

Original article

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Dynamic characteristics of heart rate during a functional six-minute walk test in patients with Chronic heart failure

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Abstract:

Objective: to perform a comparative analysis of heart rate (HR) spectral indices during the six-minute walk test (6MWT), considering β -blocker intake, and to determine parameters capable of characterizing cardiac contractility and chamber dimensions in chronic heart failure (CHF).

Materials and Methods. The study involved patients with stable CHF of either ischemic or hypertensive etiology: those receiving β -blockers (the main group) and those who had refrained from β -blocker use for over one month before undergoing the 6MWT (the control group). All participants completed Doppler echocardiography and the 6MWT. Spectral indices of HR within the frequency range [0; 1] Hz were measured at every stage of the 6MWT. Evaluated parameters included the ratio of predominant frequencies in the spectrum for stages II vs. I (fII/I), stages II vs. IV (fII/IV) of the 6MWT, and mean HR recovery time.

Results. No statistically significant correlations were identified between HR frequency composition ratios, Doppler echocardiography metrics, and the NYHA class of CHF in the main group. However, in the control group, a larger left ventricular ejection fraction correlated positively with increased fII/I ratios and reduced HR recovery times.

Conclusion. The spectral characteristics of HR during the 6MWT could serve as markers of compliance with β -blocker treatment and might indirectly indicate cardiac contractility and chamber size in CHF patients not currently using β -blockers.

Keywords: six-minute walk test, chronic heart failure, heart rate, continuous wavelet transformation, β -blocker

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Introduction

The six-minute walk test (6MWT) is a significant diagnostic method for determining the functional abilities of patients with various medical conditions [1]. The results of the 6MWT demonstrate high correlation both clinically and prognostically with the indicators of the gold standard for assessing the functional reserve of patients, particularly those with cardiac and respiratory pathologies — cardiorespiratory stress testing [2].

In addition to the well-known and widely used algorithm for determining the functional class of heart failure according to the New York Heart Association (NYHA class), classification based on the distance covered during the 6MWT, this test also allows to study the adaptive capabilities of cardiac patients, which helps not only to clarify the prognosis but also, if necessary, optimize patient therapy [3]. Over the past 15 years, numerous clinical studies have highly evaluated the reliability, specificity, and prognostic value of 6MWT. A unique advantage is that the 6MWT does not require any special equipment. To perform the 6MWT, you only need: a 30-meter flat, solid walking path marked every 3 meters; a stopwatch; a lap counter; two turning point markers. In addition to the standard method, heart rate

(HR), blood pressure, and oxygen saturation can also be measured before and after the test [1]. Valuable prognostic information can also be obtained by performing a double 6MWT, that is, conducting it twice with a 20-30 minutes break in between. At the same time, parameters such as the patient's adaptation index, indicators of their cardiac function, and several others are calculated [3]. It should be noted that almost all formulas for determining such calculated indicators of compensatory reserve in patients with CHF (chronic heart failure) use values related to HR (heart rate recovery time, etc.). Therefore, the issue of using these indicators while patients are taking beta-blockers remains open. However, the routine use of the 6MWT is associated with significant organizational challenges. The necessity for direct involvement of trained medical personnel to monitor compliance with the standardized protocol and ensure patient safety transforms the test from a simple procedure into a rather time-consuming and resource-intensive method. This creates barriers to its widespread application in real clinical practice [2].

Due to these limitations, the development of solutions for automating the 6MWT has become an urgent task in modern cardiology. The advancement of remote monitoring technologies, miniaturization of medical sensors, and new

methods for analyzing biophysical signals are opening up new prospects for transforming this test. The integration of data from wearable devices, such as single-channel electrocardiographs (ECG), accelerometers, and photoplethysmography (PPG) sensors, allows going beyond simple measurement of the distance covered. A comprehensive analysis of heart rate variability, myocardial repolarization parameters, and gait characteristics in real-time mode can significantly enhance the informativeness of 6MWT [4, 5]. The possibility of implementing technologies for remote monitoring of ECG and walking parameters [6, 7] can substantially reduce the workload on medical personnel during this test.

The objective is to conduct a comparative analysis of spectral heart rate variability (HRV) parameters during the 6MWT, depending on the use of beta-blockers, and to identify parameters capable to estimate contractility and the size of the cardiac chamber dimensions in patients with CHF (chronic heart failure).

Materials and Methods

The study was conducted in accordance with the principles of the Helsinki Declaration and received approval from the Ethics Committee of the Federal State Budgetary Educational Institution of Higher Education «Saratov State Medical University named after V.I. Razumovsky» of the Ministry of Health of Russia (protocol No. 09 dated April 2, 2024). Informed consent was obtained from all study participants.

The study group included 46 individuals with compensated CHF (NYHA class II-III) that developed against the background of existing coronary heart disease and/or hypertension. The age of the examined participants ranged from 42 to 65 years. All patients in the main group received basic therapy for CHF (including beta-blockers), as well as for coronary heart disease and/or hypertension, in accordance with current clinical guidelines [8].

The exclusion criteria were as follows: limited distance during the 6MWT (due to significant musculoskeletal disorders); acute myocardial infarction; surgical cardiovascular or percutaneous coronary intervention within 3 months prior to inclusion; unstable angina within 1 month; pre-test measurements showing: heart rate (HR) above 120 bpm at rest; systolic blood pressure (SBP) > 180mmHg; diastolic blood pressure (DBP) > 100mmHg; any pathological condition that could interfere with participation in the study (e.g., blindness, deafness, speech problems, etc.); life-threatening or uncontrolled rhythm disturbances, including those with clinical manifestation, or persistent ventricular tachycardia and atrial fibrillation or flutter; taking medications, except beta-blockers, that could affect heart rate; current or past history of malignant neoplasms in any organ system (except localized basal cell skin cancer); any other patient's disease/condition, which according to investigator could possibly expose the patient to higher health risks due to study participation or interfere with the patient's ability to comply with study requirements and prevent the patient from completing the study.

The control group consisted of 28 individuals aged 41 to 65 years who were not taking β -blockers at the time of 6MWT and for at least 1 prior to its administration. As a rule, patients independently halted taking β -blockers, which was

revealed during routine consultation as part of follow-up observation. After completing 6MWT, patients were advised to resume taking β -blockers. The remaining inclusion and exclusion criteria for the control group were the same as those for the main group patients. The clinical characteristics of the examined patients are presented in *Table 1*.

Table 1. The main clinical characteristics in the groups of examined patients.

Parameter	Main group (n=46)	Control group (n=28)	p value
Age, years, Me (Q25, Q75)	60 (56.0; 64.0)	60 (55.0; 65.0)	0.975
Male, n (%)	30 (65.22)	18 (64.29)	-
Female, n (%)	16 (34.78)	10 (35.71)	-
Height, cm, Me (Q25, Q75)	166.8±7.7	167.1±6.6	0.885
Body weight, kg, Me (Q25, Q75)	86.2 (74.3;94.2)	82.7 (70.2; 90.3)	0.921
BMI, kg/m ² , Me (Q25, Q75)	32.07 (25.64; 35.14)	29.13 (28.12; 30.22)	0.806
NYHA class, n (%): II III	16 (34.7) 30 (55.3)	12 (42.9) 16 (57.1)	0.309
<i>Doppler echocardiography parameters</i>			
LVEDD, cm, Me (Q25, Q75)	5.08 (4.7;5.2)	5,2 (4.8;5.3)	0.578
LVESD, cm, Me (Q25, Q75)	3.22 (2.9; 3.6)	3,13 (3.1; 3.6)	0.888
LAESD, cm, Me (Q25, Q75)	3.7 (3.5; 4.1)	3.7 (3.6; 4.1)	0.527
LVEF, %, Me (Q25, Q75)	64.0 (58.0; 66.0)	61.0 (59.0; 67.0)	0.737
LVMI, g/m ² , Me (Q25, Q75)	108.0 (99.0; 128.0)	105.0 (94.0; 150.0)	0.283
MPAP, mmHg., Me (Q25, Q75)	28.0 (25.0; 36.0)	27.0 (24.0; 27.0)	0,052
TAPSE, cm, Me (Q25, Q75)	2.12 (2.0; 2.22)	2.1 (2.0; 2.2)	0,599

As shown in *Table 1*, the groups of subjects were homogeneous and comparable with each other in terms of the main characteristics of their clinical status. After signing informed consent forms and undergoing a standard clinical examination, all study participants underwent Doppler echocardiography (ECHO) and 6MWT. During ECHO the following parameters were assessed: left ventricular end-diastolic dimension (LVEDD); left ventricular end-systolic dimension (LVESD); left atrial end-systolic dimension (LAESD); left ventricular ejection fraction (LVEF); left ventricular mass index (LVMI); mean pulmonary artery pressure (MPAP); TAPSE (Tricuspid Annular Plane Systolic Excursion). The performance of 6MWT was in accordance with standard clinical guidelines [1, 3]. During the 6MWT, electrocardiogram (ECG) and photoplethysmography (PPG) records were continuously registered using certified cardiorespiratory monitoring equipment (LLC Research and Production Design Company “Medicom MTD”). The recordings included both pre- and post-walking periods, approximately 3 minutes before and 4–5 minutes after walking, respectively. Measurements of heart rate, oxygen saturation, and dyspnea assessment based on the Borg scale before and after the 6MWT [1] were also presented.

Based on the PPG signal recordings, the heart rate was continuously calculated according to the method presented in the study [9]. The method including the analysis of oscillatory patterns of continuous wavelet transform (CWT), allowed to assess the changes in heart rate (HR) during periods of intense patient’s walk, not only in states of relative rest corresponding to the pre- and post-6-minute walk test (6MWT) phases.

For each patient, the entire HR recording was divided into four consecutive stages: stage I—rest before the 6MWT; stage II—a six-minute walking period; stage III—the state immediately after the 6 MWT, i.e., the period of a sharp decrease in HR to the average value in stage I; stage IV—rest after HR stabilization. This diagram is clearly shown in the upper chart of *Figs. 1–2*.

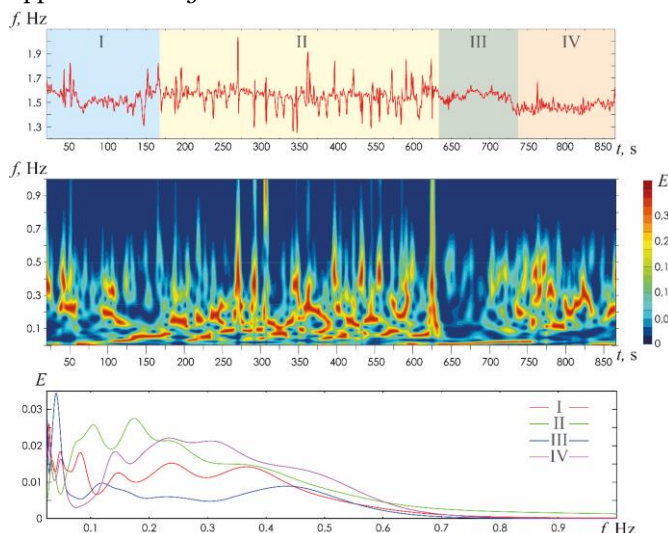


Figure 1 — (a) HR changes of the patient from the main group during the 6MWT, colors indicate stages I–IV of the test execution; (b) energy surfaces of the CWT, where the energy amplitude of a certain oscillation frequency at each moment of the time is encoded using the color scale shown to the right of the figure; (c) normalized CWT energy in the range [0; 1] Hz, an analogue of the classical Fourier spectrum, calculated for stages I–IV of the test execution

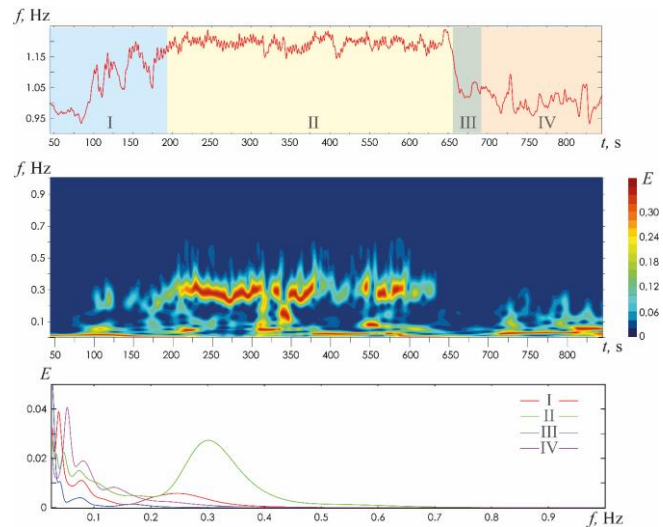


Figure 2 — (a) HR variability of the patient from the control group during the 6MWT, colors indicate stages I–IV of the test execution; (b) energy surfaces of the CWT, where the energy amplitude of a certain oscillation frequency at each moment of the time is encoded using the color scale shown to the right of the figure; (c) normalized CWT energy in the range [0; 1] Hz, an analogue of the classical Fourier spectrum, calculated for stages I–IV of the test execution

Statistical analysis of the obtained data was carried out using the Statistica 10.0 program. Quantitative indicators are presented as median and interquartile range. Qualitative parameters are given as the percentages of the total number of observations in the group. The significance of differences between various groups was assessed using the Mann–Whitney test. Differences were considered statistically significant at $p < 0.05$. The Pearson correlation coefficient was utilized to identify the interrelations between the variables. The article reports only statistically significant correlation coefficients.

An analysis of heart rate variability dynamics was performed to refine the assessment of each patient’s heart rhythm based on the CWT. This approach allows to visualize the oscillatory structure of the heart rhythm for each moment of the time as shown in *Figure 1(b)*. The assessment of the energy distribution of the CWT in the frequency range [0; 1] Hz was made for the patient’s heart rate at each stage of the 6MWT. The frequency ratios that are most expressed in the spectrum were calculated for stages II and I (f_{II}/I) II and IV (f_{II}/IV).

Results

Table 2 presents statistical data on the 6MWT performance for different groups of patients. The results of the performed numerical analysis of HR dynamics during the 6MWT demonstrate differences in HR spectral components between the main group and the control group ($p < 0.05$). Visual representation of typical heart rate characteristics is demonstrated in *Fig. 1* (main group) and *Fig. 2* (control group). The average heart rate recovery time in the main group was longer than in the control group after the 6MWT.

It was established through paired correlation analysis that in the control group, the HR recovery time and f_{II}/I ratio were significantly associated with the left ventricular ejection fraction and NYHA class of chronic heart failure. Thus, it was established that a higher LVEF was associated with a greater

fII/I ratio and lower HRR time ($R = 0.62$ and $R = -0.42$, respectively); while NYHA class had an inverse relationship with the fII/IV ratio ($R = -0.27$). Moreover, in the patients of control group, significant inverse correlations were found between the fII ratio and LVESD ($R = -0.41$); LVEDD ($R = -0.33$); LAESD ($R = -0.31$); LVMMI ($R = -0.39$). Direct correlations were found with TAPSE ($R = 0.31$). Longer HRR time was significantly associated with: LVEDD ($R = 0.68$); LVESD ($R = 0.49$); LAESD ($R = 0.51$); LVMMI ($R = 0.46$). The obtained results confirm a lower compensatory reserve in patients with a higher severity of CHF.

There was no significant correlation between the values of the frequency band ratios of HR and HRR time with ECHO parameters and NYHA class in the main group of subjects taking β -blockers. Thus, the assessment of compensatory reserve based on various heart rate ratios during the 6MWT while taking medications affecting HR does not demonstrate significant prognostic capabilities.

Discussion

Recently, there has been a substantial rise in the number of studies employing the 6MWT as a diagnostic tool for evaluating patient health, concurrently monitoring various physiological parameters such as hemodynamics, ECG, photoplethysmography (PPG), blood oxygen saturation, and additional relevant factors using wearable digital technologies. Currently, PPG stands out as one of the leading engineering tools for designing wearable medical equipment due to its low cost, ease of integration into consumer-friendly devices, high-quality signals, and superior resistance to interference, providing an ideal combination of advantages. Advanced computational techniques applied to processed digital biomarkers enable comprehensive assessments of numerous key features of cardiovascular function via PPG measurements, including heart rhythm, heart rate and its variability, properties of the arterial pulse waveform, regulation of vascular tone, vessel wall elasticity, respiratory fluctuations, and many others [9, 10].

Table 2. Statistical data of 6MWT performance in the studied groups

Indicator	Group		p value
	main (n=46)	control (n=28)	
6MWT parameters			
Distance, m, <i>Me</i> (Q_{25} , Q_{75})	362.0 (310.0; 440.0)	394.0 (375.0; 451.0)	0.328
HR recovery time, 6MWT, sec, <i>Me</i> (Q_{25} , Q_{75})	94.0 (41.0; 197.0)	62.5 (45.0; 68.0)	
Parameters of frequency characteristics of heart rate ECG			
f_{II} , <i>Me</i> (Q_{25} , Q_{75})	110.0 (98.7; 150.2)	20.0 (15.0; 35.9)	0.005
$f_{II/IV}$, <i>Me</i> (Q_{25} , Q_{75})	75.2 (51.0; 91.0)	15.4 (10.2; 35.8)	0.007

The expression of spectral indicators of the heart rate, as well as the ratios of frequency components, depends on many factors, including the heart autonomic regulation, the degree of ischemia, and the pharmacological influence of medication. That research revealed that patients on β -blocker therapy, unlike those in the primary group, showed no correlations between spectral parameters and standard echocardiographic indicators, likely due to the pharmacological inhibition of the sympathetic nervous system. It is also important to consider that heart rate variability and its spectral characteristics can be sensitive to external stressors, the patient's emotional state, as well as respiratory parameters and other physiological rhythms. The results of the study substantiate the need to develop standardized methods for taking them into account when interpreting spectral data in wearable medical devices being developed.

The study has revealed significant correlations between spectral components and left ventricular parameters, suggesting that spectral analysis could be a valuable tool for evaluating cardiovascular reserve capacity in CHF patients. Such an approach would enhance the ability to clarify decompensation risk of CHF and assess the efficacy of pharmacological treatment. Currently, heart rate variability is one of the most thoroughly investigated phenomena, widely applied in research settings and clinical practice [11]. Classical HRV analysis is based on determining the RR series (the time elapsed between two consecutive R waves on the ECG). In this study, the wavelet approach is used to extract heart rate variability (HRV) based on continuous heart rate assessment [9]. The frequency components of heart rate variability reflect different processes involved in cardiac regulation, mainly chronotropic control of the heart. In particular, high-frequency components within the range of 0.15–0.4 Hz are determined by vagal nerve activity and respiratory effects on heart rate [11]. However, there is no consensus among researchers regarding the nature of different HRV frequency components, and the debate remains ongoing [12]. This research focuses on analyzing frequency composition of heart rate variability by evaluating independent frequency components (peak spectral values) without linking them to particular oscillatory processes. Such an assessment of indicators, based solely on objective quantitative measurements of these components, could offer significant potential value for clinical practice [11, 12].

Despite the importance of the findings, the research possesses certain limitations. First of all, the limited number of participants restricts the generalizability of the obtained data to the broader population of CHF patients. Secondly, the administration of pharmacological drugs such as β -blockers affects heart rate variability, significantly complicating the interpretation of spectral data and restricting the practical application of the method in clinical practice. Another important limitation is the observation time – as circadian rhythms and chronotypes may influence the real-time dynamics of hemodynamic and autonomic processes during the day. Going forward, it will be essential to increase sample size and implement multi-day-monitoring studies to gather more accurate data regarding patients' heart rate variability while considering the mentioned factors. Nevertheless, the results of the conducted pilot study emphasize the importance of assessment of the therapy received by cardiac patients during stress diagnostic tests.

A promising future direction for this work is the integration of advanced spectral analysis of cardiovascular system biophysical signals, as described in [13], to expand the estimation capabilities of cardiorespiratory interactions. The creation of these algorithms for the automatic identification of heart rate patterns and variability, tailored to individual patient characteristics, is expected to significantly improve diagnostic accuracy and patient monitoring in individuals suffering from chronic heart failure.

Conclusion

Analysis of the frequency composition of heart rate during the 6MWT can serve as an indicator of adherence to beta-blocker therapy. Furthermore, in situations where beta-blockers are not being administered, this approach can offer an indirect evaluation of cardiac contractility and chamber dimensions in patients suffering from CHF.

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Conflict of Interest. The authors declare that there is no conflict of interest.

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