Sequential Spectral Analysis of 24-Hour Blood Pressure and Pulse Interval in Humans

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Blood pressure and pulse interval are characterized not only by erratic variations but also by rhythmic fluctuations at low-, mid-, and high-frequency (0.025–0.07, 0.07–0.14, and 0.14–0.35 Hz, respectively). However, information on these phenomena has largely been derived from analysis of short-term recordings taken in standardized laboratory conditions. In seven normotensive and 10 untreated mild essential hypertensive subjects, power spectrum analysis was performed on the intra-arterial blood pressure and pulse interval signal collected over a 24-hour period using the fast Fourier transform algorithm and splitting the recording into contiguous segments of 256 beats. About 70% of the segments were suitable for the analysis; the segments excluded for a nonstationary signal amounted to only 30%. All powers were characterized by a high segment-to-segment variability, but in each subject the mid- and high-frequency powers of diastolic blood pressure and the mid-frequency power of systolic blood pressure were markedly reduced during the night as compared with the daytime period, whereas the opposite occurred for the low- and high-frequency powers of the pulse interval. Over the 24-hour period, mid- and high-frequency powers of blood pressure were positively correlated to each other, but both accounted for less than 25% of the 24-hour blood pressure variance. No difference between mean normalized power values of normotensive and hypertensive subjects was observed. Thus, at both normal and mildly elevated blood pressure, rhythmic blood pressure and pulse interval oscillations falling in the low-, mid-, and high-frequency ranges are not masked by the erratic environmental stimuli of daily life but can be identified over most of the 24-hour time period. The magnitude of these phenomena is only a fraction of the overall variability and is subjected to large moment-to-moment modifications. In several circumstances, however, the nighttime period was accompanied by systematic and pronounced changes that may help in determining the mechanisms that underlie these events. (Hypertension 1990;16:414–421)

Several studies have shown that blood pressure and heart rate change not only in relation to behavioral and environmental factors but also as a result of regular fluctuations unrelated to external stimuli. This is an interesting finding because regular fluctuations mean that influences with an inner rhythm affect the cardiovascular system.

Blood pressure and heart rate may fluctuate with periods of minutes and hours, and fluctuations occurring at frequencies from 0.025 to 0.35 Hz have raised special interest because of their possible relation with neurohumoral factors involved in cardiovascular control, particularly with sympathetic and parasympathetic influences. These fluctuations, however, have usually been analyzed through short-term tracings recorded while the experimental subject was in a steady-state condition at rest or during standardized stimuli (e.g., physical exercise, changes in posture, infusion of vasoactive drugs). Thus, little is known on the occurrence of these phenomena in daily life. We have shown that in hypertensive patients spectral analysis can be applied to 24-hour blood pressure and heart rate tracings, and this finding has recently been confirmed. It is not known, however, whether rhythmic blood pressure and heart rate events systematically characterize most of the 24-hour period and how they are modified by behavioral circumstances. Whether these events differ at normal and high blood pressure and to what degree they contribute to overall blood
pressure and heart rate variabilities is also unknown. Our study has addressed this problem in ambulatory normotensive and hypertensive subjects in whom intra-arterial blood pressure and heart rate were continuously recorded for 24 hours.

Methods

Subjects and Blood Pressure Recording

The study was carried out in 10 normotensive subjects (office blood pressure ≤140/90 mm Hg at two separate visits) and in 13 inpatients with an untreated mild essential hypertension. Blood pressure was continuously recorded in all subjects for 24 hours. The recording was obtained, after local anesthesia with 2% lidocaine, by inserting a thin catheter (11 cm length, 1.3 mm i.d.) into a radial artery. The catheter was connected via a rigid-walled plastic tube to a transducer placed in a Plexiglas box at the level of the heart, which also contained a 40 ml saline reservoir and an electric pump for continuous arterial perfusion. The transduced pressure signal was modulated and stored on a portable magnetic casette tape recorder fastened to the subject's waist. The recording was demodulated by a playback unit, and the pressure signal was sent to a VAX 750 computer for subsequent analysis. The overall frequency response of the transducer-recorder-decoder apparatus was 0–8 Hz (–3 dB level). Other details of the blood pressure recording technique have been described in previous studies.20-22

During the recording period the patients were asked to conform to the hospital schedule for meal and sleep times; in the remaining hours they were free to move within the hospital area and to engage in the social activities of the hospital inpatients not confined to bed (e.g., playing cards, watching TV, meeting relatives, walking within the hospital area). All subjects gave informed consent.

The blood pressure signal was not regarded as adequate in three normotensive and three hypertensive subjects. Thus, the analysis of the 24-hour blood pressure recording was performed in seven normotensive (age 46.3±5.9 years, mean±SEM; range 26–70 years) and 10 hypertensive subjects (age 50.0±4.2 years; range 23–70 years). The recording was sampled at 166 Hz and digitized on 12 bits. The digitized signal was edited from artifacts by an interactive procedure and subdivided into separate pulse waves from which systolic and diastolic blood pressure were computed. The pulse interval was derived from the blood pressure, and pulse interval variance and multiplied by 100. The normalized power spectrum was estimated from the areas of the respective frequency segments (Figure 1). For pulse interval the spectra corresponded to those obtained by considering the R-R interval (through analysis of electrocardiogram recordings), thus validating the intervals derived by use of blood pressure signal only (Figure 2).

Running Power Spectrum Analysis

Extending the spectral analysis from short, isolated blood pressure and heart rate segments recorded in standardized conditions to consecutive segments recorded throughout a 24-hour period presented the following problems: 1) the great amount of data involved (about a hundred thousand pulse waves) and 2) the occurrence of abrupt changes in blood pressure and pulse interval induced by daily life stimuli, behavioral activities, and other sources of nonrhythmic cardiovascular changes. These were overcome by making data analysis largely automatic and using fast algorithms that reduced the computational time required.21,22 In addition, the blood pressure signal was dynamically conditioned to detect and remove segments of data containing nonstationarities (see below). A detailed mathematical description of the procedure used has been provided elsewhere.18

In brief, each series was processed as follows: 1) the signal was filtered twice by a high pass Chebyshev filter with the cutoff frequency placed at ωc=0.025 rad/sec to remove the blood pressure and pulse interval oscillations with a period greater than 30 seconds,24 2) the high pass filtered series were split into contiguous segments of 256 values, 3) the segments containing nonstationarities were detected and excluded by a procedure based on the reverse arrangement test,25 4) the power spectral density (PSD) of each stationary segment was estimated using the standard fast Fourier transform algorithm after a 10% cosine taping of the raw data. This algorithm was chosen because previous data by our group have shown that its results are superimposable on those obtained by a more sophisticated algorithm based on autoregressive modeling of the data,18,23,29 and 5) the powers of the oscillations at frequencies between 0.025 and 0.07 Hz (low frequency [LF]), 0.07 and 0.14 Hz (mid frequency [MF]), and 0.14 and 0.35 Hz (high frequency [HF]) were calculated for each segment (Figure 1). For pulse interval the spectra corresponded to those obtained by considering the R-R interval (through analysis of electrocardiogram recordings), thus validating the intervals derived by use of blood pressure signal only (Figure 2).

LF, MF, and HF powers were calculated in absolute values from the areas of the respective frequency ranges. Because their magnitude showed large inter-individual differences, data were also normalized by dividing individual power values by the corresponding 24-hour systolic blood pressure (see below), diastolic blood pressure, and pulse interval variance and multiplying the ratio by 100. The normalized power spectral data were averaged to obtain half-hourly mean values. Individual half-hourly values were averaged separately for normotensive and hypertensive subjects to obtain half-hourly mean values (±SEM) for each group. Differences among half-hourly powers were statistically evaluated by two-tailed t test after logarithmic transformation of the data. A p<0.02 was taken as the level of statistical significance.

Blood Pressure and Pulse Interval Means and Overall Variabilities

In addition to power spectrum analysis, systolic blood pressure, diastolic blood pressure, and pulse interval were analyzed in terms of half-hourly mean values and standard deviations or variances. The
FIGURE 1. Ranges of low- (LF), mid- (MF), and high-frequency (HF) rhythmic oscillations of systolic blood pressure (SBP) considered in our study. Data refer to power spectrum density (PSD) computed over a 4-minute period.

FIGURE 2. Low- (LF), mid- (MF), and high- (HF) frequency powers of heart interval over the 24-hour period in an individual subject. Data obtained by power spectrum analysis of R-R interval changes (electrocardiogram recording, right panels) are compared with those obtained by power spectrum analysis of pulse interval changes (computed as distance between two consecutive systolic peaks from intra-arterial recording, left panels).
SYSTOLIC BLOOD PRESSURE

Subject: 1BE

Figure 3. Sequential power spectrum densities (PSD) of low-(LF), mid- (MF), and high-(HF) frequency rhythmic oscillations of systolic blood pressure (SBP) computed over consecutive segments of 256 beats throughout the 24-hour period. SBP mean values and standard deviations (SD) for each half hour of recording are also shown. Data are derived from a 24-hour intra-arterial ambulatory blood pressure recording of a representative subject (B.E.). Dotted lines on right panel refer to segments in which PSD could not be estimated because of nonstationarities in the recorded signal.

standard deviations or variances were taken as measures of the overall blood pressure and pulse interval variabilities (i.e., the variabilities due not only to rhythmic but also to nonrhythmic oscillations). 1,3 Individual data were averaged for normotensive and hypertensive subjects.

Results

As exemplified in the systolic blood pressure tracing of Figure 3, 24-hour blood pressure and pulse interval showed in each subject nonstationary segments unsuitable for power spectrum analysis. However, these segments represented less than 30% of the total number of segments available during the recording time. Thus, power spectrum analysis could be performed on the majority of the recorded signals. There was no systematic difference in the number of segments suitable for power spectral analysis (i.e., stationary segments) between different periods of the day and between the daytime and nighttime periods.

Figure 3 also shows that the spectra of systolic blood pressure obtained over the 24-hour period showed a large segment-to-segment variability in power and a grouping of the HF power around a narrower frequency during the night than during the day. This was the case for diastolic blood pressure and pulse interval as well. It was also the case for all subjects whether their blood pressure level was normal or high.

In normotensive subjects, mean 24-hour systolic blood pressure was 114.2±5.4 mm Hg, mean 24-hour diastolic blood pressure was 65.2±3.2 mm Hg, and mean 24-hour pulse interval was 733.5±26.3 msec. As shown in Figure 4, the mean half-hourly powers for all three variables showed systematic differences between the daytime and nighttime periods. Compared with daytime, the LF and HF powers for pulse interval increased during the nighttime period. Furthermore, the MF power for systolic and diastolic blood pressure and the HF power for systolic blood pressure showed a pronounced reduction at night. Finally, the HF power for diastolic blood pressure also showed a reduction at night, although this was less evident than for the HF power for systolic blood pressure. Hypertensive subjects (mean 24-hour systolic blood pressure 145.6±8.3 mm Hg, mean 24-
AVERAGE (±SE) POWERS NORMALIZED OVER TOTAL VARIANCE IN NORMOTENSIVE SUBJECTS

Figure 4. Graphs showing low- (LF), mid- (MF), and high- (HF) frequency powers of systolic blood pressure (SBP), diastolic blood pressure (DBP), and pulse interval (PI) for seven normotensive subjects included in the present study. Data are averaged for each half hour and shown as mean±SEM. Powers are represented as percent of the 24-hour variance. Asterisks refer to statistical significance of difference between subperiods of day (a) and night (b). Subperiod duration is indicated by horizontal bar.

In normotensive and hypertensive subjects the half-hourly means and variances of systolic blood pressure, diastolic blood pressure, and pulse interval varied widely within the 24-hour period. There was a fall in blood pressure, heart rate, blood pressure variance, and to a less consistent degree, in pulse interval variance during the night. In both groups of subjects these changes were associated with a nocturnal fall in the absolute powers of MF systolic and diastolic blood pressure oscillations and in those of HF diastolic blood pressure oscillations. They were also associated with an increase at night in the absolute powers of LF and HF pulse interval oscillations (Figures 6 and 7). In normotensive subjects, the quantitative contribution of MF and HF powers combined to 24-hour variance was 19.6% for systolic blood pressure, 17.8% for diastolic blood pressure, and 15.6% for pulse interval.

The respective features in hypertensive subjects were 22.8%, 17.7%, and 13.3%.

Discussion

Our data demonstrate that blood pressure and pulse interval oscillations at frequencies ranging from 0.025 to 0.35 Hz (the so-called LF, MF, and HF oscillations) occur in ambulatory subjects and that they can be identified over most of the daytime and nighttime periods. This implies that the heart and the systemic circulation are subjected to a rhythmic functional modulation not only during standardized short-term laboratory conditions but also over the variety of behavioral patterns taking place in daily life. It also implies that the mechanisms responsible for these rhythmic events are not superseded by the erratic hemodynamic influences of environmental stimuli.

Several other new findings of our study deserve to be mentioned. First, rhythmic blood pressure and pulse interval oscillations showed systematic differences between the daytime and nighttime periods. These differences consisted of a nighttime reduction in the segment-to-segment variability of the MF and HF blood pressure powers (see below) and a pro-
AVERAGE (±SE) POWERS NORMALIZED OVER TOTAL VARIANCE IN HYPERTENSIVE SUBJECTS

**FIGURE 5.** Graphs showing low- (LF), mid- (MF), and high- (HF) frequency powers of systolic blood pressure (SBP), diastolic blood pressure (DBP), and pulse interval (PI) for the 10 hypertensive subjects included in the present study. Data are averaged for each half hour and shown as mean±SEM. Powers are represented as percent of 24-hour variance. Asterisks refer to statistical significance of difference between subperiods of day (a) and night (b). Subperiod duration is indicated by horizontal bar.

nounced nighttime reduction of the MF and HF powers for blood pressure, indicating that the well-known reduction in blood pressure variability that occurs during sleep is paralleled by a reduction in the amplitude of these two relatively fast rhythmic blood pressure changes. However, other blood pressure powers (the LF powers) did not change and some pulse interval powers (the LF and HF powers) increased during the night in sharp contrast with the reduction in overall pulse interval variability taking place under this circumstance. Thus, not all rhythmic hemodynamic phenomena are blunted during sleep.

Second, the changes in blood pressure and pulse interval powers over the 24-hour period were similar in subjects with normal and high blood pressure, suggesting that the mechanisms dynamically modulating these rhythmic phenomena are not deranged in hypertension. This applies, however, to the mild hypertensive condition shown by our patients; the 24-hour pattern of blood pressure and pulse interval powers within the LF, MF, and HF range in more severe hypertensive patients remains to be explored.

Third, the magnitude of LF, MF, and HF changes in blood pressure and pulse interval powers over the 24-hour period showed pronounced segment-to-segment differences, indicating that rhythmic blood pressure and heart rate phenomena have a high moment-to-moment variability. This phenomenon, which is more pronounced during the day (see above), raises the possibility that power spectrum analysis of short-term periods falls short of representing the overall power spectrum pattern of a 24-hour period.

Fourth, in both the normotensive and hypertensive group MF and HF changes represented less than one fourth of the blood pressure or pulse interval variance. Although a strict comparison between the two variables is made difficult by the fact that the powers of the rhythmic oscillations were computed over 4-minute periods while the variance was estimated on a beat-to-beat basis, this suggests that fast rhythmic phenomena represent only a small fraction of the blood pressure and heart rate variations that occur over a 24-hour period. It is likely that oscillations occurring at lower frequencies than those considered in the present study increase the contribution of rhythmic events to overall blood pressure and pulse interval variability. It is also likely, however, that a large fraction of variability phenomena have a nonrhythmic nature. Therefore, a quantitative identification of spectral powers with overall variability phenomena should be avoided.

Finally, sleep is known to cause a reduction in sympathetic vascular tone and an increase in cardiac vagal tone. Thus, the decrease in MF blood pres-
FIGURE 6. Line graphs showing means and variances (lower panels) and power spectrum densities of low- (LF), mid- (MF), and high- (HF) frequency oscillations (upper panels) of systolic blood pressure (SBP), diastolic blood pressure (DBP), and pulse interval (PI). Data are shown as absolute average values of each half hour of recording in the seven normotensive subjects of the present study.

FIGURE 7. Line graphs showing mean values and variances (lower panels) and power spectrum densities of low- (LF), mid- (MF), and high- (HF) frequency oscillations (upper panels) of systolic blood pressure (SBP), diastolic blood pressure (DBP), and pulse interval (PI). Data are shown as absolute average values of each half hour of recording in the 10 hypertensive subjects of the present study.
sured and the increase in HF pulse interval powers that were observed during the night are compatible with the hypothesis that the former reflects sympathetic vascular modulation and the latter parasympathetic cardiac drive.\textsuperscript{10,11,13,15,28} However, the reduction in the HF blood pressure and the increase in LF pulse interval power that occurred during the night are not easily explained by the same hypothesis because sympathetic influences may be too sluggish to modulate changes in vascular tone at frequencies higher than 0.15 Hz,\textsuperscript{29,30} whereas vagal influences are usually fast and unrelated with slow pulse interval changes. The issue is complicated by the relation of HF blood pressure and pulse interval fluctuations with ventilation,\textsuperscript{31} the rate of which is modified by sleep.\textsuperscript{27} Thus, the changes in blood pressure and pulse interval LF, MF, and HF powers occurring during a 24-hour period cannot be safely ascribed only to autonomic cardiovascular modulation, and some uncertainty about the mechanisms responsible for these events remains.

**References**


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