

Breathing and the Heart: A Method for Assessing the Synchronization of Breathing and Heart Activity

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Abstract—This paper presents a method and results of a joint study of human respiration and cardiac activity, based on the authors' long-term research. The results confirm that synchronization between the cardiac and respiratory systems occurs at high frequencies (3–5 Hz) corresponding to eddy airflow. In patients with pathology, phase trajectories reveal additional structures, indicating cardiorespiratory interaction disorders. The obtained data demonstrate the potential of using respiratory parameters for non-invasive assessment of the cardiovascular system state.

I. INTRODUCTION

For a long time, the authors have been studying oscillatory processes and their interrelation using measurements with various sensors. The data processing was fundamentally based on methods applied in the study of dynamic systems. Cardiorespiratory interactions are known to play a fundamental role in maintaining homeostasis, with heart rate variability serving as an important index of a healthy cardiovascular system.

In studies [1, 2], a measurement system for analyzing the dynamics of vortex airflow in the human nasal passages was presented. The sensor enabled simultaneous recording of three physical quantities: flow velocity (a hot-wire anemometer based on a miniature thermistor), temperature (thermistors), and pressure. The obtained results revealed the existence of a specific airflow structure and its connection with respiratory diseases.

Modeling of the internal structure of the nasal passages and human breathing was also conducted [3], which proved identical to the measurements taken with the sensor inside the human nasal cavity [2]. Subsequently, the modeling of the internal structure was replicated on nasal cavity models created using 3D printing based on computed tomography data from specific patients [4–6]. These measurements also demonstrated the concordance of sensor readings with previous studies.

Furthermore, measurements of CO₂ concentration fluctuations at the nostril inlet were performed [7–10]. These results were analogous to those obtained with the aforementioned sensor: the concentration fluctuations exhibited the same characteristics as those measured by the sensor [2].

Simultaneous measurements of eddy air movement in the upper respiratory tract and heart rate were also carried out. It was found that in a healthy person, high-frequency eddy

pulsations in the nasal passages (with a frequency of 3–5 Hz) are synchronized with the R-waves on the electrocardiogram and occur without a phase shift. In patients, a phase shift appears at these frequencies [11], [12].

Modeling of the relationship between the respiratory and cardiac systems was performed using nonlinear dynamic models [13], [14]. This modeling demonstrated that, given this model, an electrocardiogram could be derived from recorded respiratory data. This indicates that there is a close relationship in the control of the organism by the respiratory and cardiac systems.

Recent studies by other research groups have significantly advanced the understanding of cardiorespiratory synchronization [15–18]. Border et al. [16] demonstrated that synchronization between cardiac and respiratory rhythms reduces cardiac power losses by approximately 10% in humans through viscoelastic dissipation mechanisms in the pulmonary vasculature.

Gómez et al. [17] successfully modeled the dynamic relationship between respiration and heart rate, showing that heart rate can be predicted from respiratory signals with a time lag of approximately 850 ms in healthy subjects.

Furthermore, Sobiech and Buchner [18] investigated triple synchronization between heart rate, respiration, and locomotor rhythm during rhythmic physical exercise on a stationary bike. In a study of 21 healthy volunteers, they found that cardiocomotor synchronization (1:1 phase coupling) occurred in 76% of subjects, with epochs lasting at least 20 seconds. Total synchronization duration was significantly higher in men and in less experienced cyclists. The authors suggest that synchronization during exercise can serve as an objective estimator of physical stress, applicable in diagnostic, therapeutic, and lifestyle scenarios.

The clinical significance of these interactions is underscored by findings that reduced heart rate variability and impaired cardiorespiratory synchronization are associated with various diseases, including hypertension, heart failure, and depression [15].

To confirm this hypothesis, experiments were conducted studying pressure pulsations in the nasal passages of patients with cardiac diseases. These studies were carried out at and in collaboration with the staff of the Dzhanelidze Research Institute of Emergency Medicine.

Previous studies conducted at ITMO University [1–14] laid the foundation for understanding the mechanisms of cardiorespiratory interaction. It was established that synchronization occurs at high frequencies (3–5 Hz), corresponding to eddy motion of air in the upper airways induced by their irregular internal structure, and provides a high heat transfer coefficient ($\alpha \approx 100$). The present work develops this approach by proposing a compact measurement system for the simultaneous recording of respiration and heart rate, tested on patients at the Dzhanelidze Research Institute of Emergency Medicine.

II. METHOD

A. Mathematical description

Nonlinear dynamics and spectral analysis methods were applied for data processing:

- correlation sum, $C(\varepsilon)$, correlation dimension, D_2 , and the correlation entropy, K_2

$$C(\varepsilon) = \lim_{m \rightarrow \infty} \frac{1}{m^2} \sum_{\substack{i,j=1 \\ i \neq j}}^m H\left(\varepsilon - \|x_i - x_j\|\right) \quad (1)$$

$$H = \begin{cases} 1, & (\varepsilon - \|x_i - x_j\|) \geq 0; \\ 0, & (\varepsilon - \|x_i - x_j\|) < 0 \end{cases} \quad (2)$$

$$D_2 = \lim_{\varepsilon \rightarrow \infty} \frac{\log C(\varepsilon)}{\log \varepsilon} \quad (3)$$

$$K_2 = \lim_{\tau \rightarrow 0} \lim_{\varepsilon \rightarrow 0} \lim_{ED \rightarrow \infty} \frac{1}{\tau} \cdot \log \left(\sum_{i_1 \dots i_N} \frac{C_{ED}(\varepsilon)}{C_{ED+1}(\varepsilon)} \right) \quad (4)$$

where, H - Heaviside step function, ε - diameter of volume elements covered an attractor, x_i, x_j - points in some metric space with distances $|x_i - x_j|$ between any pair of points, $C_{ED}(\varepsilon)$ - correlation integral of embedding dimension;

- calculation of power spectral density through the discrete Fourier transform, so, the time signal $x(t)$ for any investigated parameter can be represented as a function $X(\omega)$ depending on frequency $\omega = 2\pi f$ using the expression

$$X(\omega) = \int_{-\infty}^{\infty} x(t) e^{-j\omega t} dt \quad (5)$$

- attractor reconstruction from time series data.

Correlation dimension and entropy were calculated using proprietary software. The results were verified by comparison with data obtained using FRACTAN, an online tool, showing good agreement. Power spectral density was computed via fast

Fourier transform in MATLAB, and attractor reconstruction was performed using a custom MATLAB script.

B. Measurement Setup

The measurement setup consists of two main modules: a rhinological device for recording respiratory parameters and a cardiorythm analyzer for recording heart rate.

The rhinological device is a prototype diagnostic instrument based on pressure sensors. The sensing element is a miniature high-speed pressure sensor mounted on a clip attached to the nasal septum. The pressure measurement range is 0–1 psi, sensitivity is 0.2 mV/Pa. The sensor signal is fed to a 24-bit analog-to-digital converter and then to a personal computer via a USB interface. The sampling rate is 1 kHz. Fig. 1 illustrates the sensory system based on a pressure sensor.



Fig. 1. A prototype of the device using two pressure sensors, with the ends of the outlet tubes attached to a clip

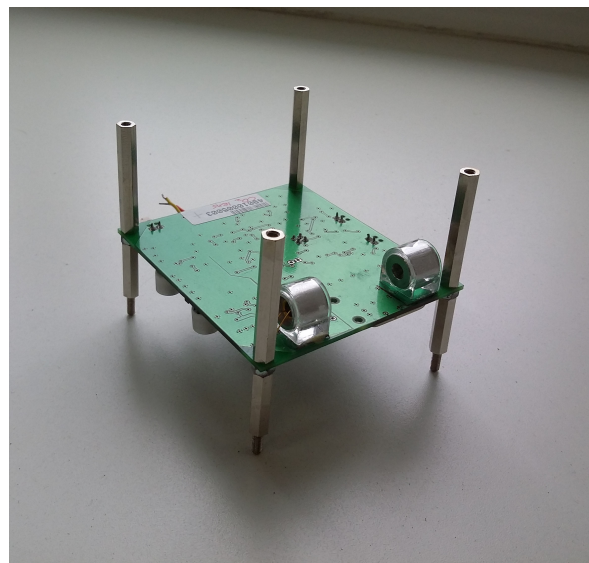


Fig. 2. Sensory prototype of a sensor system for analyzing human respiration by optocouple

The CO₂ measurement sensor is based on a matched LED-emitter-receiver pair with a wavelength of 4.3 μm (fig. 2).

The "Expert-01" cardiorythm analyzer (NPO "Markiz", St. Petersburg) is a portable device for recording electrocardiogram signals in three leads. The instrument measures RR-interval duration with a resolution of 1 ms and transmits data to a computer via a Bluetooth interface. Standard lead II was used in this study.

Synchronization of the two modules is performed using the computer's internal timer. Software developed in the LabVIEW environment enables simultaneous start of signal recording from both devices and saves the data in a single file with a common time stamp.

C. Experimental Procedure

Collaborative work between the authors and the Dzhanlidze Research Institute of Emergency Medicine on the registration of heart rate and respiratory rhythms has been ongoing since 2019. This paper presents six cases that most clearly demonstrate the synchronization of these rhythms.

The study involved six male patients aged 65 to 80 years with diagnosed cardiovascular disorders from the Cardiology and Rheumatology Department of the Dzhanlidze Research Institute of Emergency Medicine. The features of eddy air movement through their upper respiratory tract were studied using pressure sensors, as described above and published in [14].

Measurements were performed at a comfortable temperature of 22–24 °C. Before the study, each patient rested in a sitting position for 5 minutes for adaptation. The experimental protocol included natural breathing for 3 minutes, during which the nasal cavity pressure signal and the electrocardiogram signal were recorded simultaneously.

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D. Signal Processing and Parameter Calculation

Data processing was performed in the MATLAB environment (R2023b). The developed algorithm included phase trajectory reconstruction using Takens' delay embedding method. The phase trajectory takes the form of an attractor, i.e., a region of attraction for its trajectories.

To construct the nonlinear dynamic model, the NARMAX method was applied [13]. From the available dataset, between 100 and 1000 samples, forming the aperture ('window') of the method, were analyzed simultaneously. The window size was established experimentally. The model was fitted to the described process exponentially. Upon completion of each iteration, the NARMAX method produced a simulation result, after which the 'window' was shifted by one sample and the next iteration was performed. The model was also used as a digital filter to eliminate unwanted noise and frequencies irrelevant to the study from the input signal.

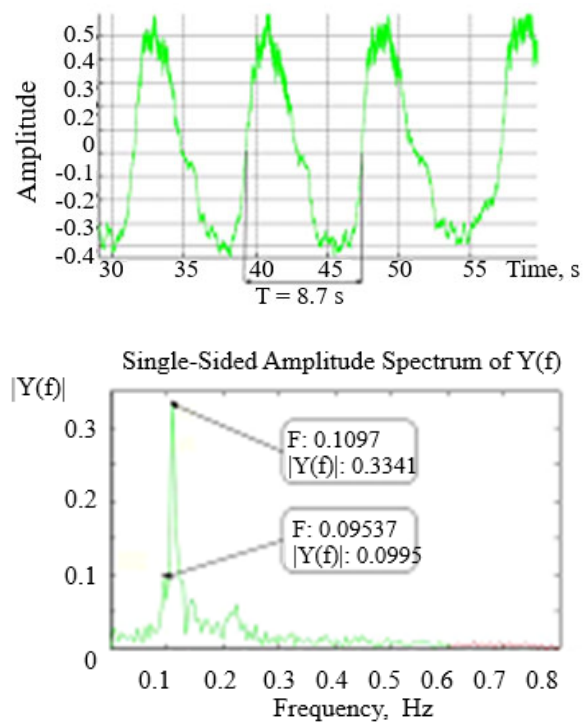


Fig. 3. The results of the measurements of respiration fluctuations and the graphs of the power spectral density for measured pressure in the right nostril

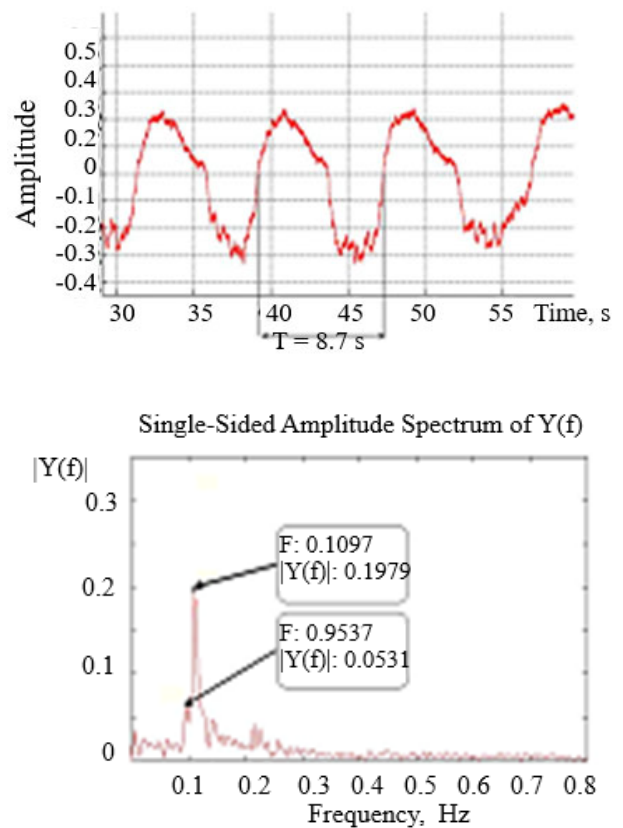


Fig. 4. The results of the measurements of respiration fluctuations and the graphs of the power spectral density for measured pressure in the left nostril

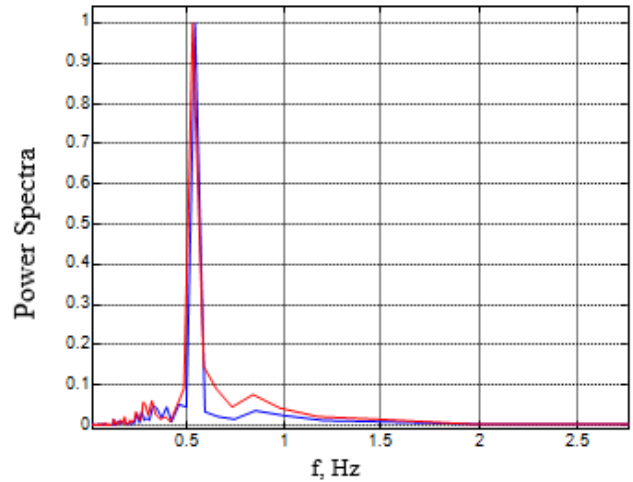
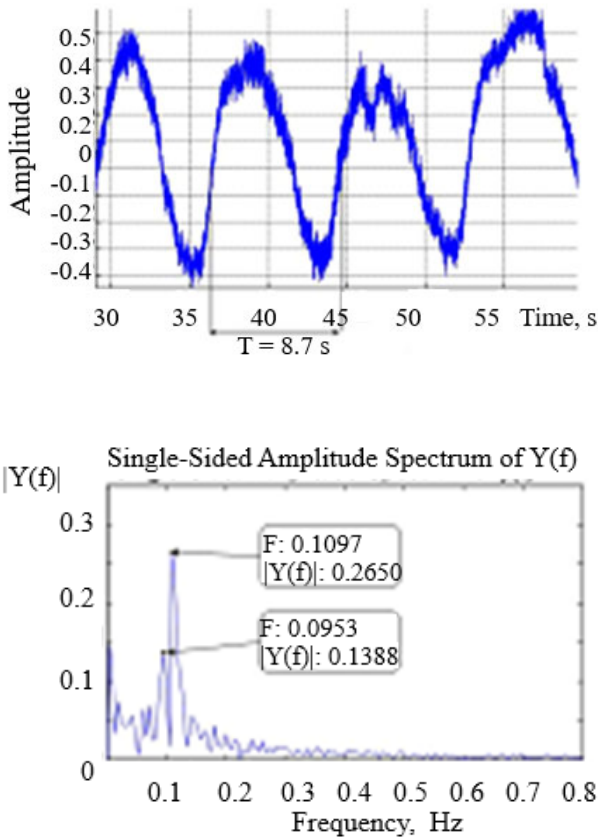


Fig. 7. Power spectral density: blue – for the initial process, red – for the NARMAX mode

Fig. 6 shows the instrument readings (pressure sensor, curve 1), to which the NARMAX model (curve 2) is exponentially fitted.

Fig. 7 shows power spectral density for the initial process and for the NARMAX mode. The model accurately describes the synchronization of CO₂ concentration with air pressure during inhalation and exhalation and can be used as a digital filter.

Then we performed simultaneous measurements of eddy air movement and heart rate.

Key finding: in healthy individuals, high-frequency eddy pulsations (3–5 Hz) are synchronized with the R-waves of the electrocardiogram – without phase shift.

In patients with cardiovascular pathology, a phase shift appears at these frequencies. This was a breakthrough: synchronization occurs not at the breath frequency, but at a much higher frequency – 3–5 Hz – corresponding to eddy motion in the upper airways (Fig. 8, 9).

The slides by Patient 1 (fig. 10), Patient 2 (fig. 11) and Patient 4 (fig. 13), as well as the slide by Patient 3 (fig. 12), show different directions of rotation during vortex motion of air in the nasal passages with a phase shift. These trajectories show a similarity in the form of glitches in part of the trajectory with a fast, swirling vortex motion - eddies. The motion during the transition from inhalation to exhalation is "smeared".

Fig. 14 and 15, in addition to the two eddy regions observed in the previous figures, reveal a third, additional region — an area in the center of the phase trajectory, which characterizes rhythm irregularity.

III. RESULTS

Figs. 3–5 present the results of experimental eddy measurements obtained using pressure sensors and an optical CO₂ sensor, along with their power spectral densities. These graphs show synchronization between pressure sensor readings and carbon dioxide concentration measurements.

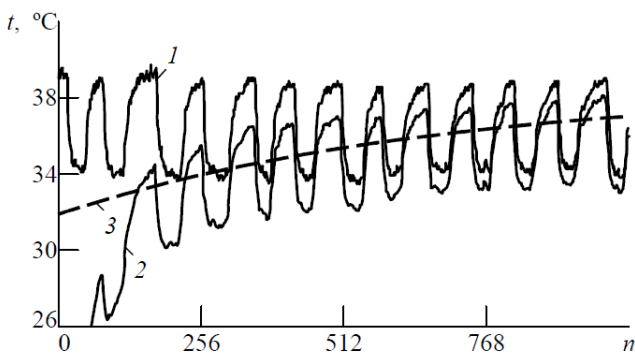


Fig. 6. Construction of a nonlinear dynamic model using the NARMAX method: curve 1 – pressure sensor readings; curve 2 – NARMAX model; curve 3 – exponential

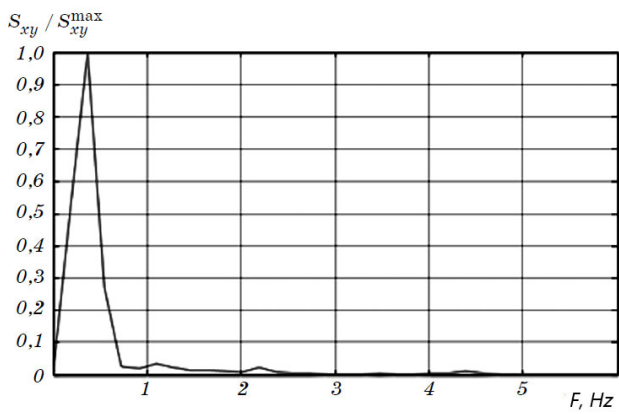


Fig. 8. Cross-spectral density of the respiratory and heart rate processes in healthy patients

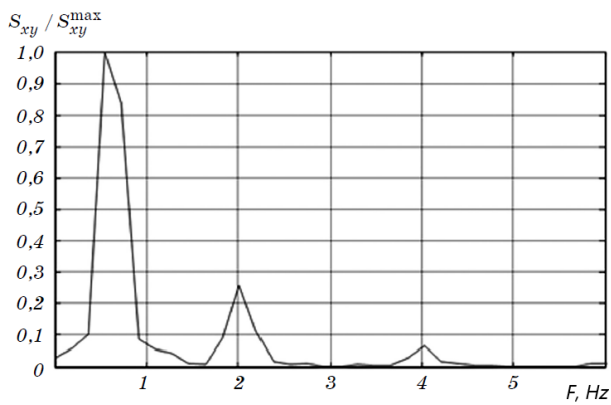


Fig. 9. Cross-spectral density of the respiratory and heart rate processes in patients with cardiac diseases. Two additional peak amplitudes are observed at frequencies of 2 and 4 Hz, which are not seen in healthy patients

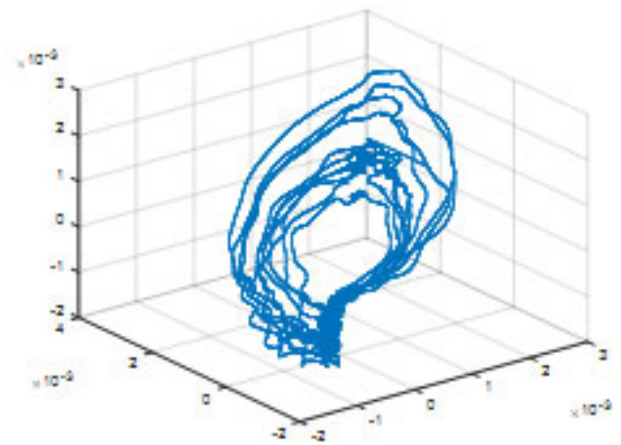


Fig. 11. Phase trajectory of Patient 2 based on diagnostic data

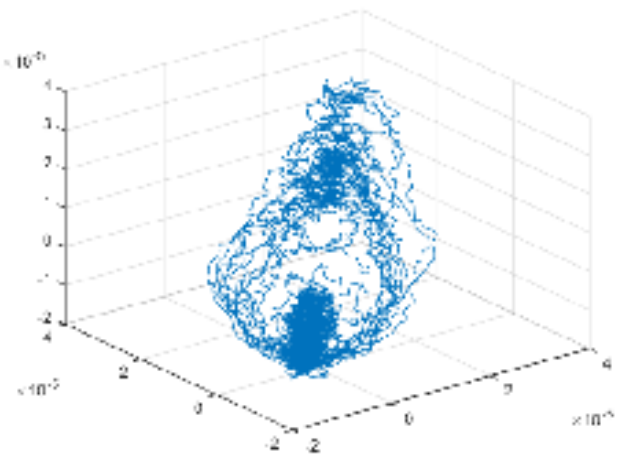


Fig. 12. Phase trajectory of Patient 3 based on diagnostic data

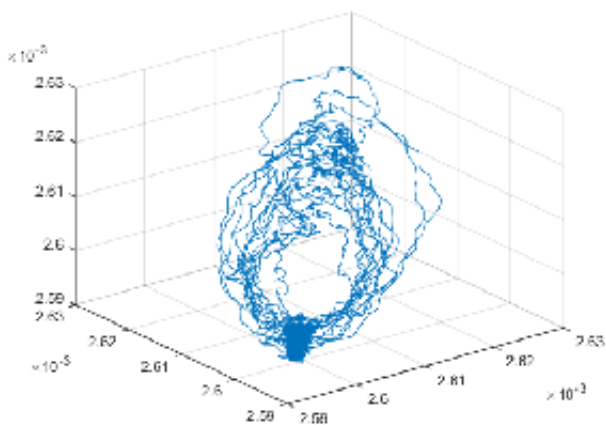


Fig. 10. Phase trajectory of Patient 1 based on diagnostic data

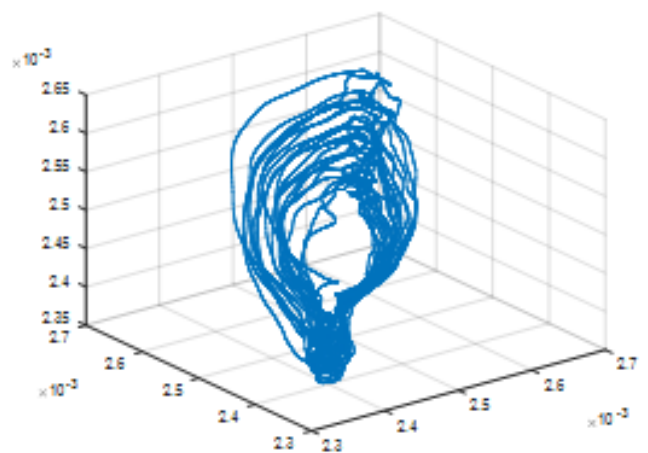


Fig. 13. Phase trajectory of Patient 4 based on diagnostic data

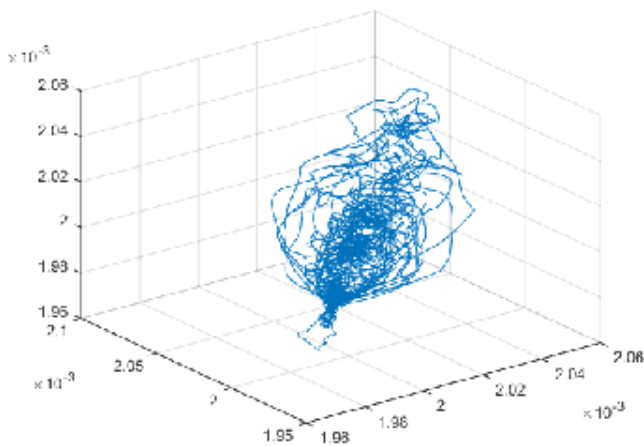


Fig. 14. Phase trajectory of Patient 5 based on diagnostic data

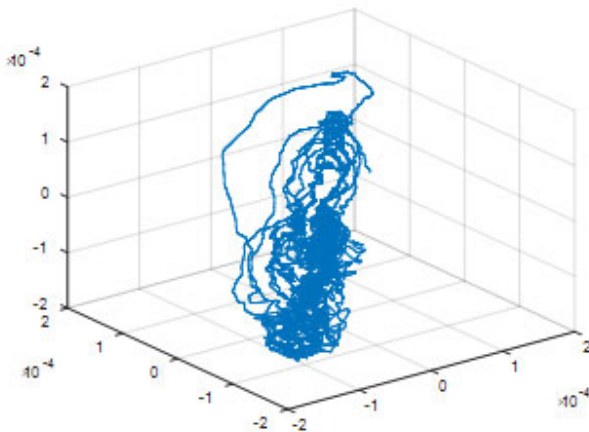


Fig. 15. Phase trajectory of Patient 6 based on diagnostic data

VII. CONCLUSION

Long-term studies conducted at ITMO University [1–14] have established the following regularities:

1) There is a stable synchronization between two sources of oscillatory processes in the human body — the cardiac system and the respiratory system. This is confirmed both by direct measurements and by the results of nonlinear dynamic modeling [9–11].

2) Synchronization occurs not at the frequency of respiratory cycles (inhalation–exhalation), but at a significantly higher frequency — in the range of 3–5 Hz, corresponding to eddy motion of air in the upper airways [2, 9, 10]. It is at these frequencies that phase synchronization with the R-waves of the electrocardiogram is observed in healthy individuals, and its disruption in patients with cardiovascular pathology.

3) Eddy motion of air, induced by the irregular internal structure of the upper airways, leads to a high heat transfer coefficient (on the order of $\alpha \approx 100$), which ensures efficient warming of the inhaled air and indicates a close relationship

between hydrodynamic and thermophysical processes in the respiratory system [3–6].

Additional studies conducted jointly with specialists from the Dzhanelidze Research Institute of Emergency Medicine confirmed that the information obtained from measurements of respiratory parameters is closely related to the state of the human cardiac system. In particular, in patients with cardiovascular disorders, additional regions appear in the center of the phase trajectories of the respiratory process, absent in healthy individuals, which indicates disorganization of the airflow and disruption of cardiorespiratory interaction.

The obtained phase trajectories (Figs. 6–11) demonstrate characteristic features of eddy motion of air in the nasal passages. In healthy individuals (according to previous studies [9, 10]), the trajectories contain two stable eddy regions corresponding to the inhalation and exhalation phases. In patients with cardiovascular pathology (Figs. 10, 11), an additional third region is observed in the center of the trajectory, indicating a violation of cardiorespiratory synchronization at high frequencies (3–5 Hz).

The obtained results open up the prospect of creating non-invasive diagnostic methods based on the analysis of respiratory parameters for assessing the state of the cardiovascular system.

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