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COMPLEX SYSTEMS BIOPHYSICS

Nonstationarity and Duration of the Cardiac Interval Time Series in Assessing the Functional State of Operator Personnel

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Abstract—The influence of nonstationarity in the time series of cardiac intervals on the assessment of the functional state (FS) of operator personnel was analyzed with a three-factor model of heart rhythm variability (HRV). ECG recordings were made in supine position at rest and in the sedentary position before and after important operator testing. In all three cases, the FS assessments were not influenced by nonstationarity of the input data. The effect of nonstationarity was also negligible for some particular HRV indices. Reliable assessments could be obtained from relatively short samples (256 down to 32 RR intervals) with prior norming of the factor indices for the corresponding segment length. The influence of the time series duration on the HRV indices was examined in various FSs; stable indices and proper recording conditions were determined.

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Key words: heart rhythm variability, RR intervals, stationarity, time series duration

INTRODUCTION

The mathematical apparatus of spectral analysis was developed assuming that the time series is stationary, i.e., the generating mechanism does not change with time and the corresponding process reaches statistical equilibrium [1]. In practice this is reflected in the estimation of first- and second-order moments: the expectation and the dispersion of a series must be constant in time [2]. This assumption imposes the requirement of checking for stationarity in calculating the spectral characteristics of heart rhythm variability (HRV), as indicated in various methodical recommendations [3, 4]. The importance of stationarity checks is noted in a number of works on HRV [5–8]. To fulfill this condition, examination with short (2–5 min) series is organized so as to ensure a stationary process: recordings are made at rest, during monotonous physical activity, upon attaining a stable physiological state. The situation proves totally different for a researcher who tries to analyze the heartbeat dynamics during complicated and important activity, when the actions as such may be preceded, attended, and followed by anxiety, excitation, emotional stress, etc. In such cases the dynamics may be far from stationary.

Some authors note that the lack of stationarity can bias the estimates for the vagal control in HRV analysis [7, 8]. However, strict conformity to the requirement of stationarity can exaggerate these estimates when spectral analysis is performed on stationary segments extracted from a nonstationary time series. Other authors think that such estimates may be even more biased [6]. A special study was made [9] of the influence of nonstationarity on some indices of vagal control: *MSD* (mean absolute difference between successive RR intervals), *RSA* (respiratory sinus arrhythmia), and *HF* (heart rhythm spectral power in the high-frequency range). Recordings were made both at rest (sitting or lying) and under functional load (hand-grip task, controlled respiration, cold pressor test, video game with award). The data collected from 21 healthy females allowed a conclusion that the nonstationarity of the time series documented in the

Table 1. Classification of human functional states (FS) in the three-factor model of HRV

Normed index	$SDNN_n$ [5–9]		$SDNN_n$ [1–4]	
	b_{1n} [1–4]	b_{1n} [5–9]	b_{1n} [5–9]	b_{1n} [1–4]
M_{NNn} [5–9]	FS1	FS3	FS6	FS8
M_{NNn} [1–4]	FS2	FS4	FS5	FS7

experiment had no appreciable effect on calculating the above indices. The minor influence of nonstationarity on *HF* is confirmed in other works [7, 10].

This state of controversy prompted us to address the influence of nonstationarity on the assessment of the human functional state (FS), which is understood as the response of the functional systems of the organism [11] to external and internal stimuli that is aimed at attaining a beneficial result [12]. In the process, we evaluated the effect of nonstationarity on a broad set of HRV indices. The FSs were diagnosed with an original three-factor model of HRV [13]. The first factor reflects the overall extent of HRV and is entered as *SDNN* (standard deviation of RR intervals between the QRS complexes of normal sinus cardiocycles N–N without artifacts and extrasystoles). The second factor characterizes the balance between the high- and low-frequency HR oscillations, b_1 (the slope of the heart rate graph regression). The third factor is closely associated with the integral level of cardiovascular performance, M_{NN} (mean normal RR interval). These factors are normed by percentiles using the data for a reference group [14] in nine ranges; the boundaries of the latter (0.1, 2.3, 15.9, 30.9, 69.1, 84.1, 97.7, 99.9%) correspond to the following SD of normal distribution [15]: –3, –2, –1, –0.5, +0.5, +1, +2, +3.

Table 1 presents the classification of human FSs based on the three normed indices [13]. FS1 (normalcy) is characteristic of rest, with low psychical (cognitive) or emotional load. FS3 (emotional excitement) and FS4 (excitement with elevated HR) reflect the influence of high emotional load and are most often observed in anticipation of an important task as well as afterwards, in anxious thinking over one's actions. FS4 was also diagnosed in neurotic disorders. FS2 and FS5–8 are typical of various forms of psychical tension: FS2 is economical regulation of the heart rhythm under psychical load, FS5 is general strain of HR-regulating systems, FS6 is characteristic of the overstrain of physiological systems leading to exhaustion, FS7 is the systemic strain with high probability of cardiovascular disorders, FS8 reflects straining on the background of fatigue.

The usual recommended duration of short-term ECG recording is 5 min [3, 4]. In reality, the specific features of the research program (brevity of the evoked FS) or technical limitations of signal recording make the researcher analyze shorter segments [16]. Several HRV indices calculated from recordings ranging from 10 s to 10 min have been compared (with values of 5-min segments as reference) [17]. Use was made of 54 long-term ECG records (21.4–24.2 h) of normal sinus rhythm (30 males aged 28.5–76 and 24 females of 58–73) from the PhysioNet database [18]. A thousand samples were taken for each segment duration. The indices were *SDNN*, *RMSSD* (root mean square of successive differences in RR intervals), *LF* (heart rhythm spectral power in the low-frequency range), *HF*, *LF*/*HF* ratio, and *TP* (total spectral power). Variation of the recording length was found to significantly affect the values of calculated indices. The least sensitive were *HF* and *RMSSD* (high-frequency filters). It must be noted, however, that these results were not evaluated statistically; all the conclusions were drawn from visual inspection of the data plots.

In view of the practical importance of handling short ECGs, the present work considers the feasibility of FS assessment with the three-factor HRV model from time series shorter than 256 RR intervals, as well as the influence of series length on separate HRV indices.

DATA AND METHODS

The experiment involved 239 applicants for operator positions at the nuclear power station in the course of examination in the Laboratory of Psychophysiological Support of the Novovoronezh Training Center for Nuclear Power Station Personnel (LPPS NTC). All were healthy males, mean age 34.0 ± 7.8.

The recording of normal cardiac sinus cycles of the electrocardiogram and the subsequent isolation of RR intervals (in milliseconds) were performed by means of the RITMON-1 and Varikard-1.51 three-channel hardware/software complexes (digitization frequency 500 Hz). The MABP.DBase-HRV software (Delphi-5, Access-2000) developed in the LPPS NTC was used to store RR intervals, edit them (correct artifacts and extrasystoles in the rhythmogram), and calculate the parameters of HRV. The least-squares linear trend [19] was removed from the time series prior to calculating the HRV indices.

The indices for time-domain HRV analysis were: M_{NN} and *SDNN* (ms), *CV* (variation coefficient, $SDNN/M_{NN} \times 100$), *MxDMn* (variation range), *Mo* and *AMo* (mode and mode amplitude calculated from the histogram with a 50-ms step), *TI* (Baevsky tension index, $AMo/(2\ Mo\ MxDMn) \times 100$), *RMSSD* (ms), and *pNN50* (percentage of pairs of successive NN intervals differing by more than 50 ms). Note that *RMSSD* is tightly correlated ($r \sim 0.9$) to mean successive difference *MSD* [20, 21]. The analysis also included the heart rate graph indices *ND* and *NRib* (number of nodes and edges/ribs) and b_1 (regression slope) [22].

Frequency-domain methods (fast Fourier transform with a Hamming spectral window) were used to calculate the HRV spectral indices: spectral power density (ms^2) in the high frequency (*HF*, 0.15–0.4 Hz), low frequency (*LF*, 0.04–0.15 Hz), and very low frequency (*VLF*, ≤0.04 Hz) ranges, as well as the normed indices *HF/TP*, $HF_n = HF/(HF + LF)$, and *LF*/*HF*.

Spectral analysis demands that the variable be measured at equal time intervals [1]. Since the RR time series does not meet this condition, it is recommended to transform it into an equidistant series [3, 4], setting a quantization step and choosing an interpolation model. Our recent comparison of the initial and equidistant series (quantized at 250 ms, linear interpolation) [23] has revealed that in the initial series the spectral frequencies depend on the mean RR duration in the sample, that the spectral features in the two series coincide at $M_{NN} = 1$ s, and that the frequencies of the spectral range boundaries can be corrected as $FD_{corr} = FD \times M_{NN}$.

ECGs were recorded three times for each testee: (1) supine position at rest, 10 min; (2) anticipating operator tests, sedentary position, 10 min; (3) recuperating after tests, sedentary position, 10 min. The testees were instructed to sit (lie) still. All records were made in the first half of the day. The FSs were determined for each condition separately. The reference group for norming the HRV indices was 848 healthy men aged 29.84 ± 6.54.

Table 2. Incidence and frequency of functional states (FS) among 239 testees in different conditions assessed from ECG samples with (St) and without (NSt) selection for stationarity

FS	At rest		Before test		After test	
	St	NSt	St	NSt	St	NSt
1	91 (38%)	90 (38%)	24 (10%)	24 (10%)	23 (10%)	22 (9%)
2	3 (1%)	3 (1%)	3 (1%)	3 (1%)	2 (1%)	2 (1%)
3	49 (21%)	51 (21%)	105 (44%)	105 (44%)	115 (48%)	119 (50%)
4	11 (5%)	11 (5%)	59 (25%)	58 (24%)	50 (21%)	49 (21%)
5	25 (10%)	25 (10%)	29 (12%)	30 (13%)	32 (13%)	33 (14%)
6	22 (9%)	23 (10%)	8 (3%)	8 (3%)	15 (6%)	12 (5%)
7	5 (2%)	5 (2%)	1 (0%)	1 (0%)	0 (0%)	0 (0%)
8	33 (14%)	31 (13%)	10 (4%)	10 (4%)	2 (1%)	2 (1%)

The Statistica for Windows 6.0 software was used for statistical analysis. Averaged parameters of "sliding" stationary samples of 256 RR intervals with a step of 10 RR intervals were used for analysis. The nonparametric Wald–Wolfowitz method [24, 25] was used to confirm that the samples were stationary. To evaluate the influence of series duration, HRV indices were also calculated from "sliding" samples of 128, 54, 32, and 16 intervals. The short segments were detrended and "cloned" to the size of the basis samples (256).

RESULTS AND DISCUSSION

Table 2 lists the frequencies of FSs diagnosed either with only stationary samples or with all samples. The agreement between such paired judgements for each recording condition was assessed with the Pearson's coefficient χ^2, first pooling the bins with incidence less than 5 [19]. The values obtained for all three conditions (respectively @@,@@,@@) suggest that HR nonstationarity in samples of 256 intervals does not significantly affect the assessment of FSs. Note the characteristic prevalence of FS1 at rest and

Table 3. Means and standard deviations of HRV indices in different conditions assessed from ECG samples with (St) and without (NSt) selection for stationarity

Index	At rest		Before test		After test	
	St	NSt	St	NSt	St	NSt
M_{NN}	849.1 (118.6)	849.0 (118.6)	771.6 (109.9)	771.4 (109.8)	777.5 (114.4)	777.5 (114.2)
SDNN	45.44 (16.25)	45.56** (16.34)	53.93 (20.58)	54.11** (20.69)	54.55 (19.99)	54.69** (20.09)
b_1	0.675 (0.152)	0.676** (0.151)	0.811 (0.098)	0.812** (0.097)	0.819 (0.087)	0.821** (0.086)
VLF	730.5 (658.7)	746.3** (696.6)	1560.6 (1573.3)	1587.8** (1604.5)	1561.0 (1597.0)	1583.6** (1625.5)
LF	826.5 (706.9)	825.6 (706.5)	1199.3 (891.9)	1198.0 (892.8)	1256.4 (929.0)	1254.2 (927.2)
HF	718.8 (749.4)	718.0 (747.8)	521.8 (552.4)	520.0 (548.6)	514.3 (551.4)	513.6 (550.6)
HF_{TP}	0.301 (0.149)	0.300** (0.149)	0.168 (0.942)	0.167** (0.933)	0.161 (0.890)	0.160** (0.887)
LF/HF	1.899 (1.701)	1.895 (1.690)	3.436 (2.344)	3.434 (2.341)	3.699 (2.530)	3.692 (2.522)
HF_n	0.435 (0.177)	0.435 (0.176)	0.291 (0.138)	0.291 (0.138)	0.276 (0.130)	0.276 (0.130)
CV	5.325 (1.702)	5.341** (1.713)	6.940 (2.278)	6.966** (2.299)	6.960 (2.124)	6.977** (2.133)
MxDMn	265.5 (94.64)	265.9 (94.93)	287.9 (97.72)	288.3** (98.31)	291.4 (95.84)	291.6 (96.06)
AMo	45.31 (11.97)	45.21** (11.91)	40.70 (12.52)	40.59** (12.50)	40.74 (11.53)	40.65** (11.53)
Mo	849.1 (121.7)	849.0 (121.8)	775.3 (117.2)	775.2 (117.2)	783.3 (122.6)	783.4 (122.5)
TI	136.6 (109.3)	136.0* (108.3)	125.5 (112.6)	125.2** (112.5)	119.8 (97.41)	119.6* (97.52)
RMSSD	36.23 (17.80)	36.22 (17.80)	31.73 (15.26)	31.71 (15.24)	31.66 (15.16)	31.64 (15.14)
*pNN*50	15.81 (15.48)	15.80 (15.47)	11.97 (12.52)	11.94 (12.46)	11.49 (11.52)	11.48 (11.50)
ND	131.3 (41.36)	131.5** (41.38)	136.7 (42.14)	136.8** (42.20)	136.6 (39.90)	136.7 (39.90)
NRib	212.. (35.11)	212.8 (35.14)	2097 (37.77)	209.8 (37.71)	209.7 (36.23)	209.8 (36.23)

Wilcoxon T-test. * – $p < 0.01$, ** – $p < 0.001$.

Table 4. Incidence and frequency of functional states (FS) among 239 testees in different conditions assessed from ECG samples of specified length (RR intervals)

FS	At rest				Before test				After test			
	128	64	32	16	128	64	32	16	128	64	32	16
1	86 (36%)	87 (36)	81 (34%)	75 (31%)	25 (10%)	25 (10%)	29 (12%)	34 (14%)	19 (8%)	22 (9%)	25 (10%)	22 (9%)
2	3 (1%)	4 (2%)	4 (2%)	3 (1%)	3 (1%)	3 (1%)	3 (1%)	2 (1%)	3 (1%)	3 (1%)	2 (1%)	3 (1%)
3	56 (23%)	54 (23%)	67 (28%)	82 (34%)	99 (41%)	95 (40%)	90 (38%)	88 (37%)	114 (48%)	111 (46%)	109 (46%)	106 (44%)
4	13 (5%)	11 (5%)	12 (5%)	15 (6%)	55 (23%)	59 (25%)	55 (23%)	55 (23%)	52 (22%)	56 (23%)	53 (22%)	45 (19%)
5	26 (11%)	26 (11%)	28 (12%)	26 (11%)	38 (16%)	37 (15%)	41 (17%)	42 (18%)	34 (14%)	34 (14%)	39 (16%)	45 (19%)
6	20 (8%)	21 (9%)	23 (10%)	20 (8%)	11 (5%)	12 (5%)	12 (5%)	13 (5%)	14 (6%)	10 (4%)	8 (3%)	12 (5%)
7	3 (1%)	4 (2%)	1 (0%)	2 (1%)	0 (0%)	0 (0%)	1 (0%)	1 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (0%)
8	32 (13%)	32 (13%)	23 (10%)	16 (7%)	8 (3%)	8 (3%)	8 (3%)	4 (2%)	3 (1%)	3 (1%)	3 (1%)	5 (2)

the elevated frequency of various forms of emotional (FS3 and 4) and general (FS5) strain before and after occupational testing.

Table 3 lists the means and standard deviations of HRV indices in different conditions. Since the distributions were not normal, the nonparametric two-sample Wilcoxon T-test was used to assess the influence of nonstationarity. No significant difference in any condition was observed for M_{NN} and *Mo* (values of the central tendency), *RMSSD*, *pNN50*, and *HF* (high-frequency filters), *LF* (low-frequency filter), the derivatives *LF*/*HF* and HF_n, and *NRib* (positively linked with high-frequency indices). The data on high-frequency indices agree with other results for vagal control indices such and *MSD* and *HF* [9]. Some effect of nonstationarity was observed for the very-low-frequency characteristics such as *VLF* and b_1, and this shifted the overall index *SDNN* and associated indices (*CV*, *MxDMn*, *AMo*, *TI*, *ND*). It is important that the deviations in b_{1n} and $SDNN_n$ did not exceed the normed limits, so the diagnosis of FSs in all cases was very stable regardless of sample nonstationarity.

Next, the FSs were assessed using shorter time series (Table 4), and the agreement with the data in Table 2 was assessed with the Pearson's coefficient χ^2 (pooling the bins with incidence less than 5). The values thus obtained were: "At rest" @@@@@@; "Before test" @@@@@@; "After test" @@@@@@. Statistically significant differences were observed only for the shortest (16) series at rest and before test. Thus, the three-factor model of HRV can be successfully used for diagnosing FSs with samples of 256–32 RR intervals, provided the indices are first normed for the corresponding time series length.

The influence of sample length on HRV indices was evaluated by grouping the ECG data according to the FSs most common among testees in all three conditions: FS1 (136), FS3 (275), FS4 (118), and FS5 (88). Table 5 lists the data for FS1 at different segment lengths. The Wilcoxon T-test showed that the most stable (next to M_{NN}) are the high-frequency indices *HF*, *RMSSD*, and *pNN50* (differences seen only

Table 5. Means and standard deviations of HRV indices in time series of different lengths (RR intervals) corresponding to FS1 (normalcy)

Index	256 R-R	128 R-R	64 R-R	32 R-R	16 R-R
M_{NN}	931.86 (97.84)	931.69** (98.30)	931.76** (98.60)	931.95** (98.78)	932.07** (98.89)
SDNN	59.72 (16.82)	57.27 (16.33)	53.79 (15.47)	49.57 (14.19)	44.94 (13.06)
b_1	0.576 (0.133)	0.532 (0.137)	0.465 (0.141)	0.374 (0.147)	0.256 (0.150)
VLF	1199.93 (1010.54)	936.92 (837.39)	568.34 (515.32)	271.97 (227.48)	–
LF	1218.65 (850.90)	1218.59** (835.04)	1211.06** (840.29)	1087.29 (755.97)	997.86 (717.37)
HF	1335.23 (922.69)	1340.78** (927.46)	1347.21** (928.81)	1343.64** (917.28)	1278.29 (862.05)
HF_{TP}	37.06 (13.52)	40.62 (13.26)	46.32 (13.20)	54.04 (12.73)	62.64 (11.89)
LF/HF	1.123 (0.718)	1.132** (0.721)	1.133** (0.717)	1.055 (0.672)	1.090** (0.791)
HF_n	0.519 (0.148)	0.519** (0.145)	0.522** (0.142)	0.548 (0.137)	0.563 (0.135)
CV	6.442 (1.814)	6.184 (1.774)	5.811 (1.687)	5.357 (1.553)	4.856 (1.425)
MxDMn	343.85 (94.49)	298.13 (83.86)	250.71 (74.26)	203.06 (60.33)	159.36 (47.21)
AMo	35.54 (7.50)	37.18 (7.58)	39.57 (7.47)	42.58 (7.37)	45.95 (7.14)
Mo	935.49 (103.53)	933.99** (104.27)	933.26** (104.38)	932.37** (104.52)	930.00 (103.25)
TI	63.91 (28.46)	79.92 (35.59)	105.26 (46.52)	145.65 (63.45)	209.37 (94.64)
RMSSD	53.66 (16.44)	53.60** (16.45)	53.53** (16.42)	53.16* (16.23)	52.37 (15.75)
*pNN*50	31.81 (13.23)	31.76** (13.17)	31.90** (13.10)	32.00** (13.06)	32.09 (13.09)
ND	170.69 (26.13)	100.94 (10.11)	55.83 (3.38)	29.65 (1.11)	15.35 (0.39)
NRib	239.97 (9.24)	123.46 (3.56)	62.47 (1.36)	31.46 (0.56)	15.79 (0.25)

Wilcoxon T-test, * – $p < 0.01$, ** – $p < 0.001$.

for the shortest sample); this statistically confirms the conclusions of other authors concerning *HF* and *RMSSD* [17]. *LF* and its derivatives proved stable in 128- and 64-interval samples.

For other FSs, most HRV indices underwent appreciable shifts with shorter segments. One can only note the stability of *LF* (128, 64) in FS3, FS4 (excitement) and complete stability of M_{NN} in FS5 (general strain).

Thus, it can be concluded that the HRV indices M_{NN}, *HF*, *RMSSD*, *pNN50* are insensitive to ECG segment length in the range of 256–32 RR intervals, and *LF*, *HF*/*LF*, HF_n are stable in the 256–64 range, provided that healthy testees are lying or sitting, control their movements, and experience no psychoemotional stress. Nonstationarity in the time series affects the very-low-frequency but not the high-frequency indices. ECG recordings of ≥32 RR intervals provide reliable assessment of the human functional state in the proposed three-factor model.

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