Even slight movements disturb analysis of cardiovascular dynamics

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Fortrat, Jacques-Olivier, Cedric Formet, Jean Frutoso, and Claude Gharib. Even slight movements disturb analysis of cardiovascular dynamics. Am. J. Physiol. 277 (Heart Circ. Physiol. 46): H261–H267, 1999.—We hypothesized that spontaneous movements (postural adjustments and ideomotion) disturb analysis of heart rate and blood pressure variability and could explain the discrepancy between studies. We measured R-R intervals and systolic blood pressure in nine healthy sitting subjects during three protocols: 1) no movement allowed, 2) movements allowed but not standing, 3) movements and standing allowed. Heart rate and blood pressure were not altered by movements. Movements with or without standing produced a twofold or greater increase of the overall variability of R-R intervals and of the low-frequency components of spectral analysis of heart rate variability. The spectral exponent β of heart rate variability (1.123 at rest) was changed by movements (1.364), and the percentage of fractal noise (79% at rest) was increased by movements (81%).

Nonlinear predictability. We suggest that future studies on dimensions of heart rate variability, but they changed its percentage of fractal noise (79% at rest) was increased by movements (81%). The fractal pattern of HRV that implies long-term correlation within the beat-by-beat variability is known as the 1/f component in the frequency domain; it largely influences the LF of cardiovascular variability. This fractal component could be a potential source of discrepancy in the interpretation of LF. Moreover, the recommendations of the Task Force are based on human recordings and cannot take into account the specificity of recordings of unrestrained animals. Movements are not controlled during such recordings, and they are not always controlled during human recordings (Holter). Fractal noise and the noise induced by movements are a potential source of discrepancy in interpretation of LF spectral markers. We hypothesized that spontaneous slight movements such as postural adjustments and ideomotor movements (i.e., unconscious movements when attention is withdrawn) are a source of noise in LF, VLF, and long-term autocorrelations of HRV and BPV and could bias the analysis and interpretation of HRV and BPV.

METHODS

Subjects. Nine healthy volunteers (6 women and 3 men) with a mean age of 23 yr (range 19–28 yr) took part in this study. The subjects had a mean weight of 57 kg (range 44–66 kg) and a mean height of 1.68 m (range 1.58–1.81 m). They had no history of cardiopulmonary disease, and none was taking any medication. One of them was a light smoker (2 cigarettes/day). They had a resting heart rate of 72 beats/min (range 57–84 beats/min) and a resting systolic blood pressure of 127 mmHg (range 103–135 mmHg). Each subject received a complete description of the procedures and potential risks involved and signed a consent form. The data collection procedure was approved by the Comité Consultatif pour la Protection des Personnes dans la Recherche Biomédicale Midi Pyrénées Toulouse.

Experimental protocols and procedures. Surface electrocardiogram and Finapres blood pressure were recorded for each subject during three different protocols: relative steady state (SM), free recording (ST), and strictly steady state (SS). All tests were done in the sitting position. During SM, the subject was only asked to remain quietly sitting without instruction about slight movements. During ST, the subject was asked to stand at least four times during the recording. SM and ST were always performed first (in a random order) to avoid the subjects receiving any suggestion of controlling slight spontaneous movements. The SS period consisted of a strictly motionless recording. The subjects were instructed to avoid any postural adjustment or any ideomotor movement, even very small movements. Respiratory rate was not controlled.

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Subjects were made familiar with the equipment and with the experimental room before the first data collection session. They were asked to breathe quietly and to be as relaxed as possible, but not to sleep, and to keep their eyes open. The finger blood pressure cuff (Finapres 2300, Ohmeda, Englewood, CO) was carefully placed on the nondominant arm. The subject carried this arm in a sling to keep the cuff at heart level and to avoid hydrostatic pressure effects. Each recording was performed in the morning in a quiet, light-attenuated room with light ambient classical music. The subject was alone with the experimenter, who was as quiet as possible so as not to disturb the subject. The recordings were extended long enough to obtain at least 2,048 cardiac beats (30–40 min). The Finapres was active only after the first 10 min and was allowed to stabilize before the servo-reset mechanism was disabled to permit continuous collection of at least 1,024 cardiac beats.

Data acquisition and pretreatment. A peak detection circuit was used to discriminate the R wave from the electrocardiogram. The impulse train was processed in real time on a personal computer via an analog-to-digital converter (DAS-16G, Keithley-Metabyte, Taunton, MA) at a sampling frequency of 1,000 Hz and a resolution of 12 bits. Beat-by-beat R-R intervals and systolic blood pressures were stored for the personal computer via an analog-to-digital converter (DAS-16G, Keithley-Metabyte, Taunton, MA) at a sampling frequency of 1,000 Hz and a resolution of 12 bits. Beat-by-beat R-R intervals and systolic blood pressures were stored for later analysis. Each series was searched for abnormal values before analysis. Very few abnormal values were identified (0–0.5%); they were defined as values 25% larger or smaller than the preceding value. Abnormal intervals were typically caused by a missed beat or by triggering on the T wave as well as the QRS complex. A beat was inserted when one was missed, whereas the two short-interval values were deleted when the T wave was triggered and a beat was inserted by interpolation. The filtered R-R interval and systolic blood pressure data were then aligned sequentially to obtain equally spaced samples of R-R interval and systolic blood pressure.

Timeseries analysis. The means and standard deviations of the R-R interval and systolic blood pressure were obtained for each recording. For each subject we obtained three series of 2,048 R-R intervals. In the middle of these series the corresponding systolic blood pressure was also obtained for 1,024 beats. An experimenter, familiar with cardiovascular dynamics analysis but blinded with respect to the phase during which the data were recorded, selected a visually estimated stationary series of 256 beats (both R-R intervals and systolic blood pressures) from the 1,024-beat series. Each series of 1,024 and 256 beats (both R-R intervals and systolic blood pressure) was analyzed by a fast Fourier transform (FFT). The spectral parameters assessed were those recommended by the Task Force (16).

The fractal components of HRV and BPV were analyzed by subjecting the 1,024-data point time series to coarse-graining spectral analysis (CGSA; Ref. 17). CGSA discriminated fractal random walks from simple harmonic motion on the basis of the fact that the original and rescaled (coarse grained) time series had random phase relationships only for fractal signals (17). Two rescaled versions [x(t)] of the original time series [x(t)] were obtained by taking the scaling factors of h = 0.5 and h = 2. This had the effect of sampling every second value (h = 0.5) or holding each value for two sample points (h = 2). The fractal component was plotted in a log-power versus log-frequency plane, and the spectral exponent (β) was estimated as the slope of the linear regression of this plot from 2.5% of the Nyquist frequency to 0.3 Hz or higher if the plot

Table 1. Spectral analysis (256 points)

<table>
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<tr>
<th></th>
<th>R-R Interval</th>
<th>Systolic Blood Pressure</th>
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<tbody>
<tr>
<td></td>
<td>SS</td>
<td>SM</td>
</tr>
<tr>
<td>T</td>
<td>1,040±204</td>
<td>2,688±946*</td>
</tr>
<tr>
<td>T – VLF</td>
<td>696±147</td>
<td>1,394±545</td>
</tr>
<tr>
<td>VLF</td>
<td>344±73</td>
<td>1,294±458*</td>
</tr>
<tr>
<td>LF</td>
<td>327±74</td>
<td>803±434*</td>
</tr>
<tr>
<td>HF</td>
<td>340±84</td>
<td>547±220</td>
</tr>
<tr>
<td>LF&lt;sub&gt;n&lt;/sub&gt;</td>
<td>49±5</td>
<td>96±7</td>
</tr>
<tr>
<td>HF&lt;sub&gt;n&lt;/sub&gt;</td>
<td>47±5</td>
<td>39±7</td>
</tr>
<tr>
<td>LF/HF</td>
<td>1.16±0.19</td>
<td>1.98±0.49</td>
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</tbody>
</table>

Values are means ± SE of parameters of fast Fourier transform of 256-beat series of R-R intervals and systolic blood pressures during 3 types of sitting recordings: strictly steady state (SS), where no movement was allowed; relative steady state (SM), where spontaneous movements were allowed; and free recording (ST), where both spontaneous movements and standing were allowed. T, total power; T – VLF, total – very low-frequency power; LF, low-frequency power; HF, high-frequency power; LF<sub>n</sub>, HF<sub>n</sub>, normalized LF and HF. *P ≤ 0.05 vs. SS; †P < 0.01 vs. SS.
in an
formed to obtain the first difference time series, as in the
time series during 3 types of sitting recordings (SS, SM, and ST).

Spectral analysis (1,024 points)
Table 2.

was still linear at higher frequencies (3). The series of 2,048
R-R intervals were analyzed by the methods of nonlinear
prediction (15) and correlation dimension (1) to test for

R-R intervals were analyzed by the methods of nonlinear
was analyzed for each M by the method of nonlinear prediction to detect any correlation (r) between
the observed and the predicted values according to the
prediction time (number of beats). This method provided
information about the dynamics of the time series. For a
random stochastic process, r should be low, close to zero, and
independent of prediction time. In a deterministic linear
process, r should be high and independent of prediction time.
For a deterministic nonlinear process, r should be high, with
an abrupt drop as the prediction time increases. The results
were fitted in a three-dimensional plot. The x-axis was the
prediction time (number of beats), the y-axis was r, and the
z-axis was M.

Correlation dimension. The data were analyzed for the
same M as described in Nonlinear prediction (from 2 to 18),
but the vectors were constructed with the raw time series.
The lag time was set at three beats (18). The time series was
analyzed for each M by the method of correlation dimension
(1). This method provides information on the static properties
of the time series. In a random stochastic process, the
correlation dimension should increase as M increases. In a
deterministic nonlinear process, the correlation dimension
should increase and then reach a plateau at a noninteger
value, when M increases. However, the stochastic 1/f noise
could bias these analyses (13). Because HRV has a 1/f component, it was necessary to determine whether the outcome
of the nonlinear analysis might have been caused by a
random stochastic process. This test was done by completing
the same analysis on a distribution-conserved isospectral surro-
gate data set. The standard isospectral surrogate (DCIS) data set
was computed for each time series. We then

We looked for differences between the observed and DCIS series should come from the nonlinear
dynamics of the observed series.

Statistical methods. Data are presented as means ± SE. A
between-period comparison was made by a Friedman test
for each spectral analysis method, short FFT, long FFT,
and CGSA. If an overall significant difference was found, we
looked for the difference by means of Wilcoxon tests for paired
data. Correlations among the short-FFT, long-FFT, and CGSA
parameters were assessed by a Spearman rank test.

We looked for differences between the observed and DCIS
series nonlinear predictions and the correlation dimensions
for each period (SS, SM, and ST). This comparison was
completed by two-way analysis of variance for each M for
nonlinear prediction and by two-way analysis of variance for
correlation dimensions. Nonlinear predictions and correla-

Table 2. Spectral analysis (1,024 points)

<table>
<thead>
<tr>
<th></th>
<th>SS</th>
<th>SM</th>
<th>ST</th>
<th>Systolic Blood Pressure</th>
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<tr>
<td></td>
<td>R-R Interval</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>T</td>
<td>1.539 ± 0.316</td>
<td>3.286 ± 954*</td>
<td>4.179 ± 1.366*</td>
</tr>
<tr>
<td></td>
<td>T – VLF</td>
<td>857 ± 213</td>
<td>1.456 ± 395</td>
<td>1.263 ± 372</td>
</tr>
<tr>
<td></td>
<td>VLF</td>
<td>602 ± 147</td>
<td>1.831 ± 623#</td>
<td>2.917 ± 1.604#</td>
</tr>
<tr>
<td></td>
<td>LF</td>
<td>396 ± 104</td>
<td>866 ± 262*</td>
<td>711 ± 178*</td>
</tr>
<tr>
<td></td>
<td>HF</td>
<td>441 ± 122</td>
<td>568 ± 188</td>
<td>508 ± 184</td>
</tr>
<tr>
<td></td>
<td>LF_n</td>
<td>48 ± 4</td>
<td>62 ± 5†</td>
<td>62 ± 4*</td>
</tr>
<tr>
<td></td>
<td>HF_n</td>
<td>50 ± 4</td>
<td>36 ± 5†</td>
<td>35 ± 4*</td>
</tr>
<tr>
<td></td>
<td>LF/HF</td>
<td>1.03 ± 0.13</td>
<td>2.01 ± 0.34†</td>
<td>2.23 ± 0.57*</td>
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Values are means ± SE of parameters of fast Fourier transform of 1,024-beat series of R-R intervals and systolic blood pressures during 3
types of sitting recordings SS, SM, and ST. *P ≤ 0.05 vs. SS; †P = 0.01 vs. SS.
tion dimensions were analyzed for differences between periods by a two-way analysis of variance only for M where the differences between observed and DCIS series were highly significant (P = 0.01), i.e., only when the nonlinear prediction profile was probably caused by the nonlinear dynamics of the data rather than by measurement noise. In other cases, the significance level was set at P = 0.05.

RESULTS

R-R interval and systolic blood pressure were not significantly different between protocols despite a slight increase in systolic blood pressure during SM and ST recording (SS: 840 ± 38 ms and 127.7 ± 9.1 mmHg; SM: 857 ± 41 ms and 134.1 ± 6.5 mmHg; ST: 780 ± 33 ms and 141.2 ± 5.5 mmHg). Examples of collected R-R interval and systolic blood pressure time series are shown in Fig. 1.

Spectral analysis. The overall R-R interval variability assessed by the total power of the spectra was significantly increased by slight movements (SM) in comparison to the SS period for short-FFT analysis (Table 1; Fig. 2). With longer FFT analysis [1,024 beats (FFT1024), Table 2], the HRV total power during the ST period was also different from that during the SS period. There was no difference in the total power of BPV assessed by FFT for 256 points (FFT256) or FFT1024, but the SS period was different from both SM and ST periods when assessed by CGSA. All these effects disappeared when the VLF power was subtracted from the total power. For the VLF and LF components of HRV, both the SM and ST periods were different from SS regardless of the length of data collection analyzed by means of FFT, whereas only the LF and VLF SM were different from SS when analyzed by CGSA. There was no difference between periods in the spectral component of systolic blood pressure assessed by FFT256 or FFT1024. The normalized HF power and the ratio of LF to HF power of BPV were significantly changed by SM and ST when assessed by FFT256 and FFT1024.

Fractal analysis. The fractal component of BPV did not change regardless of the period considered (SS, SM, or ST) (Table 3). Standing during recording (ST) induced an increase of the percentage of fractal noise in HRV. Slight movements without or with standing (SM and ST) induced an increase in the spectral exponent β of HRV.

Nonlinear analysis of HRV. During all three periods (SS, SM, and ST) the pattern of nonlinear prediction for R-R interval series was one of an initially high value that decreased as the prediction time (number of beats) increased (Fig. 3). There were highly significant differences (P ≤ 0.01) between the observed series and the DCIS nonlinear prediction of R-R interval series for each M (M = 2–18). These findings support the conclusion of nonlinear dynamics in the pattern of HRV. The nonlinear prediction of the observed R-R interval series during the SS period is different from that during both SM and ST periods for all M (P ≤ 0.01; SM vs. ST, no significant difference). The correlation dimensions of the R-R interval series were different between observed and DCIS only for M = 6 and 14–18 during SS and for M = 6–18 during SM, and no difference was observed during ST (Fig. 4). There was no difference in correlation dimensions between periods.

DISCUSSION

The primary aim of this experiment was to assess the validity of comparisons between cardiovascular variability studies in which data are collected 1) on human healthy volunteers in a laboratory setting, 2) on patients by means of regular or Holter electrocardiogram, and 3) on freely moving animals. Our results show that even slight spontaneous movements influence spectral analysis and change the nonlinear dynamics of HRV. Comparisons between studies must take into account differences in data collection procedure. This could explain the discrepancy in interpretation of the harmonic components of spectral analysis, especially for

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<th>Table 3. Coarse-graining spectral analysis</th>
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<tr>
<td>R-R Interval</td>
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<td>T−VLF</td>
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<tr>
<td>VLF</td>
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<td>LF</td>
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<td>HF</td>
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<td>LF/Fⁿ</td>
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<tr>
<td>LF/HF</td>
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<tr>
<td>%Frac</td>
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<tr>
<td>β</td>
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<tr>
<td>Systolic Blood Pressure</td>
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<tr>
<td>T</td>
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<tr>
<td>T−VLF</td>
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<tr>
<td>VLF</td>
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<td>LF</td>
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<td>LF/HF</td>
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<td>β</td>
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Values are means ± SE of parameters of coarse-graining spectral analysis of 1,024-beat series of R-R intervals and systolic blood pressures during 3 types of sitting recordings SS, SM, and ST. % Frac, % fractal noise; β, spectral exponent. *P = 0.05 vs. SS; †P ≤ 0.01 vs. SS; ‡P ≤ 0.01 vs. SM.
LF, and the lack of consensus about the nonlinear dynamics of HRV.

DeBoer’s model (5) identifies the Mayer wave (0.1 Hz in humans) as a resonance phenomenon caused by the delay in the sympathetic control loop of the baroreflex despite an oversimplification of the complexity of the neural cardiovascular control. This supposes that these oscillation phenomena occur in an unperturbed system and result only from spontaneous blood pressure and heart rate fluctuations. Exploring human resting cardiovascular regulation in a strictly controlled steady state avoids any external perturbation of the reflex loops. Bernardi et al. (2) demonstrated that the results of spectral analysis of HRV collected by means of Holter electrocardiogram are influenced by physical activity.

**Fig. 3.** Nonlinear predictions of R-R interval series computed in embedding dimensions (ED) from 2 to 18 during 3 types of sitting recordings [SS (A), SM (B), and ST (C)]. ρ, mean prediction coefficients of 9 subjects. Nonlinear predictions of R-R interval series during SS were different from those during both SM and ST for each ED (P ≤ 0.01; SM vs. ST, no significant difference).

**Fig. 4.** Correlation dimensions (D2) of R-R interval series (○) and their distribution-conserved isospectral surrogate series (DCIS, ▲) computed in ED from 2 to 18 during 3 types of sitting recordings [SS (A), SM (B), and ST (C)]. Values are means of 9 subjects; *P ≤ 0.01.
Our study extends and complements this previous observation and shows that slight spontaneous movements could increase the VLF and LF of R-R interval variability. This effect is limited when the time series are analyzed by means of short-term regular FFT (256 points) and when the spectral parameters are normalized. An alteration in autonomic activity should parallel movements, even slight, in comparison with the absolute resting sympathetic activity. However, these movements occurring from time to time should change the stationarity of the sympathetic activity during the recordings and then influence the fluctuations related to noise in the cardiovascular time series. There is no more increase in the LF component, even when normalized, during ST in comparison to SM (Tables 1, 2, and 3) as expected during a rest recording (17). A bigger \( b \) is expected for standing HRV (3). However, slight movements increased this exponent even on sitting recordings (SM), meaning that the fractal component was less organized.

Instructing a subject to stay quiet and keep his or her eyes open for a few minutes will result in repeated postural adjustments and ideomotor movements, and this is why we usually train our subjects to be quiet and motionless during the data recording. This is difficult in animals, which are usually unrestrained to avoid anesthetic effects. The purpose of a Holter electrocardiogram is to record heart rate during daily regular activity, during which more movement means more variability. There is no way to compare such different recordings because of the data length differences (100,000 beats for 24-h and 300 beats for 5-min human recordings) or the heart rate difference (60 beats/min in humans, 350 beats/min in rats). The recording cables and the sling limited the spontaneous movements of our subjects. Our results show that the cardiovascular dynamics analysis is clearly different between SS and SM despite this limitation. We did not analyze the nonlinear dynamics of blood pressure because we did not record the Finapres signal during all 40 min of the protocols. The quality of the signal could be limited because the servo mechanism was turned off over such a long duration.

The nonlinear prediction patterns of HRV are compatible with those of chaotic time series with a dropping pattern as the prediction time increases, but the quality of the prediction is better on the SS recordings than on those from SM or ST (Fig. 3). The noise induced by slight spontaneous movements and standing probably limits the quality of the nonlinear prediction. Whether there are nonlinear dynamics in the patterns of HRV is still debated (6, 9). This is illustrated by the unclear difference between the correlation dimensions of the observed and DCIS R-R interval series recorded during SS. When slight movements were not restricted (SM), there was evidence for nonlinear dynamics in the pattern of HRV. This would support the concept that under normal resting conditions, regular postural adjustments and spontaneous movements may induce chaos in the pattern of HRV. The rhythm of the pathological stereotypes was demonstrated to be nonlinear (11). It is possible that the rhythm of ideomotion of some subjects is nonlinear, inducing a nonlinear disturbance in cardiovascular fluctuations. The correlation dimensions (mean of 9 subjects) of SM recordings did not reach a plateau despite the clear difference between observed and DCIS series and the high embedding dimensions (Fig. 4). However, individual results are very informative. Figure 5 shows the correlation dimension of a subject. The pattern of the observed correla-
tion dimension during the SM recording is typical of a chaotic time series (plateau). Two subjects presented this typical pattern during SM. The correlation dimensions of the other subjects are only lower during SM than during SS, which explains why the mean curve did not reach a plateau during SM.

We conclude that more than one-half of cardiovascular variability is caused by spontaneous movements when they are not controlled during data recordings. These spontaneous movements disturb spectral analysis and nonlinear prediction of the heart rate variability and can induce a plateau in the result of its correlation dimensions. We suggest that future studies on short-term cardiovascular variability must control spontaneous movements or at least precisely describe the recording conditions and that the specific value of the very low frequency component could provide a crude assessment of the “quality” of the recording conditions.

The authors thank Dr. John Carew for the English language correction of this paper and thank the subjects for their willing cooperation.

This work was supported by grants from Centre National d’Etudes Spatiales and Groupement d’Intérêt Public Exercice, St-Etienne, France.

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Received 19 August 1998; accepted in final form 11 March 1999.

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