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Signal Indicators of Regulatory Changes in the Respiratory System under Physiological Deviation Conditions

Aleksanyants Gaik*, Pogodina Svetlana*, Yuferev Vladimir*, Igor Epishkin*

*Kuban State University of Physical Education, Sport and Tourism

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ABSTRACT: the problem of assessing regulatory changes in the respiratory system during physiological changes in the vegetative nervous and hormonal profile of professional athletes in different periods of the menstrual cycle is described in the article. Observations were conducted for athletes of age ranges (16-26 and 37-45 years), specializing in long distances of sports swimming, athletics and cycling. A series of studies with the use of immunoenzyme, rheographic, spiropnevmotachometric and gasometric types of analysis were conducted. In the in vitro test in the range of 37-45 years anovulatory nature is defined and in the range of 16-26 years ovulatory character of the menstrual cycle is defined. The author's technique of definition of signal indicators and diagnostics of periodic changes in the respiratory rhythm using the phonogram of respiration and Fourier analysis are detailed. The material on the influence of the regulatory factors of the anovulatory and ovarian-menstrual cycle on the respiratory rhythm of athletes is presented. In athletes with ovarian-menstrual cycle, respiration at a relatively high frequency ($0.36 \pm 0.175\ s^{-1}$) was recorded from 13 to 16 days from the onset of menstruation, which indicates the increased rate of respiration. A relatively low respiratory rate ($0.19 \pm 0.138\ s^{-1}$), that is, a rare rhythm of respiration, was noted between 8 and 9 days. For athletes with anovulatory menstruation cycle is characterized by an increase in the frequency of respiration from the menstrual period to the period from 20 to 22 days ($0.33 \pm 0.021\ s^{-1}$) and decrease in the respiratory rate during the period from 26 to 27 days ($0.23 \pm 0.021\ s^{-1}$). Significant changes in the periods of the respiratory cycle on the respiratory periodogram of athletes were correlated with changes in the activity of segmental parts of the autonomic nervous system. Statistically significant correlations between the parameters of the ventilator and nervous regulatory functions were revealed. The obtained data accent attention on the effective use of periodogram analysis of respiratory rhythm for predicting periodic changes in respiratory function of athletes, depending on the conditions of preservation of the ovarian-menstrual function. © *2018 Bull. Georg. Natl. Acad. Sci.*

Key words: menstrual cycle, autonomic nervous system, heart rate variability, spiropneumotachometric method, cardiointervalography

Regulation of various functions in the human body is one of the most important scientific aspects of general and applied physiology, since it concerns the problem of controlling physiological mechanisms and the possibility of their correction [1]. It is known that the study of central mechanisms of breathing regulation is methodically very difficult and requires special expensive laboratory equipment [2]. Therefore, most often the assessment of regulatory processes in the respiratory system is carried out on the basis of an analysis of ventilatory parameters, characterizing the changes in the flow-volume and volume-time relationship with pathological deviations [3]. Despite all the positive aspects of this technique, it has a number of shortcomings regarding the complexity of identifying current functional changes in the respiratory system, caused by physiological deviant conditions in the body - for example, such as periodic neurohormonal changes in the menstrual cycle of a woman [4]. The data of the literature testify to the necessity of monitoring respiratory functions and their respiratory support in different periods of the menstrual cycle (MC) in highly skilled athletes, since stable effective regulation of respiration provides a high level of realization of the bioenergetic capabilities of the organism with intense muscular activity [5].

The following theoretical premises exist to identify current physiological abnormalities in the regulation of the athlete's breathing system. Breathing rate, and the respiratory rhythm that it determines, are the result of multi-loop control of regulatory systems [6]. The leading regulatory loop in the respiratory system is autonomic nervous regulation [7]. In the menstrual cycle of a woman there are periods with prevalence of activity of segmental parts of the autonomic nervous system (ANS) – sympathetic and parasympathetic [8]. The main structural component of the respiratory rhythm is the duration of the respiratory cycle, which forms the patterns of respiration and correlates with the indices of the vegetative balance. The respiratory rhythm is a periodic process, and therefore can be investigated using the methods of mathematical analysis to assess current regulatory changes in different periods of MC [9]. The aim of the work was to study the possibility of estimating periodic regulatory changes in the athlete's breathing system by means of mathematical analysis of the signals of the phonogram of the respiratory rhythm and comparison of the signal indices with the level of respiratory functions.

Material and methods. Research was conducted in the age groups of professional athletes (n = 48), training in sports with the primary development of aerobic endurance (long distances of sports swimming, athletics and cycling) and having a different character of neurohumoral regulation of MC [10]: ovarian-menstrual cycle (OMC), (athletes 16-26 years old); anovulatory menstrual cycle (AMC) (athletes 37-45 years old). Duration of MC is 28-32 days. The study of the studied indicators was carried out in different periods of MC - for the menstrual period were 1-2 days from the beginning of the MC, for the post-menstrual were 8-9 days, for the ovulatory were 13-16 days, for the postovulatory were 20-22 days, for the premenstrual were 26-27 days.

The study protocol included 3 empirical series. A series of studies of the structure of the respiratory rhythm of athletes was carried out according to the methodology [11], which provided for recording a breathing phonogram with a microphone on a digital medium (Fig. 1).

The source of sound was formed when inhaled air enters the human nasopharynx and expel the exhaled air from it. The microphone was fixed in front of the entrance to the nasal cavity. A computer program was used to detect periodic signals in time series for the mathematical processing of the phonogram [12]. Recorded breathing data which were investigated for the presence of periodicity was sent at the entrance of the program. At the

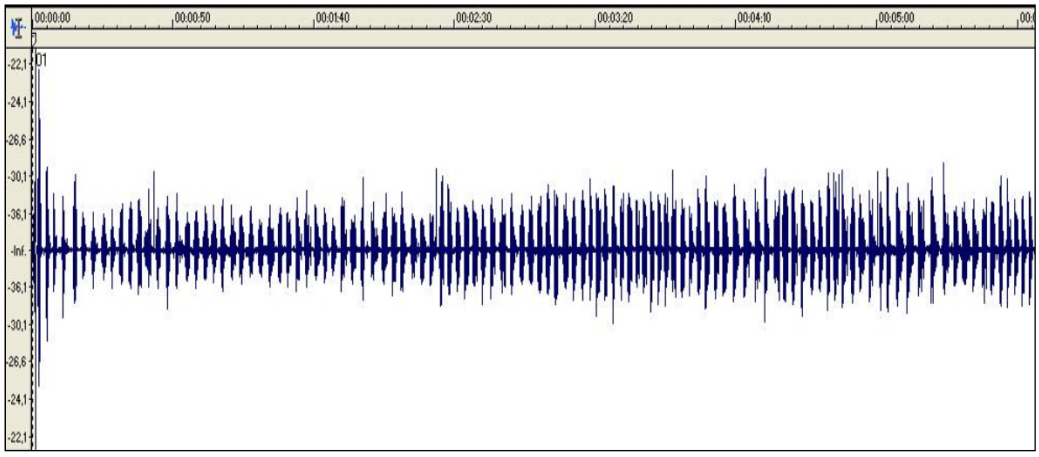

Fig. 1. Fragment of a breathing phonogram at rest.

output, the program determined the existence of different periods in the time series of the investigated periodic process. Mathematical processing of the breathing phonogram was carried out using parametric periodogram analysis of Fourier [13].

A series of studies of autonomic nervous regulation used technology of HRV (heart rate variability) using an eight-channel tetrapolar rheograph REOCOM Standard (production of KhAI-MEDIKA, Ukraine). HRV was studied by recording an electrocardiogram, and in particular of its 5-minute fragments - cardiointervalography (CIG) [14]. The spectral analysis was used to analyze the wave structure of heart rhythm. To determine the power and ratio of three types of waves of different frequency characteristics: HF (ms^{-2}) – with high-frequency oscillations in the range from 0.15 to 0.4 Hz, LF (ms^{-2}) – with low-frequency oscillations in the range from 0.04 to 0.15 Hz and VLF (ms^{-2}) – with oscillations of a very low frequency - within the limits of 0 to 0.04 Hz.

The function of the external respiration system was studied by spiropneumotachometric method using a spirometer of the pneumotachometric type SPIROBANK G (production of Italy), with subsequent computer processing of the recorded indicators. As the studied ventilation indicators used: volume of pulmonary ventilation (V_E, l), relative volume of pulmonary ventilation (V_E, $ml \bullet kg^{-1}$), respiratory volume (V_T, ml), relative respiratory volume (V_T, $ml \bullet kg^{-1}$), respiratory rate (f_T, min^{-1}). All volume indicators are given to conditions of BTPS. Determination of the gas composition of exhaled air were carried out using an optical-acoustic gas analyzer of carbon dioxide Kedr-1A (Russia) and thermochemical oxygen detector "Shield-3" (Ukraine). The following indicators were studied: oxygen pressure in the exhaled air (PEO_2, mm Hg), carbon dioxide pressure in the exhaled air ($PECO_2$, mm Hg), the rate of oxygen consumption (VO_2, ml/min), the rate of carbon dioxide emission (VCO_2, ml/min), gas exchange ratio (VCO_2/VO_2, f. unit), ventilator equivalent of oxygen (VEO_2, f. unit), ventilator equivalent of carbon dioxide ($VECO_2$, f. unit), Oxygen cost of the respiratory cycle (VO_2/f, ml/min/cycle). All gas exchange rates are given to STPD conditions. For the study of vegetative and ventilatory reactions were used conditions of the standard bicycle ergometric test of a step-increasing load with the performance of at least 5 minutes of physical work in the following modes (W): aerobic (regenerative) W1–50 W, heart rate – 130-140 beats/min, aerobic-anaerobic (developing) W2 - 100-120 W, heart rate 150-160 beats / min, anaerobic-aerobic (W3 - 150-220 W, heart rate – 170-185 beats / min [2].

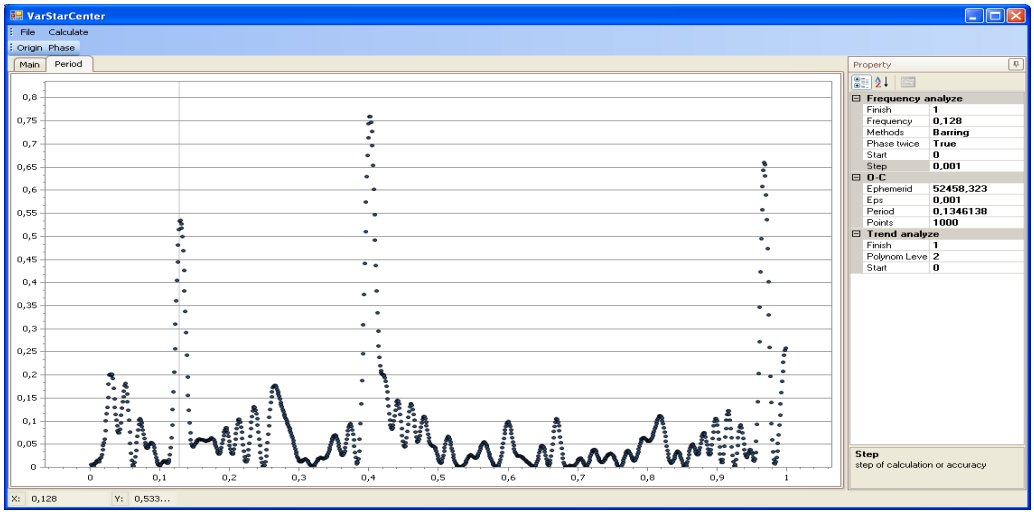

Fig. 2. Periodogram of the respiratory rhythm obtained as a result of the fourier transform.

The resulting digital material was processed on a personal computer using programs STATISTICA 10.0 and «OriginPro 8.5.1». Checking the consistency of the distribution of statistical data with the law of normal distribution using the Shapiro-Wilk test. Statistical processing of the material was carried out by calculating the mean value of the investigated quantities and the error of the arithmetic mean. Statistically significant differences between the samples were determined using Student's t-test. Statistically significant differences were calculated at $p < 0.05$.

Table 1. Change in respiratory rate (ύ) in different periods of OMC and AMC

Days MC	OMC ύ (s^{-1})	AMC ύ (s^{-1})
1-3 da	0.23±0.051	0.26±0.007
8-9 day	0.19±0.138*	0.28±0.012*
13-16 day	0.36±0.075***	0.31±0.053*
20-22 day	0.26±0.057**	0.33±0.021*
26-27 day	0.24±0.094	0.23±0.021**

Note – significant differences are indicated in relation to background indicators, *p<0.05; **p<0.01; ***p<0.001.

Results. In a series of studies of the amplitude-frequency characteristics of the output oscillations of the wave structure of the periodogram of the respiratory rhythm of athletes using Fourier analysis method was determined the presence of the main period of the respiratory cycle on the periodogram, which was manifested in the presence of a brightly expressed peak in a certain frequency band. In the case shown in Fig. 2, peak in the middle of the periodogram indicates the presence in the respiratory rhythm of the period at the frequency (ύ) equal to 0.4 c^{-1}. If to consider that ύ = 1/ t period, where ύ – the frequency, and t – the period time, then the period time will be 2.5 s.

In a series of researches HRV studied the processes of nervous vegetative regulation and further changes in the rhythm of respiration were compared with the activity of segmental departments of the ANS at different periods of MC. The power values of the LF- and HF- waves, characterizing the degree of sympathetic and parasympathetic influences [15] indicated, that in the age groups of athletes at rest there was a conjugate increase in the tone of the sympathetic and parasympathetic departments of the ANS during the first half of the MC and the associated decrease in the second half of the cycle. Lack of conformity between the dynamics of changes in respiratory rate and shifts in vegetative nervous regulatory activity indicates different degrees of stationarity of the dynamic series and reflects differences in the regulation of blood circulation and respiration in the initial state.

At the same time, the fact of influence of the periods of MC on the vegetative tone can cause a change in the nature of vegetative reactions. In this regard, the dosed high-intensity dynamic load can be a criterion determining the true level of nervous regulation. The determination of the vegetative tone during the exercise showed, that the kinetics of vegetative reactions is in a cause-effect relationship with the dynamics of respiratory rate.

Comparison of HRV data and periodogram of respiration indicates the coincidence of the periods of the respiratory cycle in a relatively high range of the frequency and reaction, connected with an increase in sympathetic tone during exercise, which among athletes with OMC falls on the period from 13-16 day, and among athletes with AMC falls on the period from 20-22 days. In turn, coincidence of the periods of the respiratory cycle in a relatively high range of the frequency and reaction, connected with an increase in parasympathetic tone during exercise, registered among female athletes with OMC in the period from 8-9 days (Fig. 3).

The results of a series of studies of the functions of external respiration showed, that changes in the structure of the ventilatory reaction are significantly expressed in the periods of OMC and AMC, for which the changes in the range of respiratory rate were characteristic. Under conditions of high-intensity load in athletes with OMC a phase ovulatory shift is set in the direction of strengthening pulmonary ventilation and gas exchange processes, increase of VO_2 in the respiratory cycle, the formation of conditions for the tension of the oxygen regime and, in particular, to reduce its economy. Thus, the increase in the value of the indicator V_E (699.72 ± 12.04 %, $p<0.05$) during the period of ovulation was greatest. A similar trend is revealed in the ratio of indicators V_T and f_T, which was expressed in the greatest increase in the period of ovulation.

In the period from 8-9 days, a significantly low intensity of elimination VCO_2 (2398.39 ± 15.12 ml•min-1, $p<0.05$) is established, which contributes to the retention of its optimal values in the body. Under these gas conditions, fan equivalents are maintained at the optimal stable level, whereas the energy value of respiration (VO_2/f) is reduced to 80.13±1.14 ml/min/cycle, $p<0.05$. Among athletes were noted gradual strengthening of ventilation and gas exchange in the period from 20-22 days. Thus, in this period of AMC under conditions of high-intensity work, the greatest increase in the VE indicator was revealed in the period from 20-22 days (880.14 ± 15.21 %, $p<0.01$), and the smallest - in the period from 26-27 days (439.07±13.05 %, $p<0.05$). Also the greatest increase in the intensity of VCO_2 (809.45 ± 16.03 %, $p<0.05$) was fount during the period from 20-22 days. In turn, the smallest increase in VCO_2 was observed in the period from 26-27 days (465.19 ± 11.52 %, $p<0.05$).

The high reactive response of V_E and caused by this significant increase in fan equivalents in the period from 20-22 days determined a drop in the effectiveness of respiratory patterns. Obviously, the main reason for the decrease in the effectiveness of breathing in the period from 20-22 days was a high respiratory rate (the period of the respiratory cycle was on the periodogram in a relatively high frequency range 0.33 ± 0.021 s^{-1}), which led to an increase in fan equivalents.

For a detailed analysis of the reasons, causing changes in fan and gas parameters in different periods of OMC and AMC, it is necessary to compare them with the indices of vegetative regulation. A correlation analysis between the parameters of the respiratory system and the spectral indices of the HRV block was made for this. High positive correlation relationships between V_E, V_E, VO_2 and LF-component (accordingly r=0.81; 0.69; 0.92) were established during the ovulation period, which means the effect of sympathetic activity on enhancing the fan parameters and explains the high reactivity of the respiratory system in this period of MC. In turn, high negative correlation relationships

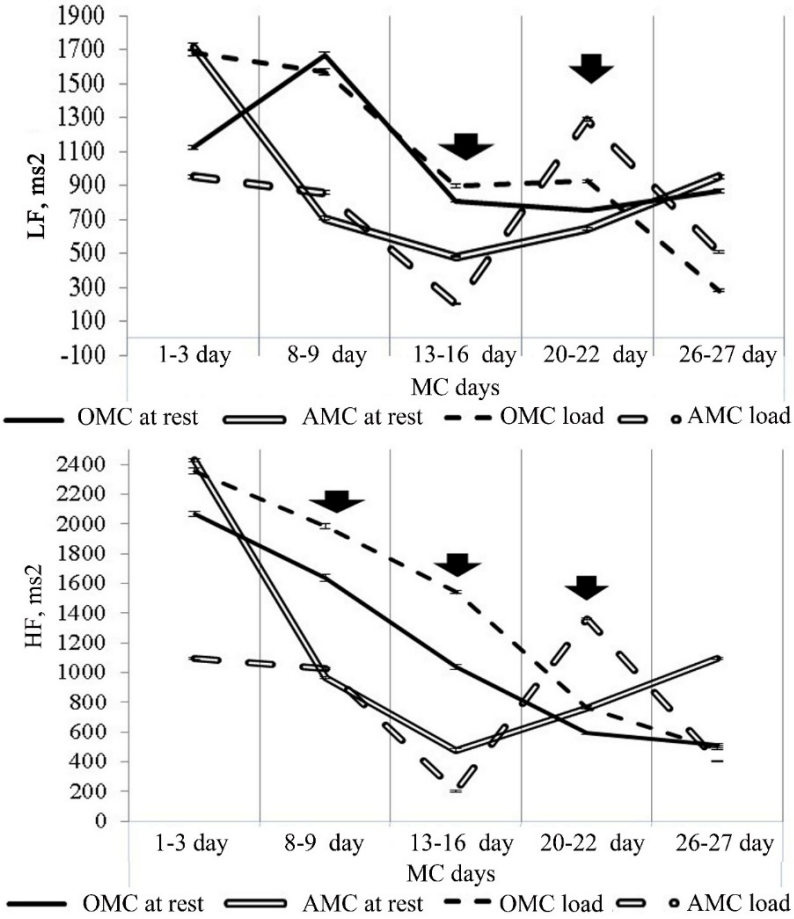

Fig. 3. Changes in the spectral characteristics of the variability of the heart rate in highly skilled athletes in different periods of OMC and AMC.

between V_E, V_T, VO_2, VCO_2 and HF-component in the period from 8-9 days (r=-0.91; -0.57; -0.75, -0.66) were revealed in the first half of the OMC. That is, the relative decrease in the elimination of VCO2 in this period of OMC can be related to the relatively high tone of the parasympathetic nervous system.

In the analysis of the interrelations of the fan parameters V_E, V_T and the LF-parameter in athletes with AMC revealed a gradual increase in the r values between these indicators in the menstrual, postmenstrual, ovulatory and postovulatory periods (r interrelated LF -V_E: 0.35, 0.59, 0.97, 0.99; r interrelated LF -V_T: 0.25, 0.35, 0.99, 1), and the change in the sign of correlation coefficients to negative in the premenstrual period (r = - 0.87). A similar trend was noted in correlation correlations VO_2 – LF (in menstrual, postmenstrual, ovulatory and postovulatory periods r = 0.5, r = 0.6, r = 0.87, r = 0.92). In this way, the available correlation relationships between ventilators and gas exchange parameters and indices of vegetative regulation testify to the conjugate change in the vegetative balance and respiratory functions in athletes during the OMC and AMC.

Conclusions

1. Significant changes in the respiratory rate range are revealed in the structure of the respiratory rhythm of athletes in different periods of the OMC and AMC.
2. Significant changes in the periods of the respiratory cycle on the periodogram of the respiratory rhythm of athletes are correlated

with periodic changes in the activity of segmental divisions of the ANS during the OMC and AMC.

3. Statistically significant correlations between the parameters of respiratory functions and indices of vegetative regulation indicate a unidirectional influence of the autonomic nervous system on the respiratory system.
4. Using the periodogram analysis of the structure of the respiratory rhythm and the signal of changing the frequency range of the respiratory cycle period, it is possible to determine and predict the vector of nerve regulatory influences, which in a certain time period of OMC or AMC are realized in different functional states of the respiratory system.

ადამიანისა და ცხოველის ფიზიოლოგია

მარეგულირებელი ცვლილებების სასიგნალო მაჩვენებლები სასუნთქ სისტემაში ფიზიოლოგიური გადახრის პირობებში

გ. ალექსანიანცი*, ს. პოგოდინა*, ვ. იუფერევი*, ი. ეპიშკინი*

*ყუბანის ფიზიკური აღზრდის, სპორტისა და ტურიზმის სახელმწიფო უნივერსიტეტი, ყუბანი, რუსეთი

(წარმოდგენილია აკადემიის წევრის ნ. მითაგვარიას მიერ)

ნაშრომში აღწერილია სასუნთქი ორგანოების სიტემაში რეგულატორული ცვლილებების შეფასების საკითხი მენსტრუალური ციკლის სხვადასხვა პერიოდში პროფესიონალი ძალოსნების ვეგეტატიურ ნერვულ და ჰორმონულ პროფილში ფიზიოლოგიური ცვლილებების დროს. დაკვირვების ქვეშ იყვნენ სხვადასხვა ასაკის (16-26 და 37-45 წლის) სპორტსმენები, დახელოვნებული დიდ მანძილზე სპორტული ცურვის, მძლეოსნობისა და ველოსპორტის სახეობაში. ჩატარებულ იქნა მთელი რიგი კვლევები იმუნოფერმენტის, რეოგრაფიული, სპირო-პნევმოტაქომეტრული და გაზომეტრული ანალიზების გამოყენებით. ინ ვიტრო ტესტის შემთხვევაში 37-45 წლამდე ასაკის სპორტსმენებში გამოვლინდა მენსტრუალური ციკლის ანოვულატორული ნიშნები, ხოლო 16-26 წლოვანების სპორტსმენებში - ციკლის ოვულაციური ნიშნები. სტატიაში ავტორის მიერ დეტალურად არის განხილული სუნთქვის ფონოგრამისა და ფურიეს ანალიზის გამოყენებით სუნთქვის რიტმში სასიგნალო ინდიკატორებისა და პერიოდული ცვლილებების განსაზღვრისა და დიაგნოსტირების მეთოდი. ნაშრომში წარმოდგენილია მასალა, თუ რა გავლენას ახდენს ანოვულატორული და ოვარიალურ-მენსტრუალური ციკლის მარეგულირებელი ფაქტორები სპორტსმენების სუნთქვის რიტმზე. ოვარიალურ-მენსტრუალური ციკლის მქონე ძალოსნებში შედარებით მაღალი სიხშირის სუნთქვა (0,36 0,175$წ^{-1}$), ანუ სუნთქვის იშვიათი რიტმი, ფიქსირდება მე-8-9

დღეს. ანოვულატორული მენსტრუალური ციკლის მქონე ძალოსნებისთვის დამახასიათებელია სუნთქვის გახშირება მენსტრუალური პერიოდიდან მეოცე-ოცდამეორე დღეების შუალედში (0,33 0,021წ$^{-1}$) და სუნთქვის სიხშირის შემცირება 26-27-ე დღეს (0,23 0,021წ$^{-1}$). სუნთქვის ციკლის პერიოდებში მნიშვნელოვანი ცვლილებები ძალოსანთა სუნთქვის პერიოდოგრამაზე კორელირებულია ვეგეტატიური ნერვული სისტემის სეგმენტური ნაწილების მოქმედებაში მომხდარ ცვლილებებთან. გამოვლენილ იქნა სტატისტიკურად მნიშვნელოვანი კორელაცია ვენტილატორის პარამეტრებსა და ნერვული სისტემის მარეგულირებელ ფუნქციებს შორის. მოპოვებული მონაცემები ყურადღებას ამახვილებს სუნთქვის რიტმის პერიოდოგრამული ანალიზის ეფექტურ გამოყენებაზე ძალოსანთა სუნთქვის ფუნქციაში პერიოდული ცვლილებების წინასწარ განსასაზღვრად, რაც ოვარიალურ-მენსტრუალური ფუნქციის შენარჩუნების პირობებზეა დამოკიდებული.

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