The comparative analysis of the results of airflow numerical modeling in a human nasal cavity

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Abstract

The technique of research of air flow in a human nasal cavity is developed on the basis of mathematical modeling by means of package ANSYS. The three-dimensional geometry of a nasal cavity is constructing on the basis of tomography pictures series received from clinic. Programs GRAPHER and GAMBIT are used for the construction. The flow in the constructed mathematical model of a nasal cavity is calculated in fluid-dynamics section FLUENT of package ANSYS on the basis of incompressible Navier - Stokes equations system. By means of a time-dependent method a stationary solution is founded for designated pressure difference between an exit and input of a nasal cavity. There are constructed about 30 models of nasal cavities of real people. For them fields of velocity, temperature, pressure are calculated and visualized. Integral characteristics are obtained, such as dependence of the volume flow rate on pressure difference, distribution of the minimum and average values of temperature along length of a nasal cavity depending on temperature of inhaled air, distribution of size of hydraulic diameter along a nasal cavity, dependence of resistance factor of nasal cavity on Reynolds number. The analysis of results is carried out for establishing of regularities and specific features in an effort to reveal the signs of physiological norm and a pathology.

Human nasal cavity has a complex structure, therefore the experimental study of air flow in it is practically eliminated. Currently, air flow in the nasal cavity is being actively studied by numerical simulation. These studies are timely in view of the development of inhaled methods of drug delivery. Numerical simulation also allows to perform virtual operations before the actual surgery.

In ITAM SB RAS the technique is developed to study the flow of air in human nasal cavity on the basis of mathematical modeling with the package ANSYS [1]. Three-dimensional geometry of nasal cavity is constructed on the basis of series of clinic tomographic images. In the construction the programs GRAPHER and GAMBIT are used. The flow in nasal cavity geometrical model is calculated in the gasdynamic section FLUENT of package ANSYS based on the Navier - Stokes equations. The time-dependent method is used to find a stationary solution for a given pressure difference between the nasal cavity inlet and exit. The models of the nasal cavity for 30 adults were constructed. Great variety of forms was noted. Fig. 1 shows the typical coronary sections of 20 nasal cavities (the sections refer to the middle of the nasal labyrinth). In the center of the picture there are shown a general view of the surface of the nasal cavity of one of the models and the trace of the coronal section in the middle of the nasal labyrinth. It can be seen that all the models have individual anatomical features in the structure of the nasal cavity and are very different from each other. Some of them (the bottom row) represents the nasal cavities characterized by physicians as pathological cases. As a rule, the right and left halves of the nasal cavity of a particular person have a notable difference, especially significant for models relating to pathology.

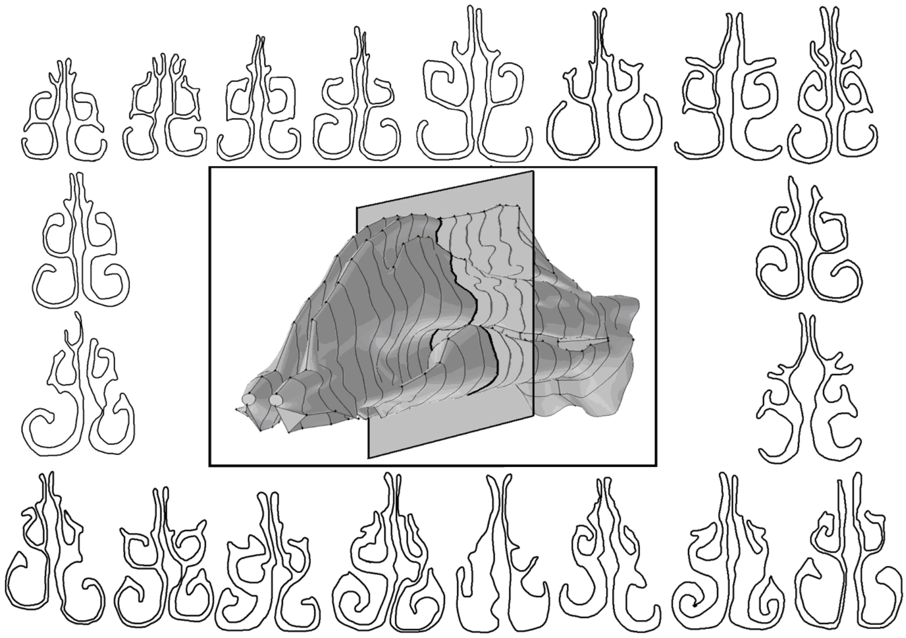

Figure 1: A variety of human nasal cavity forms.

The main criterion for medical evaluation of nasal breathing effectiveness is a nasal traffic capacity, expressed as a specific consumption of air through the nasal cavity as a function of respiratory effort. For a normal nasal breathing air flow rate should be approximately 500 ml/s through the nasal cavity, which corresponds to respiratory effort of about 30 $\div$ 50 Pa for a healthy person. Fig. 2 shows plots of the air flow rate (the sum of the flow rate through the right and left half of the nasal cavity) versus respiratory effort (pressure drop ΔP) obtained in the calculations for different models. In the graph the solid lines show the model relating to the physiology cases (patients with no complaints of nasal breathing) and the dashed lines show the model related to the disease (patients complaining of nasal breathing). Lines with dots denote the two models that were tested after surgery. It can be seen that all the curves related to physiology, correspond to the condition of quiet nasal breathing and have small deviations from each other.

Most of the curves relating to the disease, are below the "physiological" dependencies. Pathology models with low consumption tend to have narrow passages, significant distortion and deformation of nasal septum, which lead to difficulty in nasal breathing. In Fig. 2 it is shown two curves for models with pathology, where air flow rate are much higher than normal. These models differ in that the nasal passages are broadened. They are performing the transport function of the nose associated with the supply of lungs by air, but at the same time a person feels discomfort when breathing, which is associated with dysfunction of the warming of inhaled air. It should be noted that the three uppermost curves correspond to "physiological" models, that have significant differences between the flow rates through the left and right halves of the nose, these differences exceed 40 %. It can be seen from Fig. 2 that the curves of the physiology and pathology of nasal breathing overlap. This does not include all 30 of the calculated curves, but the picture shows the general. Unfortunately, at this stage we could not find a single criterion for traffic capacity, if at all possible, having regard to great diversity of nasal cavity forms.

To assess the thermoregulatory function of nasal cavity the graphs of distribution of

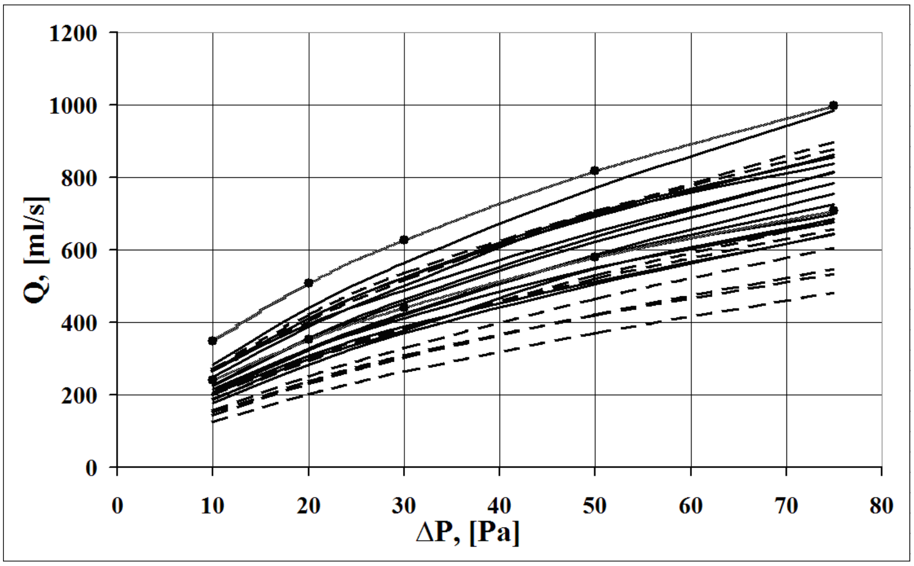

Figure 2: Flow rate versus generated respiratory effort.

average and minimum temperatures in the coronary sections along nasal cavity length were built by results of the calculations . Curves were plotted for two values of the inhaled air temperature: 23 and 0 °C. Fig. 3 shows average values (solid line) and minimum (dashed) temperatures in the section corresponding to choana - the place where nose septum ends. This values correspond to inlet temperature 0 °C and a pressure drop of 50 Pa. Here are the data for the 25 models for the left and right halves of the nose alone - a total of 50 variants. Numbering options held in order of decreasing values of the average temperature. The graph shows that at the nasal cavity outlet the average temperature is close to body temperature for the first issues, for the latter it is 15 degrees below. A similar difference for the minimum temperature is 20 degrees. All the narrow nasal cavities are at the top curves, all the wide cavities are in the end. The last two points, where the average temperature at the inlet to nasopharynx is 22 degrees, while the minimum is close to 15 degrees, correspond to the nasal cavity, where the operation was carried out to enlarge the nasal lumen. In Fig. 2 this case corresponds to the topmost curve. From this we can conclude that the consequence of the surgery, which improved the transport function of the nose cavity, was the weakening of its thermoregulatory function.

In search of an approach to compare the anatomical structures there was calculated and plotted the distribution of hydraulic diameter D_h along the nasal cavity. The results are shown in Fig. 4. The hydraulic diameter is defined as $D_h = 4S/L_p$, where S - area of the coronary section, L_p - wetted perimeter of this section. The abscissa is the distance from the entrance to nose, normalized by the length of the nasal cavity. The icons shows the data belonging to the individuals, the solid line is approximation polynomial. It is seen that the polynomial describes well the calculated data. The graph shows the data for the 15 models that fall within the physiological range according to clinical criteria. The graph shows that the minimum hydraulic diameter is in the middle part of the nasal cavity, and maximum is at nasal cavity exit and corresponds to choana. The calculations revealed that the distribution of hydraulic diameter for pathology cases differs significantly from the mean value obtained for the physiology.

The hydraulic diameter D_h is used to calculate the dimensionless Reynolds number. In Fig. 5 there is shown the distribution of the drag coefficient C_d of nasal cavity as a function of Re. In a number of published studies the velocity was taken equal to its value

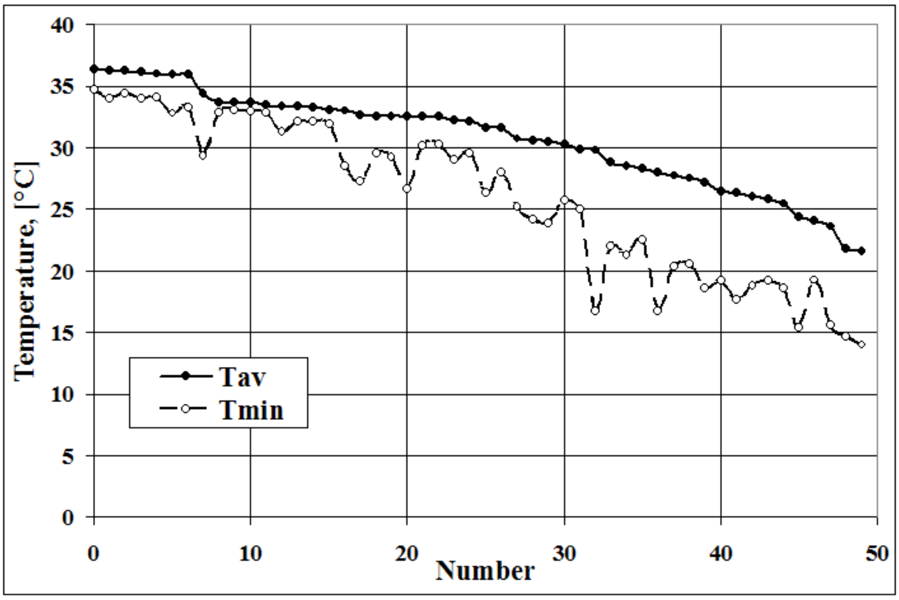

Figure 3: Dependence of the average and minimum temperature in the outlet cross-section during inspiration.

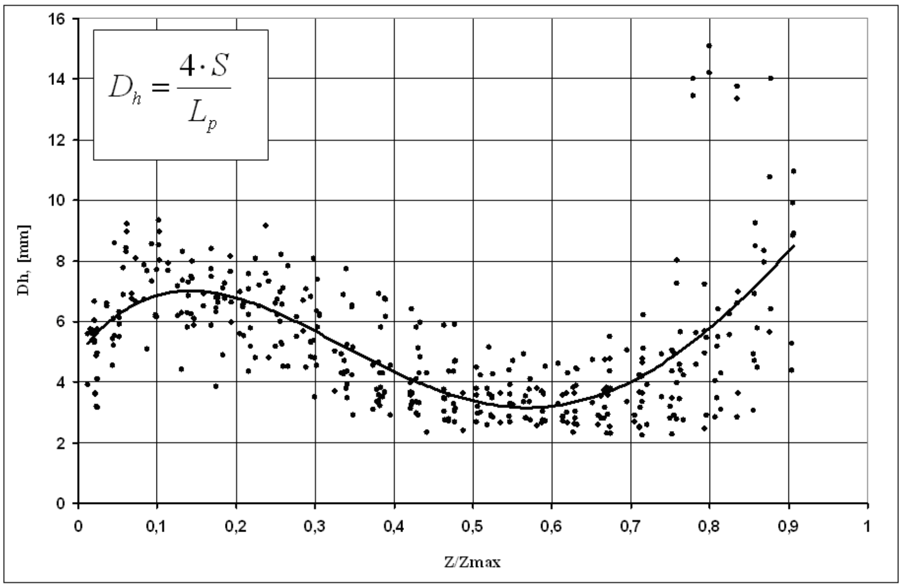

Figure 4: The distribution of hydraulic diameter.

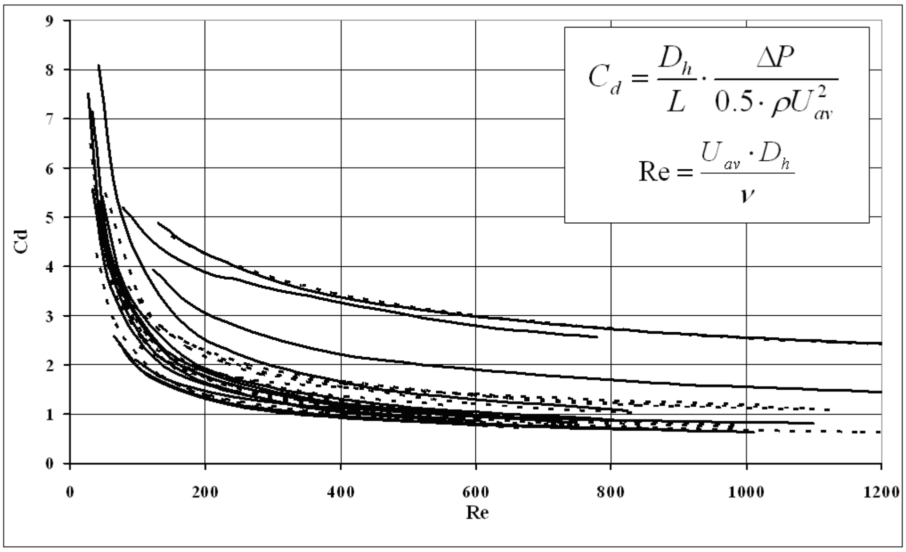

Figure 5: Drag coefficient of nasal cavity.

at the inlet for Reynolds number calculation. It seems that for this purpose it is more suitable the velocity averaged over the volume U_{av}. The used formulas have the following notation: L - length of the nasal cavity, ΔP - generated respiratory effort, ρ - density, v - kinematic viscosity. The average hydraulic diameter was used as the linear size. Solid lines indicate the left half of the nasal cavities, dashed lines are for the right half. It is seen that most of the curves are close to each other, these models belong to the physiological norm. The upper curves correspond to the model of nasal cavities with pathological disorders. Moreover, these curves are stratified by type of pathology.

In the present work the analysis of the results is performed in order to identify regularities and individual features for signs of physiological norm and pathology. A comparison of the integral characteristics is carried out, such as the dependence of flow rate on the pressure drop, the distribution of minimum and average temperatures along the nasal cavity, depending on the temperature of the inhaled air. It is shown that there is not enough to know only the nasal flow rate characteristics for determining of physiological norm. One must also consider thermoregulatory function. The hydraulic diameter distribution along the nasal cavity and the dependence of the drug coefficient on the Reynolds number are obtained. It is shown that distribution of hydraulic diameter is well approximated by a polynomial in the case of physiology. Significant deviations from this polynomial can be interpreted as the pathology of nasal breathing. It is observed lamination of drug coefficient dependences on belonging of nasal cavity to physiology or pathology cases.

References

[1] V. M. Fomin, V. L. Ganimedov, M. I. Muchnaya, A. S. Sadovsky, V. N. Shepelenko, M. N. Melnikov, A. A. Savina. Air flow in human nasal cavity. J. Appl. Mech. Tech. Phys. 2010. Vol. 51, No. 2. P. 107–115.

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