Sensor System for Analyzing Human Respiration in Arctic Conditions

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Abstract— **A sensor for monitoring the dynamics of changes in the concentration of carbon dioxide in humans during respiration is presented. The sensor is based on a matched pair of LED-emitter-receiver. It was revealed that the shape of the nasal cavity affects the hydrodynamics and heat transfer in the respiratory system. It has been shown that dynamic parameter analysis is necessary for the diagnosis of respiratory diseases.**

I. Introduction

Respiration is one of the most significant physiological processes that ensure human activity. According to medical statistics, the share of respiratory diseases is 41% of the total number of registered diseases per year [1]. One of the functions of breathing is to warm up the air in the nasal cavity to the temperature of the human body. If the air does not have time to warm up to the required temperature, the appearance of colds is inevitable. It was previously determined that the heat transfer coefficient in front of the nose of a healthy person is α=50 W/m^{2}K [2]. Such a high value of the heat transfer coefficient is obtained due to the complex structure of the nasal passages surface. As a result, the air is heated or cooled to the temperature of the human body as it moves through the respiratory system before it reaches the lungs.

Earlier studies in the field of otorhinolaryngology made it possible to distinguish the evolutionary formation of three types of nasal cavity shape - leptocavital (narrow nose), mesocavital (middle nose) and platycavital (wide nose) [3, 4]. Conventionally, these types of forms of the nasal cavity belong to the Mongoloid (middle nose), Negroid-Australoid (wide nose) and Europeoid (narrow nose) races (classification by N.N. Cheboksarov). Each of these forms is evolutionarily adapted to specific climatic conditions and has slightly different anatomy. For example, the indigenous population of the Arctic (belongs to the Mongoloid race) has adapted for centuries to live in harsh climatic conditions, as reflected in the anatomical features of the nasal cavity structure. The Negroid-Australoid race natives (Indians, Africans, etc.) are more adapted for living in tropical climatic conditions.

The research [5] shows, that the Neanderthal nasal passage morphology may represent an adaptation to cold that improves conditioning of inspired air, albeit a less efficient solution to that found in modern humans. They were one of the branches of archaic people, lived at the Ice Age and had wide prominent noses to warm up inhaled air.

The study of the individual characteristics of the physiology of respiration, as well as heat transfer processes in it, can be useful in the conditions of human exploration of the Arctic, in particular, in the formation of scientific expeditions and the development of Arctic oil fields. The article presents the results of many years of research on heat transfer and hydrodynamic processes in the human respiratory system. These studies have developed in two main directions - (1) diagnostics, development of a diagnostic method and equipment [6-7], and (2) experimental and numerical simulation [8-9]. The study focused on the anatomical features of the shape of the nose cavity.

II. Materials and methods

A. *Features of respiratory physiology*

In [2, 4, 6–9], it was shown that the general pattern of movement of the air stream during inhalation and exhalation through the upper respiratory tract is the presence of vortices. Due to the arising vortex structures during inhalation, the air manages to warm up to body temperature. In [2], the relationship of the observed phenomenon with the growth of the heat transfer coefficient was studied using the methods of numerical simulation (k-ω and DES methods). Thus, the values of the heat transfer coefficient near the wall surface varied from 3 W/m^{2}K when flowing around a laminar jet to 40-50 W/m^{2}K in the recirculation regions after flow separation. Based on the study, it was concluded that vortices contribute to a significant intensification of heat exchange processes at the entrance to the nasal canals, and as a result, sufficient heating of the air entering the respiratory tract.

The shape of the nasal cavity affects the movement of air flow and the formation of vortices [3], [4]. The results of the study were taken as the basis for the selection of prototypes of nasal cavity models in this work [4].

In our research, we've tried to measure different parameters of breathing such as pressure, air flow velocity, temperature and CO_2 concentration. We measured them near the nostrils. All these measurements revealed a characteristic form of oscillation with the presence of a high-frequency component [6-7]. The presence of fluctuations, both during inhalation and exhalation, allowed us to use nonlinear dynamics methods to analyze the result. For the measured parameters, we calculated:

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

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

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

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

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

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.

We used our own software in calculating the correlation dimension and entropy.We used FRACTAN to compare the data we obtained, which was then publicly available on the Internet. The comparison showed the same results. For calculating power spectral density we used fast Fourier transform in MATLAB. Also we wrote small program for attractor reconstruction in MATLAB.

The nonlinear dynamic methods we applied showed the identity of the result, regardless of the choice of the measured parameter [7].

B. *Sensor system*

The miniaturization of the cavity structure, its irregular internal section is the cause of difficulties in the study of the physiology of respiration. It is practically impossible to place sensors directly inside the nasal cavity. That is why, despite the fact that research in this area has been under way for more than 100 years, there is still no single concept of the air movement during inhalation and exhalation.

Of particular interest for arctic conditions is the possibility of monitoring the dynamics of gas exchange during breathing, since there is evidence of a change in the nature of gas exchange in humans in the Arctic [10].

For our research, we have implemented an integrated approach combining diagnostics and process simulation. Sensor system has been developed to measure CO_2 concentration. The sensor is based on a matched pair of LED-emitter-receiver of radiation at a wavelength of 4.3 microns. The general view of the sensor is shown in Fig. 1. Fig. 2 shows a sketch of a sensor system for diagnostics.

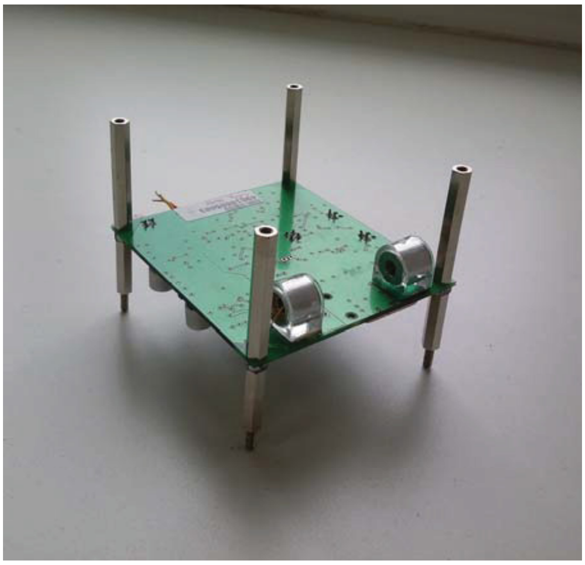


Fig. 1. Sensory prototype

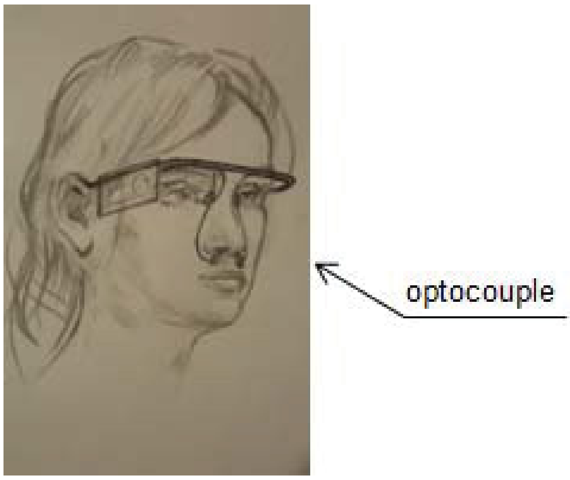


Fig. 2. Sketch of a sensor system for analyzing human respiration

Carbon dioxide plays a leading role in the humoral mechanism of the regulation of respiration. It is known that the concentration of CO_2 changes during respiration: the proportion of CO_2 at inhalation is 0.03% and that at exhalation is 4.00%. This parameter is important in the breath diagnostics and is very informative.

Infrared optocouples (IR LEDs) as sensitive elements in compact and cheap sensors detecting breath abnormalities associated with respiratory and other diseases had been used. One of the studied IR LEDs was used as a part of LED-photodiode optocouple for the measurements of CO_2 during the breathing of a patient. The photodetector used in the optocouple was based on the same semiconductor material system as the LED, namely narrow–gap semiconductor InAs(Sb,P) system.

A characteristic feature of the oscillatory cycle is the fluctuations of CO_2 concentration, both during inhalation and exhalation. Therefore as we wrote earlier the basis of diagnosis is methods of nonlinear dynamics.

C. *Experimental and numerical simulation of breathing parameters*

Since the capabilities of the sensory system are limited by the location of the measuring sensors (in our case they are located at the nostrils), we used modeling methods to obtain a broad picture of the movement of air flow in the nasal cavity. In our case, the numerical simulation method in the ANSYS program and the experimental method of thermal imaging of the thermal field were used.

Fig. 3. An experimental stand for measuring temperature field in a solid-state model of the nose, where 1 is a solid-state model of the nose, 2 is an outlet tube for breathing simulation, 3 is a Testo 890 thermal imager

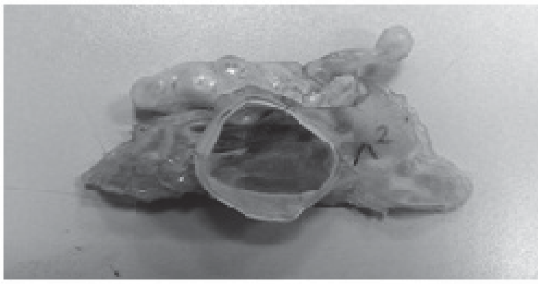
Models for experimental and numerical simulations were performed based on CT data. Three characteristic nose cavity tomograms were selected for 3D-model generation. They are lepto-, meso- and platycavital forms. Models were generated in three phases:

- model reconstruction with a CAT scan step;
- image processing and segmentation into walls (cavity bone structure boundary), input (allocation of nostrils);
- output (allocation of choanae).

The generated models became the basis for further experimental and numeric simulation of hydrodynamic and heat transfer processes.

Three Virtual 3D models had been designed to simulate the air flow inside the nasal cavity. The geometric shape recovery in the model was performed by using the software package Mercury Amira. The allocation of borders "entrance", "exit", "wall" was made with a software package Altair Hypermesh. The reconstruction of the finite element computational grid was made by using a software package Ansys Icem CFD. In this computational model the volumetric irregular grid was given from $1{,}5x10^7$ tetrahedral finite element.

The model basic requirements are to preserve of breathing rhythms in the extreme and to observe internal vortex motion of the air flow in the nasal cavity. For this goals we applied the derivative Detached Eddy Simulation model (DES-model). The feature of the model is to preserve all of the information about the high-frequency pulsations of the studied variables when filtering by the field of space.



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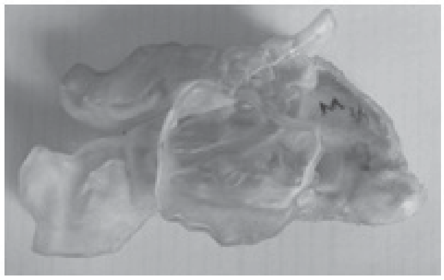

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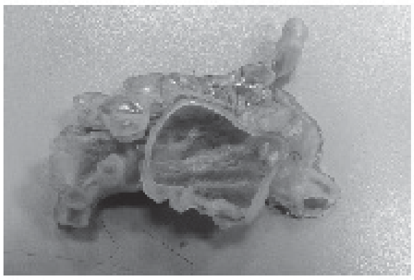


c

Fig. 4. Solid state 3D models of the right half of the nose: a – leptocavital ; b – mesocavital; c – platycavital

Non-stationary air flows are simulated with the following boundary conditions. The pressure and temperature at the entrance to the nose were taken constant: 0 Pa and 293 K (20 ° C). The air velocity on the walls is zero; the wall temperature is constant and equal to 310 K (37 ° C). The pressure at the exit from the nasal cavity during inhalation and exhalation is subject to the law of harmonic oscillation:

$$\begin{cases} P = 50 \cdot \sin\left(\pi\left(1.18\tau + 0.5\right)\right) - 50 \to \tau < 1.7c \\ P = 50 \cdot \cos\left(\pi\left(0.87\tau + 0.5\right)\right) + 50 \to \tau > 1.7c \end{cases}, \quad (6)$$

The inhalation-exhalation cycle time is 4 s. Of these: 1.7 s is the inhalation time, 2.3 s is the exhalation time. Simulation step is 0.1 s. The result of the simulation was a field of velocities, temperatures and pressures in the three shapes of the nose cavity being studied.

The experimental simulation consisted in visualizing the movement of air flows in the nasal cavities by the method of thermometry of the walls of the model [8]. Solid-state models of the right half of the nose, made of transparent plastic on a scale of 1:1, were used as the object of the study. The experimenter breathed through a tube attached to the output of the model, forming inhalation and exhalation of breath air flows. The model-oriented thermal imaging camera Testo 890 changes in the wall temperature fields in the solid state model while simulating respiration. The experimental stand is shown in Fig. 3. We used it for process simulation. In this model, at the breathing modeling, an air flow with a temperature of 35 °C and a peak flow rate of 10 l/min was provided using a PVC tube that was putting at the nasopharynx. The air flow distribution was estimated using the Testo 890 thermal imager at the temperature range of 20-30 °C. The solid-state models of the right half of the nose are shown on Fig. 4.

III. Results and discussion

A. Diagnostic results

Diagnostic measurements using the sensory system were performed for a group of ten patients, male, aged 30 to 40 years, who consulted an otorhinolaryngologist about difficulty in breathing. All patients had rhinedema. The measurements were taken before and after the prescribed medication. The obtained results of measuring the concentration of CO_2 during the breathing were used to determine the correlation dimension and entropy, which are shown in the Table I. There was a tendency towards a decrease in the values of the correlation dimension and entropy for patients after treatment of nasal diseases.

Fig. 5a shows the fluctuations of CO_2 during inhalation and exhalation in the nasal region, captured by the sensor system. Both during inhalation and during exhalation, rapid fluctuations of concentration are observed. Similar fluctuations are also recorded when measuring temperature, pressure or air flow velocity in this area of the nose [7]. This indicates that there is the presence of a vortex of air during inhalation and exhalation. The vortex nature of the movement is caused by the surface structure of the surface of the nasal passages and leads to a high value of the heat transfer coefficient α in the region of the nose vestibule [2].

Fig. 5b shows a graph of the power spectral density for such oscillations. It can be seen that the frequency of the main breathing cycle (cycle inhalation-exhalation, about 8,7 s on fig. 5a) corresponds to a peak of 0.1 Hz. The peaks at higher frequencies (1 Hz and higher) are caused by the vortex movement of the air.

TABLE I. Correlation dimension and correlation entropy for group of patients

Patient	Correlation dimension		Correlation entropy	
	before treatment	after treatment	before treatment	after treatment
Patient1	2.22	2.09	0.36	0.32
Patient2	2.05	2.05	0.34	0.38
Patient3	2.19	2.10	0.38	0.35
Patient4	2.34	2.09	0.42	0.33
Patient5	2.21	2.08	0.36	0.35
Patient6	2.15	2.08	0.39	0.40
Patient7	2.18	2.08	0.39	0.33
Patient8	2.20	2.09	0.25	0.26
Patient9	2.33	2.11	0.40	0.27
Patient10	2.23	2.16	0.26	0.34

B. Results of numerical and experimental simulation

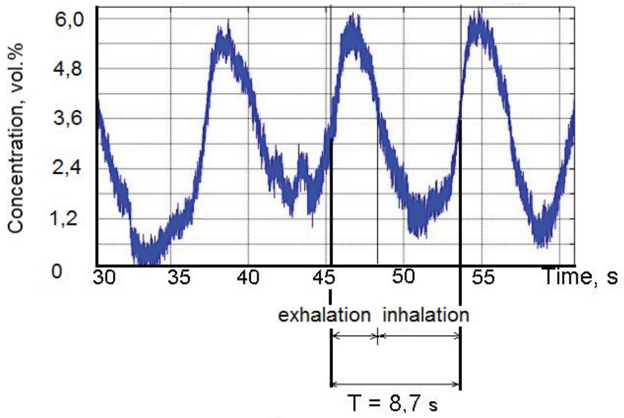
The results of numerical simulation of the velocity field in the upper respiratory tract are shown in Fig. 6 [2]. The presence of vortices in the area of the sphenoid sinus and in the lower lobes of the nasal cavity has been detected. Similar results for models of the mesocavital and platycavital forms of the nasal cavity are shown in Fig. 6 and Fig. 7.

Analysis of the results shows that depending on the shape of the nasal cavity, the movement of air flow in the nasal cavity will be different. So, in the case of the leptocavital nose, it turned out that the bulk of the air during inhalation and exhalation moves along the bottom of the nasal cavity. The most of the air goes through the lower lobes of the model when inhale in case of mesocavital form of nose; and the air is evenly distributed between the middle and lower regions when exhale. For the platycavital form when inhalation and exhalation, the air tends to the upper parts of the nasal cavity. Thus, the direction of air flow for the platycavital form of the nasal cavity is significantly different from the mesocavital and leptocavital forms.

Application of tiny high-speed sensors allows to receive essential information about the studied process and it is better to understand its behavior at fast changes of conditions. For deeper understanding, it is also necessary to apply various models, to specify them on the basis of comparison to results of measurements. Among such models there can be numerical computer models, natural models, and also dynamic models.

Behavior of the studied objects can be investigated in more details by the research of the dynamic processes. The term "dynamic" is often interpreted not in terms of the passing of the test process, as, for example, of the possibilities of the sensors used in the measurements.

This information can be used to refine existing models of the processes and, in turn, allows better understand the evolution of the processes.



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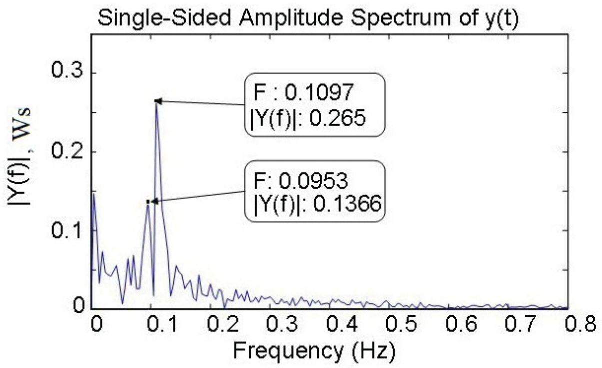

b

Fig. 5. Result of the measurements of CO_2 concentration fluctuations during breathing (a) and the graphs of the power spectral density (b) presented for sensor system

VII. Conclusion

Of particular interest for arctic conditions is the possibility of monitoring the dynamics of gas exchange during breathing, since there is evidence of a change in the nature of gas exchange in humans in the Arctic. For this purpose, we have developed and tested a sensor for monitoring the dynamics of changes in CO2 concentration in humans during respiration. The sensor is based on a matched pair of LED-emitter-receiver of radiation at a wavelength of 4.3 microns. The peculiarity of the method is the positioning of the measuring sensors directly in the nose cavity, in the direction of the inhaled air, which increases the sensitivity of the method. It can be seen that a characteristic feature of the oscillatory cycle is the fluctuations of CO2 concentration, both during inhalation and exhalation. The presence of vortices in the stream of inhaled air leads to the need for spectral analysis.

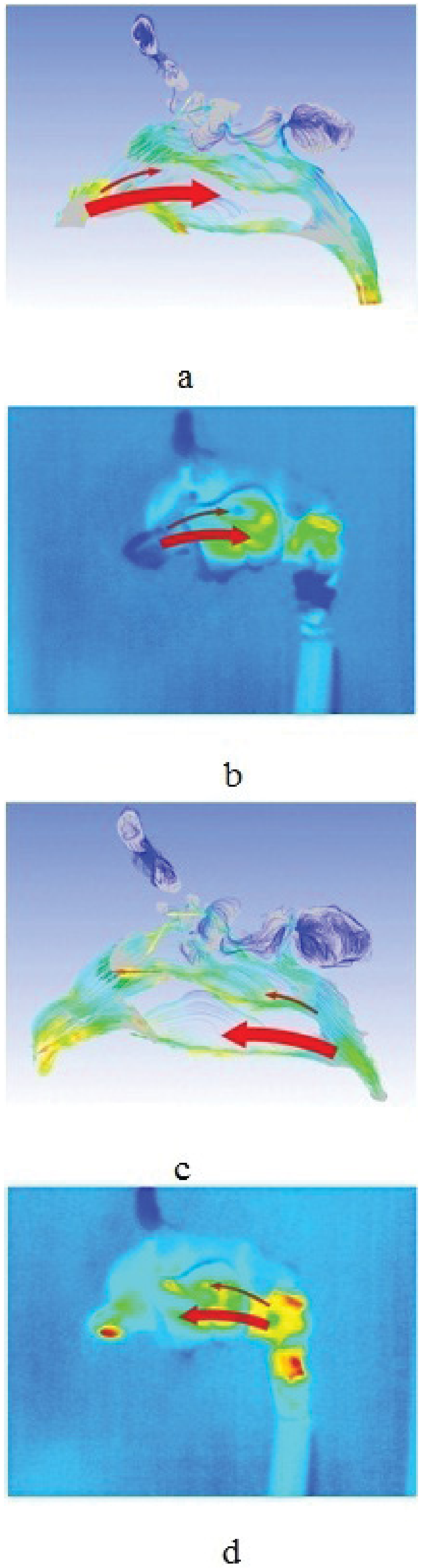

Fig. 6. Results of numerical (a, c) and experimental simulation (b, d) of the temperature field; results of inhalation simulation (a, b) and exhalation simulation (c, d) in the leptocavital model of the nose

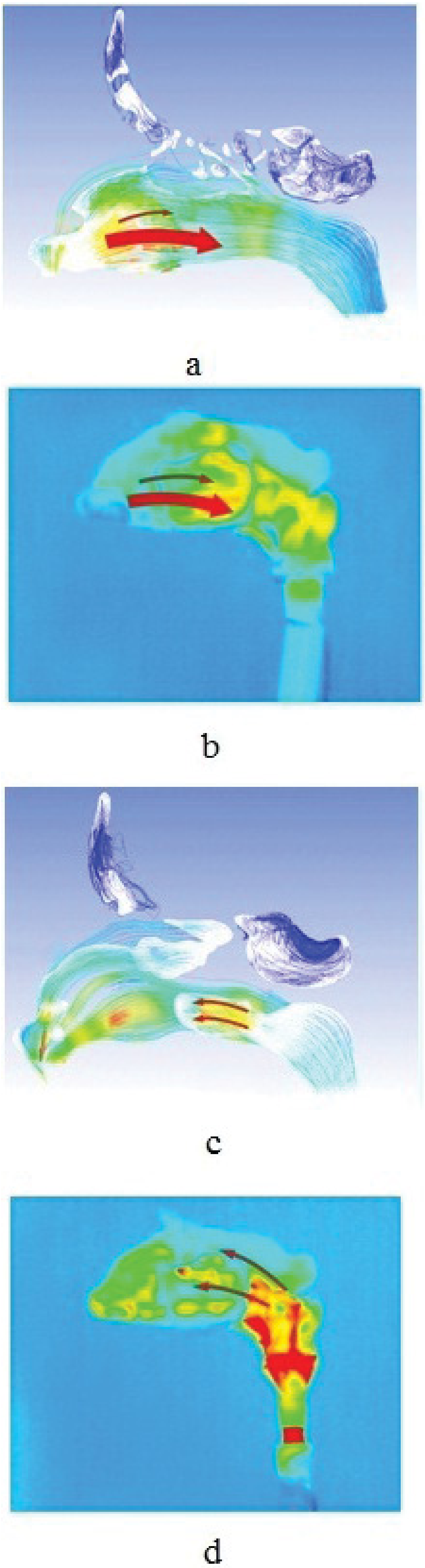

Fig. 6. Results of numerical (a, c) and experimental simulation (b, d) of the temperature field; results of inhalation simulation (a, b) and exhalation simulation (c, d) in the mesocavital model of the nose

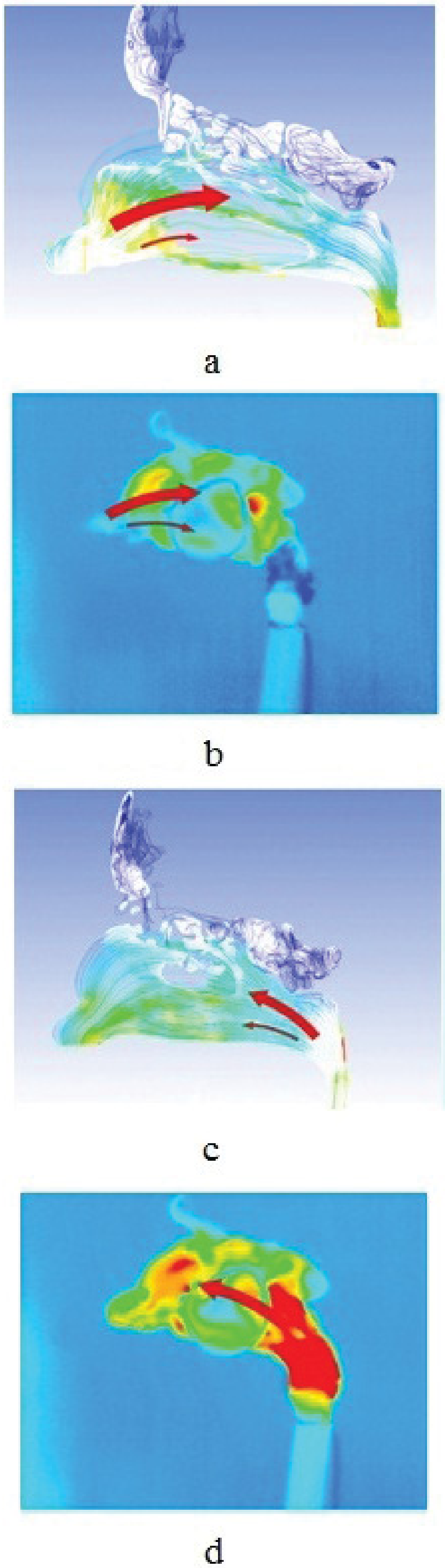

Fig. 7. Results of numerical (a, c) and experimental simulation (b, d) of the temperature field; results of inhalation simulation (a, b) and exhalation simulation (c, d) in the platycavital model of the nose

It has been revealed that the shape of the nasal cavity affects hydrodynamics and heat transfer in the respiratory organs, which can be manifested by a predisposition to respiratory diseases in carriers of the platycavital form of the nose in the extreme environmental conditions of the Arctic. Based on the study results, it is possible to recommend a tomographic examination of the nose cavity of the non-indigenous population of the Arctic for the purpose of detecting a predisposition to respiratory diseases.

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