

Medical Devices and Devices for Control of the Environment,
Substances, Materials and Products

УДК 615.47+681.2.08

Original article

<https://doi.org/10.32603/1993-8985-2020-23-1-96-104>

A Method for Predicting the Main Indicators of Cardiopulmonary Stress Testing for Patients with Chronic Heart Failure

Alexander S. Krasichkov^{1,2}✉, Eliachim Mbazumutima¹,
Fabian Shikema¹, Evgeny M. Nifontov²

¹Saint Petersburg Electrotechnical University, St Petersburg, Russia

²Pavlov First Saint Petersburg State Medical University, St Petersburg, Russia

✉ krass33@mail.ru

Abstract

Introduction. Cardiopulmonary stress testing provides significant diagnostic and prognostic information on the condition of patients with cardiovascular and pulmonary diseases. However, the final stage of such tests requires significant physical effort from the patient, which may aggravate the existing cardiovascular or pulmonary pathology. A possible solution consists in the development of methods for calculating the final-stage testing parameters on the basis of the data obtained at the initial test stages.

Aim. To develop a method for calculating the values of peak heart rate and peak oxygen consumption for patients with chronic heart failure at the end of a cardiopulmonary stress test on the basis of the data obtained at the initial test stages.

Materials and methods. 149 anonymized rhythmograms and oxygen consumption records for chronic heart failure patients were used. The patients underwent a cardiopulmonary stress test using a bicycle ergometer. The load was raised gradually by increasing the load power by 10 W following each 1-minute stage.

Results. Following an analysis of the data obtained, a method for evaluating the maximum values of heart rate and oxygen consumption in patients with chronic heart failure was developed.

Conclusion. When calculating peak heart rate values, the relative error did not exceed 10%, which renders this method feasible for practical application. When calculating the peak oxygen consumption after completing 70% of the load protocol, the relative error did not exceed 20% in most cases. Further research should be aimed at improving the accuracy of the method for use in medical applications testing the performance of the cardiopulmonary system.

Keywords: human stress testing system, electrocardiogram, heart rate (HR), exhaled breath analysis, regression analysis, test performance prediction

For citation: Krasichkov A. S., Mbazumutima E., Shikema F., Nifontov E. M. A Method for Predicting the Main Indicators of Cardiopulmonary Stress Testing for Patients with Chronic Heart Failure. Journal of the Russian Universities. Radioelectronics. 2020, vol. 23, no. 1, pp. 96–104. doi: 10.32603/1993-8985-2020-23-1-96-104

Acknowledgements. We express gratitude to the Almazov National Medical Research Centre for providing anonymized data on the cardiorespiratory stress test of patients.

Conflict of interest. Authors declare no conflict of interest.

Submitted 25.10.2019; accepted 28.11.2019; published online 28.02.2020



Приборы медицинского назначения, контроля среды, веществ, материалов и изделий

Оригинальная статья

Метод прогнозирования основных показателей кардиопульмонального нагрузочного тестирования для больных с хронической сердечной недостаточностью

А. С. Красичков^{1,2}✉, Э. Мбазумутима¹, Ф. Шикама¹, Е. М. Нифонтов²

¹Санкт-Петербургский государственный электротехнический университет "ЛЭТИ" им. В. И. Ульянова (Ленина), Санкт-Петербург, Россия

²Первый Санкт-Петербургский государственный медицинский университет им. акад. И. П. Павлова, Санкт-Петербург, Россия

✉ krass33@mail.ru

Аннотация

Введение. Кардиопульмональный нагрузочный тест предоставляет значимую диагностическую и прогностическую информацию о состоянии больных с сердечно-сосудистыми и легочными заболеваниями. Существует серьезная проблема, состоящая в том, что выполнение нагрузочного тестирования испытуемым в его завершающей фазе является физически тяжелым упражнением для человека. Присутствует значительный риск возникновения и развития патологических состояний сердечно-сосудистой системы пациента. Одним из решений данной проблемы является разработка методов оценивания биологических параметров пациентов в конце выполнения нагрузочного протокола на основе данных первых этапов теста.

Цель работы. Разработка метода нахождения оценки максимальной частоты сердечных сокращений (ЧСС) и пикового потребления кислорода (ПК) у больных с хронической сердечной недостаточностью (ХСН) в конце выполнения кардиореспираторного нагрузочного стресс-теста на основе результатов исследования, полученных на первоначальных ступенях теста.

Материалы и методы. Для проведения исследования использованы 149 обезличенных записей ритмограмм и данных изменения ПК пациентов с ХСН, которые проходили кардиопульмональный нагрузочный тест на велоэргометре с использованием ступенчатого нагрузочного протокола (прирост мощности нагрузки на каждой ступени составлял 10 Вт, длительность ступени нагрузки была равна 1 мин).

Результаты. На основе анализа полученных данных разработан метод оценки пиковых значений ЧСС и ПК у больных с ХСН.

Заключение. Относительная ошибка предложенной оценки пикового значения ЧСС в большинстве случаев не превосходила 10 %, что позволяет ее использовать для практических целей. Установлено, что при выполнении 70 % нагрузочного протокола ошибка предложенной оценки пикового ПК в большинстве случаев не превышает 20 %. Необходимы дополнительные исследования для повышения точности данной оценки с целью использования в медицинских приложениях, направленных на модернизацию методов и аппаратуры для нагрузочного тестирования пациентов.

Ключевые слова: система нагрузочного тестирования человека, электрокардиосигнал, частота сердечных сокращений (ЧСС), анализ выдыхаемого воздуха, регрессионный анализ, предсказание показателей тестирования

Для цитирования: Метод прогнозирования основных показателей кардиопульмонального нагрузочного тестирования для больных с хронической сердечной недостаточностью / А. С. Красичков, Э. Мбазумутима, Ф. Шикама, Е. М. Нифонтов // Изв. вузов России. Радиоэлектроника. 2020. Т. 23, № 1. С. 96–104. doi: 10.32603/1993-8985-2020-23-1-96-104

Благодарности. Выражаем благодарность Национальному медицинскому исследовательскому центру им. В. А. Алмазова Министерства здравоохранения Российской Федерации за предоставление обезличенных данных кардиореспираторного нагрузочного теста пациентов.

Конфликт интересов. Авторы заявляют об отсутствии конфликта интересов.

Статья поступила в редакцию 25.10.2019; принята к публикации после рецензирования 28.11.2019; опубликована онлайн 28.02.2020

Introduction. The growing incidence of cardiovascular pathologies among the human population requires the development of non-invasive diagnostic methods aimed at early detection and prevention of such conditions.

Load stress testing (Fig. 1) [1] is most frequently used as a non-invasive and reproducible method for diagnosing the performance of the cardiovascular system and predicting treatment outcomes of cardiovascular diseases [2]. The system of load stress testing includes equipment for performing physical exercise of various intensity (a bicycle ergometer or a treadmill), sensors for recording human biological signals (e.g., electrocardiogram, blood pressure, etc.) and computing devices for processing the data using software applications [3].

Cardiopulmonary stress testing (CPST) refers to load stress testing with an additional measurement of gas exchange parameters at rest, during exercise and during recovery. As a rule, the following main indicators are measured: the volume of oxygen consumed ($\dot{V}O_2$), the volume of exhaled carbon dioxide ($\dot{V}CO_2$), ventilation parameters, as well as the electrocardiographic parameters, such as heart rate (HR) and blood pressure. Fig. 1, *a* exemplifies a system for simultaneous monitoring of respiration, blood pressure and pulse during exercise.

CPST is a reliable diagnostic tool that provides significant clinical and prognostic information about

the condition of patients with cardiovascular and pulmonary diseases, thus allowing treatment outcomes to be predicted [4, 5].

When conducting clinical load testing, the selection of its modality and protocol is of decisive importance (Fig. 1, *b*). Existing protocols typically include an initial warm-up period followed by a progressive dosed load and a recovery period after maximum effort.

The selection of a workload protocol depends on the purpose of testing. The most frequently used protocol is that based on a stepwise increase of the load [3, 6, 7]. The as-obtained data is continuously displayed on a monitor and recorded in the device memory for further processing (Fig. 1, *c*).

A serious problem in the application of CPST consists in the increased risk of overload at maximal exercise for some patients, which may lead to aggravating the patient's physical condition. This is why CPST is performed only at medical institutions having intensive care units. A possible solution to this problem is the development of methods for calculating (predicting) the functional state of patients at the end stage of the load protocol based on the data registered at initial test stages.

This article proposes an approach, according to which only the initial SPST cycle, rather the entire load protocol, is realized. The parameters obtained at the initial stages are further used to calculate the results of the final, most energy-consuming phase of

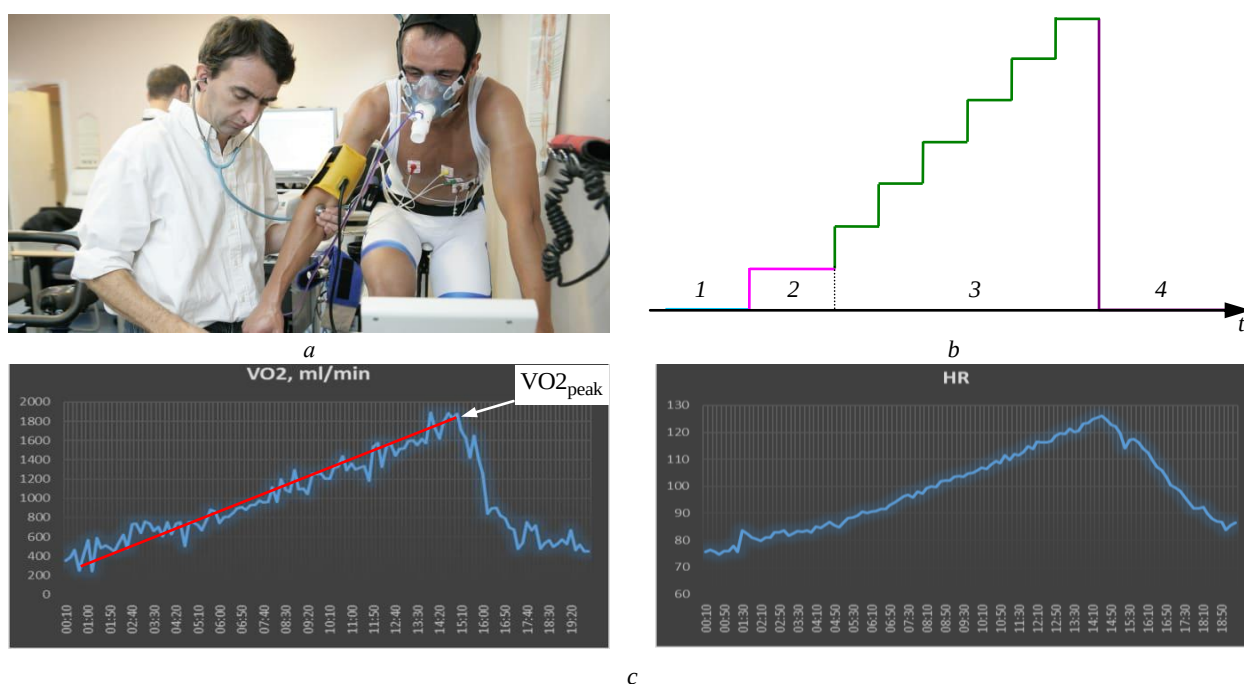


Fig. 1. Stress Testing: *a* – training apparatus; *b* – test protocol (1 – training, 2...3 min; 2 – warm-up, 1...3 min; 3 – test implementation, 8...15 min; 4 – recovery, 3...10 min); *c* – test results

SPST. Thus, it becomes possible to reduce the risk of overburdening the patient by decreasing the duration of the load protocol without losing diagnostically important information.

The task of predicting some CPST indicators was considered in previous research. Thus, [8–11] investigated the possibility of predicting HR at peak loads in patients with cardiovascular pathologies using linear regression equations. A similar approach was applied in [12–14] to obtain the peak oxygen consumption ($V_{O_{2peak}}$). A method for predicting

$V_{O_{2peak}}$ based on a linear relationship between HR and V_{O_2} was proposed in [15]. However, in all the aforementioned works, the main SPST parameters were evaluated on the basis of the data obtained during the resting state, not taking into account the information received at the initial stages of the load protocol. Thus, the dynamic properties of biological signals during load testing were actually ignored.

In this work, we describe a method for determining the peak HR and $V_{O_{2peak}}$ in patients with chronic heart failure (CHF) at the end of a cardiorespiratory load stress test based on the results obtained at initial test stages.

Materials and methods. The research material comprised 149 anonymized records of rhythmograms and oxygen consumption variations in CHF patients (97 men and 52 women). All the patients underwent CPST on a bicycle ergometer using a stepwise load protocol: the load power was raised by 10 W after each 1-minute stage. The testing was conducted at the Almazov National Medical Research Centre.

Symptoms that resulted in test termination included:

- 1) pain;
- 2) fatigue;
- 3) critical changes in the ECG, blood pressure, oxygen saturation (these were continuously monitored by medical personnel).

Following an analysis of the data obtained, a method for calculating peak HR and $V_{O_{2peak}}$ values at maximal exercise in CHF patients was developed. The proposed method consists of three stages, which are shown in Fig. 2.

The first stage involves an estimation of the peak HR value $\hat{HR}_{peak}$ (prediction) at maximal exercise (the final phase of the CPST protocol). To this end, a

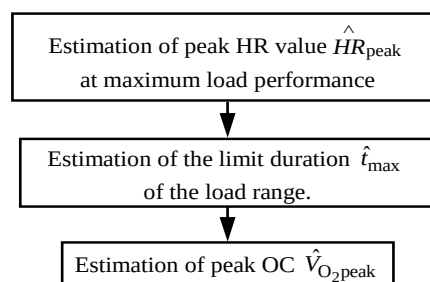


Fig. 2. The Structural Scheme of the Method for Assessing the Peak Values of HR and OC for Patients with Chronic Heart Failure

regression equation was obtained empirically following the analysis of rhythmograms:

$$\hat{HR}_{peak} = k_1 + k_2 HR_{rest} + k_3 HR_{slope}, \quad (1)$$

where HR_{rest} is the heart rate at rest before the test; HR_{slope} is the angular coefficient of the straight line approximating the dependence of changes in the heart rate level during the first three stages of the load to the desired estimate. The coefficients k were determined using the least square method

$$\sum_N \left(HR_{peak} - \hat{HR}_{peak} \right)^2 = \sum_N \left(HR_{peak} - k_1 - k_2 HR_{rest} - k_3 HR_{slope} \right)^2 \rightarrow \min,$$

where N is the number of analyzed rhythmograms; HR_{peak} is the true peak heart rate.

The as-obtained coefficients for various groups of CHF patients are summarized in Table. It can be seen that the k coefficients included in the regression expression (1) vary significantly depending on the method of group formation.

The Values of the Regression Equation Coefficients

Coefficient	Group		
	males	females	combined
k_1	14.935	27.228	24.263
k_2	1.081	0.898	0.988
k_3	32.086	22.215	22.205

On the basis of the obtained peak HR value $\hat{HR}_{peak}$ and by approximating changes in HR from the $HR(t)$ time across the load interval by the quadratic dependence

$$HR(t) = a_1 t^2 + a_2 t + a_3; \quad HR(t_{max}) = HR_{peak},$$

an estimate of the duration of the load interval is found:

$$\hat{t}_{\max} = \frac{-a_2 + \sqrt{a_2^2 - 4a_1(a_3 - \hat{HR}_{\text{peak}})}}{2a_1}. \quad (2)$$

It should be noted that the coefficients a_1 , a_2 , a_3 are determined in the first steps of the load interval.

At the final (3rd stage), the $V_{O_2\text{peak}}$ estimate $\hat{V}_{O_2\text{peak}}$ is found. This estimate is based on the previously obtained estimate $\hat{HR}_{\text{peak}}$, as well as assuming a linear dependence of oxygen consumption changes across the load interval: $V_{O_2}(t) = c_1t + c_2$. Then, $V_{O_2\text{peak}}$ is estimated by the formula

$$\hat{V}_{O_2\text{peak}} = c_1\hat{t}_{\max} + c_2, \quad (3)$$

where c_1 and c_2 are the angular coefficient and the free term of the linear dependence, respectively. The coefficients are obtained by approximating the dependence of changes in $V_{O_2\text{peak}}$ at the initial stages of the load interval.

Results. Fig. 3 shows the range of the relative error when using the proposed method for calculating HR at maximal exercise (1) by the formula

$$\Delta_{HR} = \frac{HR_{\text{peak}} - \hat{HR}_{\text{peak}}}{HR_{\text{peak}}}, \quad (4)$$

where HR_{peak} is the empirical (true) HR value at a peak load; $\hat{HR}_{\text{peak}}$ is the HR estimate at a peak load obtained using (1).

It can be seen from Fig. 3 that, when estimating peak HR values, the relative error does not exceed 10% in most cases. In addition, the use of the proposed method for assessing CPST parameters for

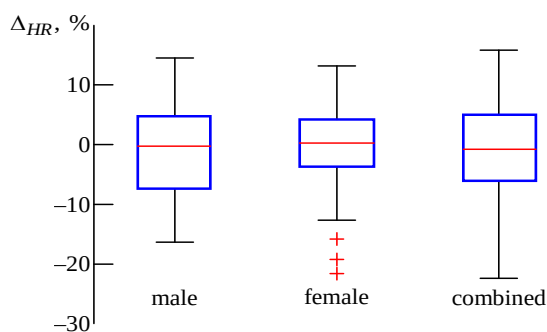


Fig. 3. Relative Error Prediction Range of Heart Rate Diagrams

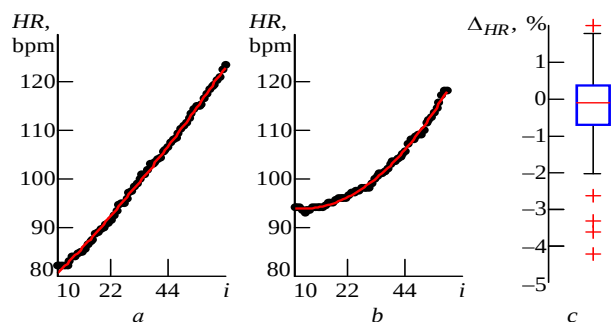


Fig. 4. Approximation of HR by Quadratic Dependence: a, b – results for two patients (markers – measurement results, red lines – approximation); c – diagram of the scale of the relative error in determining HR at the peak of the load using a quadratic model

different groups of patients gives similar results when combining the groups.

Fig. 4 exemplifies the results of approximating changes in the HR during exercise by quadratic dependence for two different patients. The vertical and horizontal axes shows the HR values and the measurement intervals i . Fig. 4, c shows the range of the relative error when determining HR at maximal exercise using a quadratic model determined by analogy with (4).

As shown in Fig. 4, the quadratic model accurately describes the dependence of HR changes across on the load interval. The relative error in estimating HR at a peak load using a quadratic model does not exceed 2% in the vast majority of cases. This result confirms the adequacy of the applied quadratic model of HR changes across the load interval.

Fig. 5 shows the range of the relative error when using the proposed method for determining $V_{O_2\text{peak}}$. The V_{O_2} level across the load interval was approximated by a linear dependence

$$\hat{V}_{O_2}(t) = c_1t + c_2; \quad \hat{V}_{O_2\text{peak}} = \hat{V}_{O_2}(t_{\max}).$$

In this case, the duration of the load testing $t_{\max}$ was known, and the coefficients c_1 , c_2 , included in

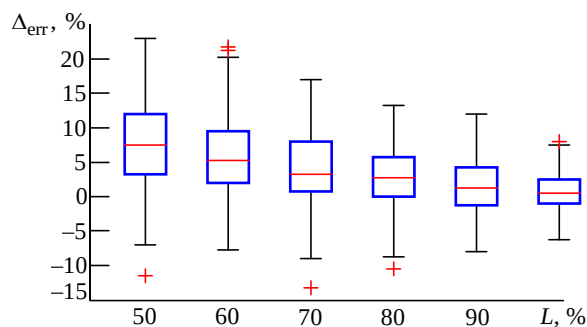


Fig. 5. Relative Error of the Determining of Peak Value of a OC with a Linear Model

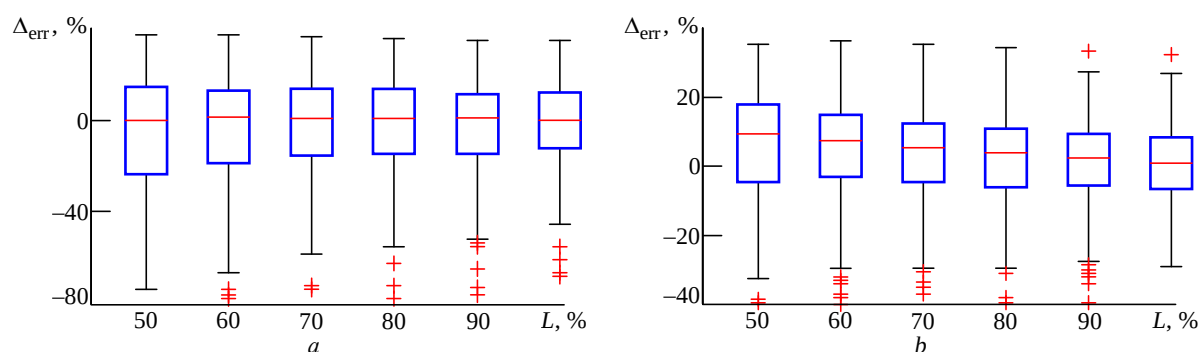


Fig. 6. Relative Error of the Determining the Peak Value of a OC with an Unknown a Priori Duration of Stress Testing: *a* – relative error of the determining the duration of stress testing; *b* – the relative error of the determining the peak value of the OC in assessing the duration of stress testing

the linear equation, were calculated depending on the percentage of test completion with respect to its maximum duration L . As follows from Fig. 5, the relative error in estimating the peak oxygen consumption using the linear model obtained when performing even the entire load stress test (100% of the maximum load duration) is not equal to zero. A possible explanation is that the $V_{O_2}(t)$ curve fluctuates significantly during testing (see Fig. 1, *c*). This is due to the technical features of the equipment (sensors in particular) used to measure gas exchange.

When estimating $V_{O_{2peak}}$ and when the duration of the load test t_{max} is not known, the dependence of the relative error on the load duration is shown in Fig. 6, *a*. In this case, the duration was predicted on the basis of (2) and (3) as a fraction of the estimate $\hat{t}_{max}$. The use of this estimate leads to an increase in the relative error range when estimating the $V_{O_{2peak}}$ value (Fig. 6, *b*). However, under a 70% completion of the CPST protocol, the relative error of the method does not exceed 20% in most cases.

It should be noted that the magnitude of the relative error is determined by several factors associated with the process of recording biological signals. Thus, the registration of electrocardiograms during CPST involves noises associated with the inevitable motor activity of the patient, which affect the quality of generated rhythmograms (false detection or omission of cardiac signals [16, 17]). Another factor is

fluctuations in the curve reflecting changes in $V_{O_2}(t)$.

Conclusions. As a result of the study, a method was proposed for reducing the duration of cardiopulmonary stress testing by means of calculating its final parameters on the basis of data obtained at the initial test stages. This approach allows the risk of exercise intolerance and respective negative complications to be minimized. An empirical linear regression equation was obtained for estimating peak heart rate values. It was found that the coefficients of the regression equation varied significantly depending on the patient gender. When estimating peak heart rate values, the relative error did not exceed 10% in most cases, which renders the method feasible for practical application. For patients suffering from chronic heart failure, the use of quadratic dependence in describing heart rate changes across the load interval of cardiopulmonary stress testing produces an adequate rhythmogram model. A linear regression equation was empirically obtained for assessing peak oxygen consumption $\hat{V}_{O_{2peak}}$. It was found that, after completing 70% of the load protocol, the relative error in estimating the peak oxygen consumption did not exceed 20% in most cases. The magnitude of this error is associated with the process of registering biological signals. Thus, additional research is needed to improve the accuracy of the proposed method for use in medical applications testing the performance of the cardiovascular system.

Authors' contribution

Alexander S. Krasichkov, management of the work and preparation of the paper text.

Eliachim Mbazumutima, analysis of the heart rate data.

Fabian Shikama, analysis of the oxygen consumption data.

Evgeny M. Nifontov, statement of the problem and discussion of the results.

References

1. Stress Tests Could Mark Bottom for Bank Stocks. Available at: <https://www.cnbc.com/2017/06/28/stress-tests-fed-bank-stocks.html> (accessed 24.01.2020).
2. Falk E., De Feyter P. J., Shah P. K. Ischemic Heart Disease. London, Manson Publishing, 2007, 312 p.
3. ACC/AHA Guidelines for Exercise Testing. A Report of the American College of Cardiology/American Heart Association. Task Force on Practice Guidelines (Committee on Exercise Testing). JACC, 1997, vol. 30, no. 1, pp. 260–315.
4. Vilcant V., Zeltser R. Treadmill Stress Testing. NCBI Bookshelf, 2019. Available at: <https://www.ncbi.nlm.nih.gov/pubmed/29763078> (accessed 24.01.2020).
5. Albouaini K., Egred M., Alahmar A., Wright D. J. Cardiopulmonary Exercise Testing and Its Application. Postgraduate medical j. 2007, vol. 83, iss. 985, pp. 675–682. doi: 10.1136/hrt.2007.121558
6. Papadakis M. A., McPhee S., Rabow M. W. Current Medical Diagnosis & Treatment. 59th ed. New York, McGraw-Hill, 2020, 1933 p.
7. Fletcher G. F., Ades P. A., Kligfield P., Arena R., Balady G. J., Bittner V. A., Coke L. A., Fleg J. L., Forman D. E., Gerber T. C., Gulati M., Madan K., Rhodes J., Thompson P. D., Williams M. A. Exercise Standards for Testing and Training. A Scientific Statement from the American Heart Association. Circulation. 2013, vol. 128, no. 8, pp. 873–934. doi: 10.1161/CIR.0b013e31829b5b44
8. Hammond H. K., Kelly T. L., Froelicher V. Radionuclide Imaging Correlates of Heart Rate Impairment during Maximal Exercise Testing. J. of the American College of Cardiology. 1983, vol. 2, no. 5, pp. 826–833. doi: 10.1016/s0735-1097(83)80228-9
9. Bruce R. A., Fisher L. D., Cooper M. N., Gey G. O. Separation of Effects of Cardiovascular Disease and Age on Ventricular Function with Maximal Exercise. American J. of Cardiology. 1974, vol. 34, no. 7, pp. 757–763. doi: 10.1016/0002-9149(74)90692-4
10. Brawner C. A., Ehrman J. K., Schairer J. R., Cao J. J., Keteyian S. J. Predicting Maximum Heart Rate Among Patients with Coronary Heart Disease Receiving β -Adrenergic Blockade Therapy. American Heart J. 2004, vol. 148, no. 5, pp. 910–914. doi: 10.1016/j.ahj.2004.04.035
11. Keteyian S. J., Kitzman D., Zannad F., Landzberg J., Arnold J. M., Brubaker P., Brawner C. A., Bensimhon D., Hellkamp A. S., Ewald G. Predicting Maximal HR in Heart Failure Patients Receiving β -Blockade Therapy. Medicine and Science in Sports and Exercise. 2012, vol. 44, no. 3, pp. 371–376. doi: 10.1249/MSS.0b013e318234316f
12. Almeida A. E., Stefani C. M., Nascimento J. A., Almeida N. M., Santos A. C., Ribeiro J. P., Stein R. An Equation for the Prediction of Oxygen Consumption in a Brazilian Population. Arquivos brasileiros de cardiologia. 2014, vol. 103, no. 4, pp. 299–307.
13. Lanier G. M., Zheng Qi, Wagman G., Tseng C.-H. Simple Prediction Formula for Peak Oxygen Consumption in Patients with Chronic Heart Failure. J. of Exercise Science & Fitness. 2012, vol. 10, no. 1, pp. 23–27. doi: 10.1016/j.jesf.2012.04.005
14. Froelicher V. F., Thompson A. J., Davis G., Stewart A. J., Triebwasser J. H. Prediction of Maximal Oxygen Consumption: Comparison of the Bruce and Balke Treadmill Protocols. Chest. 1975, vol. 68, no. 3, pp. 331–336. doi: 10.1378/chest.68.3.331
15. McArdle W. D., Katch F. I., Katch V. L. Essentials of Exercise Physiology. New York, Lippincott Williams & Wilkins, 2010, 790 p.
16. Krasichkov A. S., Grigoriev E. B., Nifontov E. M. Influence of Myographic Interference and Isoelectric Line Drift on Correlation Coefficient in Classification of Cardiac complexes. Biomedical Engineering. 2015, vol. 49, iss. 4, pp. 220–223. doi: 10.1007/s10527-015-9533-7
17. Krasichkov A. S., Grigoriev E. B., Bogachev M. I., Nifontov E. M. Shape Anomaly Detection under Strong Measurement Noise: an Analytical Approach to Adaptive Thresholding. Physical Review E. 2015, vol. 92, iss. 4, 042927. doi: 10.1103/PhysRevE.92.042927

Information about the authors

Alexander S. Krasichkov, Dr. Sci. (Eng.) (2017), Associate Professor of the Department of Radio System of Saint Petersburg Electrotechnical University. The author of more than 100 scientific publications. Area of expertise: statistical radio engineering; signal processing.

Address: Saint Petersburg Electrotechnical University, 5 Professor Popov Str., St Petersburg 197376, Russia

E-mail: krass33@mail.ru

<https://orcid.org/0000-0002-8120-3293>

Eliachim Mbazumutima, Master (2019) in Biotechnical Systems and Technologies, postgraduate student of the Department of Bioengineering Systems of Saint Petersburg Electrotechnical University. The author of 1 scientific publication. Area of expertise: digital processing of biomedical signals; machine learning; pattern recognition.

Address: Saint Petersburg Electrotechnical University, 5 Professor Popov Str., St Petersburg 197376, Russia

E-mail: eliachim2013@yandex.ru

Fabian Shikama, Master (2016) in Biotechnical Systems and Technologies, postgraduate student of the Department of Bioengineering Systems of Saint Petersburg Electrotechnical University. Area of expertise: digital processing of biomedical signals; prosthetics and rehabilitation.

Address: Saint Petersburg Electrotechnical University, 5 Professor Popov Str., St Petersburg 197376, Russia

E-mail: fshikama@mail.ru

Evgeny M. Nifontov, Dr. Sci. (Medicine) (2003), Professor (2009) of Pavlov First Saint Petersburg State Medical University. The author of more than 150 scientific publications. Area of expertise: fundamental medicine; cardiology.

Address: Pavlov First Saint Petersburg State Medical University, 6-8 L'va Tolstogo Str., St Petersburg 197022, Russia

E-mail: nifontov@spmu.rssi.ru

Авторский вклад

Красичков Александр Сергеевич – руководство работой, подготовка текста статьи.

Мбазумутима Элиаким – анализ ритмограмм.

Шикама Фабиен – анализ данных потребления кислорода.

Нифонтов Евгений Михайлович – постановка задачи и участие в обсуждении результатов.

Список литературы

1. Stress tests could mark bottom for bank stocks. URL: <https://www.cnbc.com/2017/06/28/stress-tests-fed-bank-stocks.html> (дата обращения 24.01.2020).
2. Falk E., De Feyter P. J., Shah P. K. Ischemic Heart Disease. London: Manson Publishing, 2007. 312 p.
3. ACC/AHA Guidelines for Exercise Testing. A Report of the American College of Cardiology/American Heart Association. Task Force on Practice Guidelines (Committee on Exercise Testing) // JACC. 1997. Vol. 30, № 1. P. 260–315.
4. Vilcant V., Zeltser R. Treadmill Stress Testing // NCBI Bookshelf. 2019. URL: <https://www.ncbi.nlm.nih.gov/pubmed/29763078> (дата обращения 24.01.2020).
5. Cardiopulmonary exercise testing and its application / K. Albouaini, M. Egred, A. Alahmar, D. J. Wright // Postgraduate medical j. 2007. Vol. 83, iss. 985. P. 675–682. doi: 10.1136/hrt.2007.121558
6. Papadakis M. A., McPhee S., Rabow M. W. Current Medical Diagnosis & Treatment. 59th ed. New York: McGraw-Hill, 2020. 1933 p.
7. Exercise Standards for Testing and Training. A Scientific Statement from the American Heart Association / G. F. Fletcher, P. A. Ades, P. Kligfield, R. Arena, G. J. Balady, V. A. Bittner, L. A. Coke, J. L. Fleg, D. E. Forman, T. C. Gerber, M. Gulati, K. Madan, J. Rhodes, P. D. Thompson, M. A. Williams // Circulation. 2013. Vol. 128, № 8. P. 873–934. doi: 10.1161/CIR.0b013e31829b5b44
8. Hammond H. K., Kelly T. L., Froelicher V. Radionuclide Imaging Correlates of Heart Rate Impairment during Maximal Exercise Testing // J. of the American College of Cardiology. 1983. Vol. 2, № 5. P. 826–833. doi: 10.1016/s0735-1097(83)80228-9
9. Separation of Effects of Cardiovascular Disease and Age on Ventricular Function with Maximal Exercise / R. A. Bruce, L. D. Fisher, M. N. Cooper, G. O. Gey // American J. of Cardiology. 1974. Vol. 34, № 7. P. 757–763. doi: 10.1016/0002-9149(74)90692-4
10. Predicting Maximum Heart Rate Among Patients with Coronary Heart Disease Receiving β -Adrenergic Blockade Therapy / C. A. Bawner, J. K. Ehrman, J. R. Schairer, J. J. Cao, S. J. Keteyian // American Heart J. 2004. Vol. 148, № 5. P. 910–914. doi: 10.1016/j.ahj.2004.04.035
11. Predicting Maximal HR in Heart Failure Patients Receiving β -Blockade Therapy / S. J. Keteyian, D. Kitzman, F. Zannad, J. Landzberg, J. M. Arnold, P. Brubaker, C. A. Bawner, D. Bensimhon, A. S. Hellkamp, G. Ewald // Medicine and science in sports and exercise. 2012. Vol. 44, № 3. P. 371–376. doi: 10.1249/MSS.0b013e318234316f
12. An Equation for the Prediction of Oxygen Consumption in a Brazilian Population / A. E. Almeida, C. M. Stefani, J. A. Nascimento, N. M. Almeida, A. C. Santos, J. P. Ribeiro, R. Stein // Arquivos brasileiros de cardiologia. 2014. Vol. 103, № 4. P. 299–307.
13. Simple Prediction Formula for Peak Oxygen Consumption in Patients with Chronic Heart Failure / G. M. Lannier, Qi Zheng, G. Wagman, C.-H. Tseng // J. of Exercise Science & Fitness. 2012. Vol. 10, № 1. P. 23–27. doi: 10.1016/j.jesf.2012.04.005
14. Prediction of maximal oxygen consumption: comparison of the Bruce and Balke treadmill protocols / V. F. Froelicher, A. J. Thompson, G. Davis, A. J. Stewart, J. H. Triebwasser // Chest. 1975. Vol. 68, № 3. P. 331–336. doi: 10.1378/chest.68.3.331
15. McArdle W. D., Katch F. I., Katch V. L. Essentials of Exercise Physiology. New York: Lippincott Williams & Wilkins, 2010. 790 p.
16. Krasichkov A. S., Grigoriev E. B., Nifontov E. M. Influence of Myographic Interference and Isoelectric Line Drift on Correlation Coefficient in Classification of Cardiac complexes // Biomedical Engineering. 2015. Vol. 49, iss. 4. P. 220–223. doi: 10.1007/s10527-015-9533-7
17. Shape Anomaly Detection under Strong Measurement Noise: an Analytical Approach to Adaptive Thresholding / A. S. Krasichkov, E. B. Grigoriev, M. I. Bogachev, E. M. Nifontov // Physical Review E. 2015. Vol. 92, iss. 4. 042927. doi: 10.1103/PhysRevE.92.042927

Информация об авторах

Красичков Александр Сергеевич – доктор технических наук (2017), доцент кафедры радиотехнических систем Санкт-Петербургского государственного электротехнического университета "ЛЭТИ" им. В. И. Ульянова (Ленина). Автор более 100 научных работ. Сфера научных интересов – статистическая радиотехника; методы обработки сигналов.

Адрес: Санкт-Петербургский государственный электротехнический университет "ЛЭТИ" им. В. И. Ульянова (Ленина), ул. Профессора Попова, д. 5, Санкт-Петербург, 197376, Россия
E-mail: krass33@mail.ru

<https://orcid.org/0000-0002-8120-3293>

Мбазумутима Элиаким – магистр по направлению "Биотехнические системы и технологии" (2019), аспирант кафедры биотехнических систем Санкт-Петербургского государственного электротехнического университета "ЛЭТИ" им. В. И. Ульянова (Ленина). Автор одной научной публикации. Сфера научных интересов – цифровая обработка биомедицинских сигналов, машинное обучение, распознавание образов.

Адрес: Санкт-Петербургский государственный электротехнический университет "ЛЭТИ" им. В. И. Ульянова (Ленина), ул. Профессора Попова, д. 5, Санкт-Петербург, 197376, Россия
E-mail: eliachim2013@yandex.ru

Шикама Фабиен – магистр по направлению "Биотехнические системы и технологии" (2016), аспирант кафедры биотехнических систем Санкт-Петербургского государственного электротехнического университета "ЛЭТИ" им. В. И. Ульянова (Ленина). Сфера научных интересов – цифровая обработка биомедицинских сигналов, протезирование и реабилитация.

Адрес: Санкт-Петербургский государственный электротехнический университет "ЛЭТИ" им. В. И. Ульянова (Ленина), ул. Профессора Попова, д. 5, Санкт-Петербург, 197376, Россия
E-mail: fshikama@mail.ru

Нифонтов Евгений Михайлович – доктор медицинских наук (2003), профессор (2009) Санкт-Петербургского государственного медицинского университета им. акад. И. П. Павлова. Автор более 150 научных работ. Сфера научных интересов – фундаментальная медицина; кардиология.

Адрес: Первый Санкт-Петербургский государственный медицинский университет им. акад. И. П. Павлова, ул. Льва Толстого, д. 6-8, Санкт-Петербург, 197022, Россия
E-mail: nifontov@spmu.rssi.ru
