter. Throughout the study, the finger wearing the cuff was kept at the same level as the intra-arterial blood pressure transducer, both being positioned approximately at heart level. Both the intra-arterial and finger pressure signals were displayed on the Grass polygraph and stored on a tape recorder. The patients entered the study after giving informed consent. The protocol of the study was approved by the Ethics Committee of our institution.

Data Analysis

The intra-arterial and finger blood pressure signals were sampled at 180 Hz and digitized at 12 bits by a personal computer (model 380/XP, Olivetti & Co, Ivrea, Italy). Both signals were then simultaneously displayed on the computer screen to allow detection and editing of (1) possible morphological aberrations, such as arrhythmias, dampening of the intra-arterial signal, or oscillations in finger blood pressure, and (2) periodical adjustments of the volume-clamp set point on the finger artery signal. The editing, which was accomplished by means of an interactive procedure, removed an average of 4.8% of the signal and left 1843.2 ± 712.1 beats (mean ± SD) available for further analysis. This consisted of calculation of systolic, diastolic, and mean blood pressures for each pulse wave and of pulse interval, ie, the reciprocal of heart rate, which was calculated from the interval between two consecutive systolic peaks. All parameters were stored in separate time series, and the average systolic, diastolic, and mean blood pressure and pulse interval values for the whole recording period were calculated in each patient. The standard deviation of these average values was also calculated and taken as a measure of the overall variability of the parameter under evaluation. In each patient, both the intra-arterial and finger blood pressure or pulse interval values were also plotted as a function of their frequency of occurrence. The features of these frequency distribution curves were quantified by computing the kurtosis (K) and skewness (S) indexes. In case of a normal distribution, the K and S values are equal to zero.

Further analysis addressed specific components of blood pressure and pulse interval variability in the frequency domain. To this end, spectral characteristics of blood pressure and pulse interval were estimated after high-pass filtering each time series to remove fluctuations having a period greater than 90 seconds. To this end, a high-pass Chebyshev filter (third order) was used. Each filtered series was then split into contiguous segments of 100 seconds, and segments containing erratic and transient blood pressure and pulse interval changes were identified by the reverse arrangement test and discarded. The spectral characteristics of the remaining stationary segments were estimated by fast Fourier transform in a sequential fashion. Cumulative powers were integrated over three frequency bands defined as low frequency (LF, 0.025 to 0.07 Hz), mid
Fig 1. Bar graphs show comparison between systolic blood pressure (SBP), diastolic blood pressure (DBP), mean arterial pressure (MAP), and pulse interval (PI) average values (top panels) and standard deviations (bottom panels) obtained intra-arterially (open bars) and by the Finapres (striped bars). Data are mean±SEM for 14 patients. Asterisks refer to statistical significance of between-method differences.

A single spectral analysis over the whole unfiltered signals was also performed in five patients, and the spectral powers of systolic blood pressure, diastolic blood pressure, and pulse interval derived from the noninvasive and invasive recordings within the frequency range from 1.0 to 0.001 Hz were compared via transfer function analysis.

Finally, computer analysis of finger and intra-arterial blood pressure signals was performed in the time domain to identify another specific component of blood pressure and pulse interval variability, ie, that accounted for by progressive increases in systolic blood pressure and pulse interval or progressive decreases in systolic blood pressure or pulse interval (+PI/+SBP and −PI/−SBP) for three consecutive beats. This analysis has been described in detail elsewhere. Briefly, the threshold for identification of the step blood pressure and pulse interval changes was 1 mm Hg and 5 milliseconds, respectively. For either event or sequence, pulse interval and systolic blood pressure changes were always linearly related to each other (r>0.85), allowing the regression coefficient to be taken as an index of the sensitivity of baroreceptor reflex control of heart rate, similar to what is done when blood pressure and pulse interval are altered by intravenous injection of phenylephrine or nitroglycerin. The regression coefficients were averaged for each patient separately for the +PI/+SBP and −PI/−SBP sequences. The within-subject variability of the regression coefficient was expressed as the coefficient of variation of its mean value.

For both the spectral and sequence analyses, individual data were averaged to obtain mean values for the group as a whole. Data obtained from the finger and intra-arterial recordings were compared by (1) a two-tailed Student's t test for paired (and for the sequence also unpaired) observations and (2) a linear regression analysis, a perfect between-method correspondence being indicated by an intercept equal to zero and correlation and regression coefficients equal to 1. Linear regression analysis between finger and intra-arterial blood pressure and pulse interval powers was performed after a logarithmic transformation of the powers to account for the large between-subject variability in the magnitude of the different spectral components. A value of P<0.05 was taken as the level of statistical significance. Unless otherwise indicated, values are shown as mean±SEM. Data obtained by coherence analysis.
Fig. 3. Tridimensional plots show spectral powers of systolic blood pressure (SBP), diastolic blood pressure (DBP), mean arterial pressure (MAP), and pulse
interval (PI) computed over consecutive periods of 100 seconds in one patient. Data are derived from a 30-minute intra-arterial (top panels) and a simultaneous 30-minute Finapres (bottom panels) blood pressure recording.
Results

Average Blood Pressure and Pulse Interval Values

The top panels of Fig 1 illustrate the average systolic blood pressure, diastolic blood pressure, mean blood pressure, and pulse interval values obtained by finger and intra-arterial blood pressure recording in the 14 patients of our study. The pulse interval values derived from the two signals were superimposable. The systolic, diastolic, and mean blood pressure values were slightly higher for finger than for intra-arterial recordings, although the average finger–intra-arterial difference (+5.9±17.7, +5.7±6.1, and +3.4±8.4 mm Hg, respectively; mean±SD) was statistically significant (P<.01) for diastolic blood pressure only.

The standard deviations of the average blood pressure values obtained for the whole recording period were also slightly higher when assessed by finger than by intra-arterial recording (Fig 1, bottom panels). The average difference, however, was statistically significant only for systolic blood pressure (+1.9±2.4 mm Hg, P<.05).

As shown in Fig 2, frequency distribution histograms for intra-arterial systolic blood pressure, diastolic blood pressure, mean arterial pressure (MAP), and pulse interval (PI) were presented. The coherence values (k^2) between these parameters computed for frequencies lower than 0.35 Hz are shown in Fig 5.
pressure, and mean arterial pressure were characterized by a slight asymmetry, S being always different from zero. However, a similar asymmetry characterized the frequency histograms of finger blood pressure values. The mean differences in K and S values between finger and intra-arterial pressure tracings were, respectively, −0.3±0.2 and +0.02±0.1 mm Hg for systolic blood pressure, −0.3±0.3 and −0.07±0.1 mm Hg for diastolic blood pressure, and +0.04±0.2 and +0.05±0.08 mm Hg for mean arterial pressure. The differences were never statistically significant.

Spectral Powers

As shown in Fig 3, the spectral powers of pulse interval were similar for finger and intra-arterial recordings. This was the case also for the spectral powers of mean and diastolic blood pressures. However, the spectral powers of systolic blood pressure located in the lower portion of the frequency band spectrum were overestimated by finger recording. These between-method similarities and differences are shown in Fig 4 as cumulative powers for the group as a whole. It is clear that pulse interval, mean blood pressure, and diastolic blood pressure cumulative powers were similar for finger and intra-arterial recordings in the LF, MF, and HF bands. This was the case also for the HF power of systolic blood pressure. On the other hand, the LF and MF powers of systolic blood pressure were overestimated when computed from finger compared with intra-arterial recordings. The average differences, which were +77.4% and +43.4%, respectively, were statistically significant.

After logarithmic transformation, the LF, MF, and HF powers of systolic blood pressure, diastolic blood pressure, mean arterial pressure, and pulse interval obtained from finger recordings almost invariably showed a close, significant correlation with the corresponding powers obtained from intra-arterial recordings, the correlation coefficients always being greater than 0.70. As shown in Fig 5 in the group as a whole, the coherence between powers obtained by finger and intra-arterial recordings was always more than 0.50 and highest at approximately 0.1 and 0.25 Hz. The coherence for pulse interval was also statistically significant and highest at 0.14 Hz or less, with a progressive decline at higher frequencies.

Finally, Fig 6 shows that the overestimation of systolic blood pressure powers associated with finger pressure recording was not limited to MF and LF components (see above) but was extended to slower fluctuations up to a period of 15 minutes, ie, with a frequency of 0.001 Hz. In these very low-frequency regions, a slight overestimation by the finger pressure recording was observed for diastolic blood pressure as well, whereas...
vers. It further shows, however, that (1) the standard deviation of systolic blood pressure measurements by the Finapres are similar to those obtained for a prolonged monitoring period; (2) the two methods provide a similar quantitative estimation of LF, MF, and HF blood pressure powers; (3) they similarly estimate the number, slope, and slope variability of spontaneous sequences characterized by progressive hypertension and bradycardia or hypotension and tachycardia. Thus, the Finapres can adequately assess both blood pressure average values and blood pressure variability. It can also characterize the complex components of this phenomenon that are detected by power spectral analysis and the cardiovascular events that allow daily life evaluation of the arterial baroreceptor reflex. Its use therefore can be recommended as a reliable substitute for intra-arterial recording when cardiovascular control mechanisms are studied by the most current methods of blood pressure signal analysis.

The Finapres performed equally well with regard to pulse interval average values, variability, and time- and frequency-domain components. However, not all data recorded by this method were similar to those obtained by simultaneous intra-arterial recording. For example, the standard deviation of systolic blood pressure powers was significantly greater when assessed by the Finapres than intra-arterially. Furthermore, Finapres-dependent LF and MF systolic blood pressure powers were greater than the corresponding intra-arterial values. Finally, the Finapres overestimated systolic blood pressure powers also in the very low-frequency range examined in our study, ie, below 0.025 Hz. Because, generally speaking, the distribution of blood pressure and pulse interval powers is inversely proportional to their frequency (ie, it shows a 1/f pattern), slower fluctuations are characterized by a greater power than faster ones. This observation, combined with the fact that the overall variance of blood pressure or heart rate is proportional to the integral of its power spectrum (Parseval's theorem), suggests that Finapres overestimation of systolic blood pressure LF powers contributes to the higher overall variability of finger systolic blood pressure.

We can speculate that these discrepancies between finger and intra-arterial data are due to an intrinsic defect of the Finapres method to precisely reproduce alterations in systolic blood pressure, although the possibility cannot be ruled out that these alterations are in fact underestimated by an intra-arterial recording, which makes use of a fluid-filled connection between the artery and the transducer. Other explanations include the possibility that, rather than being overestimated, systolic blood pressure variability and powers were greater at the arterial site used for the Finapres measurements because the site was somewhat distal to the radial intra-arterial measurement. This site was characterized by (1) an amplification of the pulse pressure waveform due to the progressive increase in systolic blood pressure from the aorta to the peripheral circulation and/or (2) a greater effect of the rhythmic changes in arteriolar tone that have been shown to occur particularly in the low- and very low-frequency bands. This implies that the Finapres may be even more accurate than it appears in quantifying the complex blood pressure events shown by power spectral analysis. Its accuracy appears satisfactory even assuming an overestimation of systolic blood pressure powers, however, because for all blood pressure powers Finapres and intra-arterial data are highly coherent over a frequency range between 0.025 and 0.35 Hz, a coher-

![Image of histograms showing number of three-beat sequences characterized by progressive increase (+PI/+SBP) or progressive decrease (−PI/−SBP) in pulse interval (PI) and systolic blood pressure (SBP) (top panel), their mean regression coefficients (middle panel), and variation coefficients of these regression coefficients (bottom panel). Data represent mean±SEM from the 14 study patients.]

**Fig 7.** Histograms show number of three-beat sequences characterized by progressive increase (+PI/+SBP) or progressive decrease (−PI/−SBP) in pulse interval (PI) and systolic blood pressure (SBP) (top panel), their mean regression coefficients (middle panel), and variation coefficients of these regression coefficients (bottom panel). Data represent mean±SEM from the 14 study patients.
ence decline being observed only at frequencies beyond this large range.

In conclusion, the beat-to-beat noninvasive blood pressure provided by the Finapres is suitable for assessment of average blood pressure values over a prolonged monitoring period. It is also suitable for assessment of overall blood pressure variability and of the more complex variability components provided by power spectrum and sequence analysis of the blood pressure signal. This method thus can be used for investigating neural and nonneural mechanisms of blood pressure control,2,4,20 avoiding invasive procedures and greatly simplifying studies in healthy and diseased humans. The Finapres estimate of these phenomena is not entirely accurate, however, and caution should be exercised particularly in the interpretation of slow systolic blood pressure oscillations because of their magnification by this noninvasive approach.

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