The Role of Paranasal Sinuses in the Aerodynamics of the Nasal Cavities

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Abstract- A simplified model of the nasal cavity contains the paranasal sinuses was constructed. The level of ventilation and pneumatization of the paranasal sinuses was also integrated into the model. It was demonstrated that during the normal operation of the nasal cavity, turbulent airflow predominates. When the nasal cavities are blocked due to pathology, the airflow is laminar.

Keywords- Nasal Cavity; Respiratory Cavity; Anastomosis; Ventilation; Turbulent; Laminar Regime

I. INTRODUCTION

At present, much attention is being paid to the study of the physiological functioning of sinuses. However, despite the large number of papers written on the subject, e.g. [1-3], the process by which air passes through the nasal passages, including the sinuses (pneumatic), is still poorly understood. The aerodynamics of the airflow passing through the nasal passage areas which contain the respiratory cavities, remains unclear. In relation to the degree of communication (i.e., the degree of obstruction) with the nasal passage, a number of pathologies have been defined, such as nasal sinusitis. The ventilation degree of the paranasal sinuses, which can be established by analyzing the distribution pattern of the airflow inside the nasal passage sections containing these sinuses, also remains unclear.

II. STATEMENT OF THE PROBLEM AND THE MODEL

In previous works [8], has been used 3-D STL model for reconstructing nasal cavity, as Computer Aided Design models, based on computed tomography (CT) scans. The numerical simulations of the aerodynamic processes for the model were carried out using a software package Flow vision (v. 2.3.3, LLC). The Initial conditions for the model were given by experimental data and obtained by computer rhinomanometry TNDA-PRH.

The purpose of this paper is to establish the basic aerodynamic laws characterizing the air passage passing through the nasal cavity, and the features that occur when the airflow branches into the sinuses. Models of the normal and the pathological (intended anatomical) position of the sinuses in relation to the nasal passage are studied to determine the basic aerodynamic differences between these cases.

The basic parameters and characteristics of the aerodynamic flow that are required to analyze its distribution in the nasal cavity are defined. It should be borne in mind that simultaneous with the airflow can be found purely turbulent, purely laminar, and mixed flows, as well as areas in which there is a succession of alternating flows.

The pressure drop Δ p balancing the frictional force on the pipe section $\Delta \ell$ refers to the resistance of the pipe and is described by the following formula:

$$\Delta p = \lambda \frac{\Delta \ell}{D} \frac{\rho u_{av}^2}{2}, \tag{1}$$

Where (D) is the diameter of the tube, λ is the coefficient of resistance, and u_{av} is the average cross-sectional flow velocity.

For the laminar flow,

$$\lambda_L = \frac{64}{Re}, \tag{2-a}$$

and for the turbulent flow (Blasius formula),

$$\lambda_T = \frac{0.3164}{Re^{0.25}}. \tag{2-b}$$

The specific hydrodynamic resistance (for the flow of liquid or gas in the pipe) is defined by:

$$\rho_{Gd}^* = \frac{8\eta}{r^2}, \tag{3}$$

Where (r) is the local radius of the tube, (η) is the coefficient of viscosity of the air (under normal conditions $\eta \approx 1{,}7 \cdot 10^{-5}$ Pa $\cdot$s).

Given these values, the Poiseuille's law can be written as follows:

$$Q = \frac{\Delta p}{\rho_{Gd}^* \frac{\Delta \ell}{S}}, \tag{4}$$

and the hydrodynamic resistance of the pipe is

$$R_{Gd} = \rho_{Gd}^* \frac{\Delta \ell}{S}. \tag{5}$$

III. ANALYSIS OF THE MODEL AND DISCUSSION OF THE RESULTS

The airflow in the nasal areas which includes the respiratory cavity anastomosis, is studied (Fig. 1). Figure 1 shows the axial (in relation to the axis of the anastomosis) section of the respiratory cavity with characteristic dimensions for the maxillary sinus, which is considered in terms of isometrics with an average size of 25 mm. We

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distinguish inside the sinus region, bounded by the inner surface of the sinus and the lateral surface of a cylinder , diameter that equal to the diameter of the maxillary sinus ostium (D), and the height equal to the sinus depth(h), and calculate the air flow of the speed vector through a given surface. Since the inner surface of the sinus is impermeable to air, the flow may be distinct from zero only on the lateral surface of the cylinder. According to the Gauss theorem, the value of this flow is equal to the speed generation volume (V) of the air in the cavity, i.e.

$$\oiint v_n dS = \frac{dV}{dt}, \tag{6}$$

where (v_n) is normal in relation to the cylinder lateral surface speed. Since there are no sources and sinks for the airflow inside the selectable surface,

$$\frac{dV}{dt} = 0, \tag{7}$$

which implies that $\oiint v_n dS = 0$. There are two possible cases: (1) at all points of the lateral surface, the normal speed (vn) equals 0; and 2) at some points, the surface speed v_n >0, and at others, v_n <0, which may lead to a total vector flow speed of zero. However, if we can divide the selected area by coplanar sections, the distance between which shaping an infinitely thin layers size as (dh), within the limits that the speed can be characterized only by a completely certain value, then the Condition (7) leads to the fact that this value should be zero, i.e., the first case is realized. However, here it is possible to move at tangential speed along (r), as shown in the figure, so that it becomes (vr). To calculate the value of this speed, we formulate the continuity equation for Point (A), which is under the condition of incompressibility; thus, the source has the following form:

$$\frac{\partial v_z}{\partial z} + \frac{\partial v_r}{\partial r} = 0. \tag{8}$$

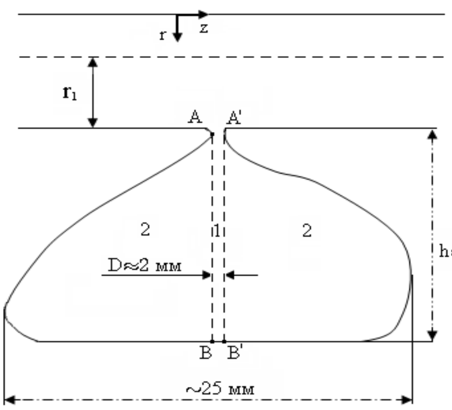

Fig.1 Axial (relative to the axis of the anastomosis) section of the pneumatic maxillary cavity

Going over this equation from the partial differentials to the final increments, and assuming that Point (A) is located directly on the tissue surface on the virtual border between the nasal passage and the anastomosis, and that the change in speed occurs abruptly at the boundary layer with thickness δ (e.g., Δz≈Δr≈δ), we obtain

$$\Delta v_z = -\Delta v_r. \tag{8-a}$$

To find these values, we write the equality flow before (z < A) and after (A < z < A′) entrance to the anastomosis:

$$\pi r_1^2 v_{z(1)} \approx \left[\pi r_1^2 + \pi\left(\frac{h}{2}\right)^2\right] v_{z(2)},$$

where $v_{z(1)}$ is the airflow before anastomosis entry (z < A), and $v_{z(2)}$ is the airflow after anastomosis entry (A <z<A'). In accordance with the data from [4, 5], the value of $v_{z(1)} \approx$ 2,75 m/s and the average radius of the nasal passage $r_1 \approx 3$ mm, and based on the figure, h ≈ 30 mm, we find that:

$v_{z(2)} \approx$ 0,04m/sec.

Please note that the calculation is an estimate.

In accordance with the data obtained on the basis of Equation (8-a), we calculate the jump in the radial speed upon anastomosis entry as:

$\Delta v_r = -\Delta v_z \approx$ 2.7 m/s,

and since the radial speed upon entrance to the anastomosis is vr(1) ≈ 0, inside the anastomosis the value is

$v_{r(2)} \approx$ 2,7 m/sec

In symmetric point (A′), if we disregard the minor effect of viscosity in this case, after repeating the same conversion, we can obtain:

$v'_{r(2)} \approx$ - 2,7 m/s,

i.e., the radial speed changes direction, going to zero at the axis of the anastomosis. In a strict sense, the radial flow speed leads to the phenomenon of ejection, i.e., involvement in the extruded flow adjacent to the jet areas of fluid or gas, but as experience has shown that a strong projectile flow surrounded by fluid (projectile) occurs in the narrowest area and when the liquid is less dense [6], this phenomenon can be considered negligible for air.

In accordance with the foregoing, the ventilation in the sinus occurs only in Volume 1 (see figure), bordering the area of the anastomosis. This volume, $V = \frac{\pi D^2}{4} \cdot h$, has a value of about 1cm^3, while the total volume of the sinuses (maxillary) is (10–20) cm^3. We assume that the radial speed varies along the (z) anastomosis based on a linear law and therefore decreases from the wall of the anastomosis to its axis down to zero and increases in modulus when approaching an opposite wall. Then we can assume that the average speed of each half anastomosis is equal to half the radial speed near the wall. At this loss in the zone, the ventilation through each of the halves of the anastomosis is:

$$Q \approx \frac{1}{2}\frac{v_{r(2)}}{2}\frac{\pi D^2}{4},$$

which is about 2 cm^3/s, and the average time of ventilation $t_v \approx 4\frac{h}{v_{r(2)}}$ is about 0.05 s.

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Thus, the ventilated part of the pneumatic cavity is about only (5–10) % of its total volume, while the remaining area is a zone of stagnation.

We study the effect of the maxillary sinus surface on the aerodynamics in the nasal cavity in normal mode when the cavity is connected with the nasal passage by the anastomosis in the pathological mode and when the cavity is clogged and cut off from the nasal passage. We provide the aerodynamic parameters for the first case as index (n), and for the second one as index (p). Calculation of the hydrodynamic resistance of the nasal passage with length $\Delta\ell \approx 0.1$ m, produced in accordance with Equations (3) and (5) for the geometrical parameters, as shown in the figure, gives approximately the same value as Rgd(n) ≈ Rgd(p) ≈ $5{,}2 \cdot 10^4$ Pa·s/m3 in both cases, with the order of value coinciding with the data received in [4]. The nearness of the values of Rgd(n) and Rgd(p) is absolutely natural due to the smallness of the hydrodynamic resistance of the section that contains the maxillary cavity versus the resistance of all nasal passages (without maxillary sinuses). However, the degree of turbulence flow for these cases may vary, ignoring the small size of Reynolds number inside the ventilated sinuses volume, where, as is evident from the flow characteristics, Re ≈ 400, as well as inside the nasal passage, where, as it was shown in [5] , Re ≈ 1400, which corresponds to the laminar flow (in this case used the critical Reynolds number for a cylindrical tube Rec ≈ 2300, which is its overstated assessment for the present case, because the geometric sharp and inhomogeneity material of the nasal passage reduces this value Rec). However, the laminar regime can exist at the obtained Reynolds numbers only in isolation from other flows. If the laminar flow that spreads through the nasal passage is partly diverted into a sinus anastomosis, then it creates a disturbance that contributes to its turbulence [6]. This process corresponds to the normal mode of breathing. In the case of blockage of the sinus cavity ("fouling" of anastomosis), the nasal passage section becomes homogeneous, and the laminar regime in it becomes more stable. The finding on the turbulent character of the flow without pathology of the nasal channels is confirmed by the results given in [7].

One feature of the turbulent flow is the hydrodynamic mixing of the moving environments, which provides a more intensive flow in relation to the laminar flow impulse transfer, heat, and mass. The turbulent transport equations in accordance with the theory of Boussinesq [6] can be represented as similar to molecular transfer equations if we replace the length of the free spring value λ with the value of the mixing and stirring path (mixing) ℓ, which is about 0.1 of the thickness of boundary layer δ. As always, we use the condition λ << δ, and the value of the turbulent thermal conductivity is much greater (more than one order) than that of the molar thermal conductivity. Moreover, the turbulent thermal conductivity in the wall region has strong anisotropy (the longitudinal thermal conductivity can exceed the lateral value by about 2-3 orders) [7].

Now consider the change in air temperature as it moves into the nasal cavity. As under the given conditions, the air can be considered as an incompressible medium [4, 5], and the change in its temperature in the adiabatic approximation can be caused only by friction losses. The loss due to friction in an arbitrarily selected volume (V) is equal to the product of the pressure drop Δ p divided by the volume. Equating the value of the losses due to friction with the thermal energy released inside the volume, and representing Δ p in accordance with (1), we obtain the following:

$$\lambda \frac{\Delta\ell}{D}\frac{\rho u_{cp}^2}{2} V = \frac{m}{\mu}\frac{i}{2} R\Delta T,$$

Where (i) is the number of degrees of freedom (for the molecules making up the air, i = 5), and (R) is the universal gas constant.

Expressing in this equation the ratio m/V by the density ρ, we have:

$$\lambda \frac{\Delta\ell}{D}\frac{u_{cp}^2}{2} = \frac{i}{2}\frac{R}{\mu}\Delta T. \quad (9)$$

We first consider the laminar flow, in which, as noted above, the value of the coefficient of resistance is associated with the Reynolds number at the ratio $\lambda_L = \frac{64}{Re}$. Substituting λ_L in Equation (9), taking into account that $Re = \frac{u_{cp} D}{\nu}$, we find the changes in temperature along the nasal passage (axial temperature gradient) in the laminar flow,

$$\left(\frac{\Delta T}{\Delta\ell}\right)_L = \frac{64\nu\mu u_{cp}}{iRD^2}. \quad (10)$$

Substituting in this formula the values of the air viscosity ν = 10-5 cm and the average molar mass of the air μ = 29 10-3 kg, and assuming that the average diameter of the nasal passage D≈ 5 ·10-3 m, and the average cross-sectional airflow rate uav ≈1m/s, we define an approximate numerical value of the axial temperature gradient in the laminar flow:

$$\left(\frac{\Delta T}{\Delta\ell}\right)_L \approx 2\cdot 10^{-2}\frac{K}{м}.$$

For the turbulent flow, the coefficient of resistance, as mentioned above, is related to the Reynolds number at the ratio $\lambda_T = \frac{0.3164}{Re^{0.25}}$, which allows the determination of the axial temperature gradient in the turbulent flow in accordance with Equation (9):

$$\left(\frac{\Delta T}{\Delta\ell}\right)_T = \frac{0{,}3164\mu u_{cp}^{7/4}}{iRD^{9/4}}\nu^{1/4}.$$

The approximate numerical value is $\left(\frac{\Delta T}{\Delta\ell}\right)_T \approx 2\frac{K}{м}$.

The obtained numerical values of the temperature changing within the nasal cavity allow us to conclude that the cold air passing through the nasal passage and entering into the bronchial tubes at a temperature close to that of the surrounding tissue is heated not due to friction losses but to the thermal conductivity resulting from turbulent mixing of the air. According to [8], warming (and moisture) of the air occurs mainly in the nasopharyngeal cavity in contact with

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an extended surface of nasal conchas and ends in the lower respiratory tract. Thus, the complex relief of conchas contributes to the formation of a turbulent flow, which causes a high-intensity heat exchange with surrounding tissues. In this sense, the English name of the nasal concha "turbinate bone" reflects its functional role.

IV. CONCLUSIONS

Pneumatic cavities are zones of stagnant air that are ventilated at about 10% of their volume.

During normal operation of the paranasal sinuses (i.e., in the absence of obstruction), the aerodynamics of the airflow in the nasal passage is mostly turbulent, while during obstruction of the sinuses, the airflow is laminar.

The heating of the air during its passage through the nasal cavity is mainly due to the mechanism of turbulent heat conductivity.

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