Possibilities Theoretical And Natural Models For Determining The Coefficient Of Human Aerodynamic Nose Resistance

Nosova Yana
Biomedical Engineering Department
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
yana.nosova@nure.ua

Oleg Avrunin
Biomedical Engineering Department
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
oleh.avrunin@nure.ua

Shushliapina Nataliia
Otorhinolaryngology Department
Kharkiv National Medical University
Kharkiv, Ukraine
shushliapina_nataliia775@ukr.net

Ibrahim Younouss Abdelhamid
Biomedical Engineering Department
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
ibrahim.younouss.abdelhamid@nure.ua

Alofie Bander Ali Saleh
Umm Al Qura University
Makkah, Saudi Arabia
aqariyat11@yahoo.com

***Abstract*—This paper presents a comparative analysis of mathematical and full-scale models in determining the aerodynamic nose drag coefficient. According to the results of experimental tests of a full-scale model obtained by 3D printing, it is possible to calculate the value of the aerodynamic nose drag coefficient by obtaining the pressure drop values total losses for the corresponding given air flow rates. The discrepancy between the values of the aerodynamic nose drag coefficients in this case did not exceed 15% and is explained by methodological errors associated with the approaches in calculating the aerodynamic model of the nasal cavity, in particular, the impossibility of taking into account all local disturbances and their mutual influence, and the properties of the plastic surface of the air channels of the full-scale model during experimental tests**

Keywords— nasal breathing, inhalation aerodynamics, air consumption, pressure drop, full-scale model, rhinomanometry

I. INTRODUCTION (*HEADING 1*)

This Rapid prototyping technologies allow to provide an important and new qualitative result in most medical fields, especially in implantology and planning of surgical interventions. A relatively short-term and fairly accurate process of manufacturing full-scale models for medical purposes is made possible by modern methods of rapid prototyping and, first of all, the methods of extrusion 3D printing, which has become the most widespread in recent years [1, 2].

In the tasks of configurational planning of functional rhinosurgical operations, it is expedient to visualize and model dynamic changes in the geometrical characteristics of the anatomical structures of the operating area [3, 4]. In addition, full-scale models can be used to predict the functional result of the operation and pre-operative verification of the decisions made using tests on special aerodynamic stands [5].

The purpose of the work is to assess the adequacy of mathematical and natural models in determining the coefficient of aerodynamic nasal resistance in order to assess the possibilities of developing an approach to computer planning of rhinosurgical interventions based on the study of geometric and functional characteristics of real personified models of the internal structure of the upper respiratory tract according to diagnostic data of computed tomography.

II. RESEARCH METHODS

The initial data for the conducted studies were sets of images of tomographic sections obtained with the help of a spiral X-ray tomograph SOMATOM + of the company SIEMENS (Germany). Patients were examined in the diagnostic center of the Kharkiv Regional Clinical Hospital (HOKB). Initially, the images are saved in the DICOM format [4], converted using the standard DICOM_IMAGE utility into a BMP (Windows bitmap) raster format with a size of 512 × 512 (x × y) and an 8-bit representation of intensity levels. Pre-processing of tomographic images was done by the method of median filtering [1, 2] to eliminate possible disturbances in the form of impulse noise. Also, for control, rhinomanometry studies of patients were carried out using a device for testing nasal breathing based on a certified block of differential flow characteristics of TNDA-PVC [6] using measurements by the type of posterior active rhinomanometry [4, 7-8] in forced breathing mode.

From the analysis of the literature, it turns out that many works are based on mathematical modeling of aerodynamic processes in the nasal cavity [9-12], correlations between various research methods, in particular, computed tomography and rhinomanometry [13-15], and are also devoted to the determination of subjective and objective signs of nasal breathing disorders [16, 17].

Determination of the coefficient of aerodynamic nasal resistance was based on a mathematical model of one-dimensional air flow in the nasal cavity [18]. Output data - sets of tomographic slices (see Figure 1) were segmented to obtain airways by the threshold method according to the intensity level corresponding to air in Hu units on the Hounsfield scale when selecting the soft tissue imaging window [4]. Next, the contours of the obtained anatomical configuration were determined with their subsequent skeletonization of the boundaries and intellectual processing [18-20] to eliminate unnecessary elements that may be incorrectly taken into account during geometric calculations. An example of a segmented model of the nasal cavity is shown in Figure 2.

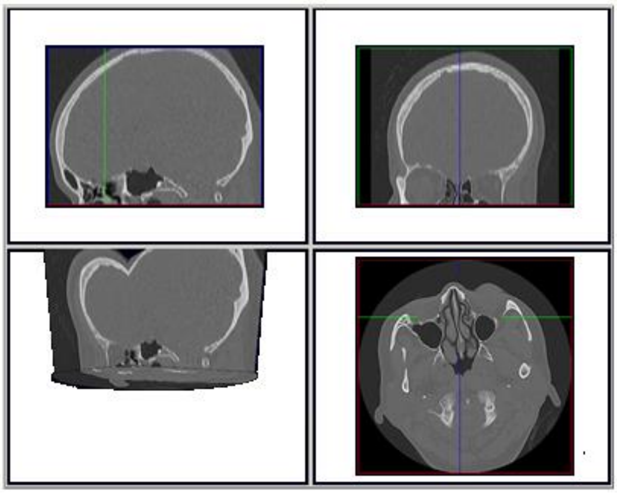

Fig. 1. Illustration of data preparation for spiral computed tomography for segmentation of nasal cavity structures in different imaging projections.

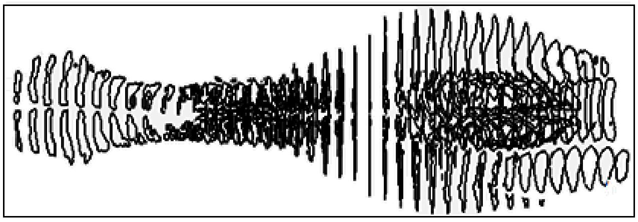

Fig. 2. Segmented model of the nasal cavity.

Determination of the theoretical coefficient of aerodynamic resistance of the nasal cavity is based on the assumption that the airways of the nose are considered as two parallel channels. The total air flow is the sum of the flow through the left Q_L and right Q_L nasal passages, respectively

$$Q_{\Sigma} = Q_L + Q_R \tag{1}$$

and the pressure drops are the same for the left Δp_L and Δp_R right nasal canals

$$\Delta p = \Delta p_L = \Delta p_R \tag{2}$$

At the same time, the nasal cavity is divided into cross-sections that are perpendicular to the air flow, and the total pressure losses along the length (l-length) $\sum \Delta p_{l_L}$ and $\sum \Delta p_{l_R}$ local (r-regional) $\sum \Delta p_{r_L}$ and $\sum \Delta p_{r_R}$ are the sums of these resistances in each cross-section. Therefore, in accordance with expression (1), pressure drops through each nasal passage will be determined by the following formulas [4, 21]

$$\Delta p_L = \sum \Delta p_{l_L} + \sum \Delta p_{r_L} = \sum \lambda_L \cdot \rho \frac{L_L}{d_{\mathrm{h}_L}} \frac{Q_L^2}{2S_L^2} + \sum \xi_L \cdot \rho \frac{Q_L^2}{2S_L^2} = Q_L^2 A_L \tag{3}$$

$$\Delta p_R = \sum \Delta p_{l_R} + \sum \Delta p_{r_R} = \sum \lambda_R \cdot \rho \frac{L_R}{d_{\mathrm{h}_R}} \frac{Q_R^2}{2S_R^2} + \sum \xi_R \cdot \rho \frac{Q_R^2}{2S_R^2} = Q_R^2 A_R \tag{4}$$

where λ_L , λ_R are the Darcy coefficients (pressure loss along the length) for the left and right nasal passages, respectively;

ξ_L , ξ_R are local resistance coefficients for the left and right nasal passages, respectively;

L_L , L_R are the lengths of the left and right nasal passages, respectively;

Q_L , Q_R – air flow through the left and right nasal passages, respectively;

ρ – air density;

d_{h_L} , d_{h_R} are the hydraulic (equivalent) diameters of the left and right nasal passages, respectively, which are expressed for each intersection of the left and right nasal canals with the planes S_L , S_R and P_L , P_R perimeters, respectively, according to the formulas

$$d_{\mathrm{h}_L} = \frac{4S_L}{P_L}; \quad d_{\mathrm{h}_R} = \frac{4S_R}{P_R}; \tag{5}$$

A_L , A_R – coefficients of aerodynamic nasal resistance for the left and right nasal channels, which are determined from formulas (3), (4) and (5) as

$$A_L = \sum \lambda_L \cdot \rho \frac{L_L}{d_{\mathrm{h}_L} \cdot 2S_L^2} + \sum \xi_L \cdot \rho \frac{1}{2S_L^2} \tag{6}$$

$$A_R = \sum \lambda_R \cdot \rho \frac{L_R}{d_{\mathrm{h}_R} \cdot 2S_R^2} + \sum \xi_R \cdot \rho \frac{1}{2S_R^2} \tag{7}$$

Based on the fact that in the proposed model it is not possible to take into account the mutual influence of local resistances, only the largest of them is determined [4, 20].

Taking into account the quadratic dependence of the pressure drop on the air flow rate Q in the turbulent flow regime during forced breathing

$$\Delta p = Q^2 \cdot A \tag{8}$$

then when using equations (6) and (7) the total coefficient of aerodynamic resistance of parallel channels will be determined from formula (8) as

$$A = \left(\frac{\sqrt{A_L} \cdot \sqrt{A_R}}{\sqrt{A_L} + \sqrt{A_R}} \right)^2 \tag{9}$$

Cross-sections of the nasal cavity were selected based on the data of multiplanar reconstructions in the frontal plane with an interval of 2 mm.

III. Construction of a Natural Model of the Upper Respiratory Tract

The development of a full-scale model of the upper respiratory tract is based on the further transformation of segmented geometric models in stl format using special slicer programs, such as Cura 3D (see Figure 3, a) in G-code, taking into account the characteristics of the 3D printing device and prototyping parameters for subsequent production. The appearance of the finished full-scale model of the nasal cavity, which was made by the method of extrusion thermal printing on the WanhaoDuplicatorM1 3D printer from PLA plastic, is shown in Figure 3, b.

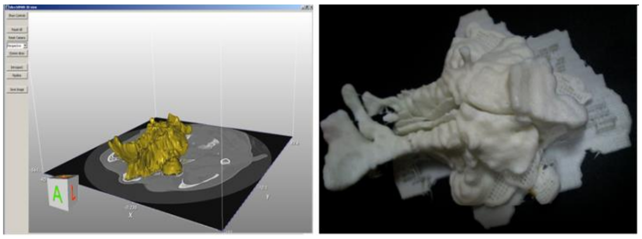

Fig. 3. A personalized model of the nasal cavity according to the data spiral computed tomography: a) virtual model; b) natural model.

The determination of the characteristics of the air flow on the model was carried out on a pneumatic stand (see Fig. 4), while the air flow Q was set with the help of a compressor, which corresponded to physiological values - from 1 to 4 l/s, and at the points of pressure measurement at the inlet and outlet of the nose of the channel, the corresponding values were obtained on the converters p_1 and p_2 (in Fig. 4 installed on the flow meter type Venturi nozzle) to obtain the pressure drop.

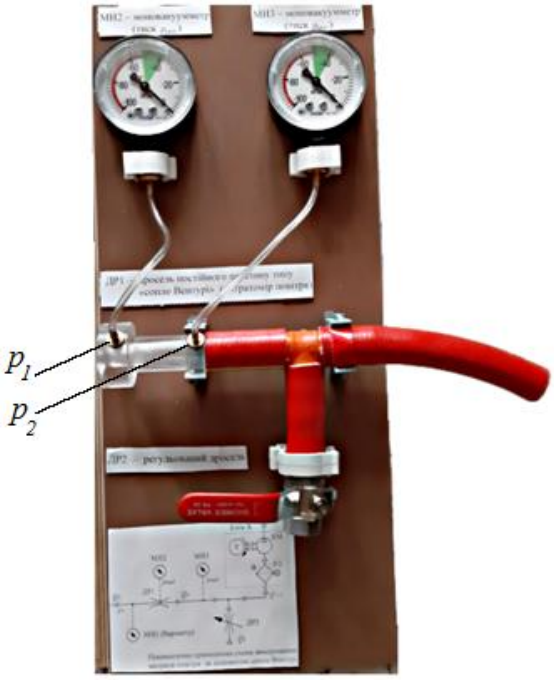

Fig. 4. Pneumatic stand for conducting aerodynamic tests.

$$\Delta p = p_2 - p_1 \tag{10}$$

Moreover, in accordance with formula (8), the aerodynamic nose drag coefficient was determined as

$$A = \frac{\Delta p}{Q^2} \tag{11}$$

Assessment of the adequacy of the models was carried out with the help of posterior active rhinomanometry [4] with the determination of the pressure drop and air flow in patients in normal conditions and in patients with nasal breathing disorders in forced mode. The structural diagram of the conducted research is shown in Figure 6.

It consists of obtaining data on the geometric configuration of the nasal cavity according to computer tomography data, segmentation and construction of a 3D model of the nasal cavity, on the basis of which the construction of mathematical and natural models of the nasal cavity is carried out, testing the latter on an aerodynamic stand, analysis of the correspondence of the received data and assessment of their adequacy (results of theoretical and natural modeling) when compared with rhinomanometry data.

IV. Results and Discussion

We got (fig. 5) theoretical (T) – according to the data of mathematical modeling of the values of aerodynamic nose drag coefficients according to formulas (6), (7), (9), natural (N) – experimental values that are obtained by means of aerodynamic tests of a printed model of the nasal cavity with obtaining values according to formulas (10), (11) and rhinomanometric (R) – real data obtained during the study of specific patients with calculations according to formula (11).

Personalized data were selected from three patients with a conditional norm (1) (without nasal breathing disorders according to the tomogram in Fig. 6, a) and with typical nasal breathing disorders with curvature of the nasal membrane (2) (with clearly expressed local resistance according to the tomogram in Fig. 6, b) and chronic sinusitis (3) – (with narrowing of the nasal cavity in most areas of the nasal cavity according to the tomogram in Fig. 6, c).

According to the data in Figure 5, it can be seen that normally (case (1) in Figure 5) aerodynamic nose drag coefficients are low enough and amount to about 0.3 kPa•s/l, while the data of the natural modeling (N), which are obtained from the natural model, and theoretical (T) are lower than rhinomanometric (R), which is caused by the properties of the plastic surface of the natural model and insufficient consideration of minor local resistances in the mathematical model (T).

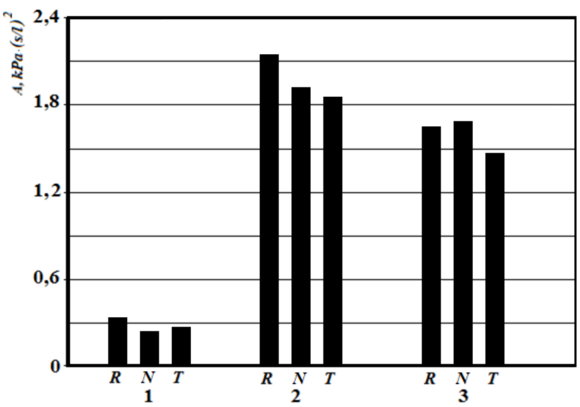

Fig. 5. The results of determining the coefficients of aerodynamic nasal resistance in case of a conditional norm (1), deviation of the nasal membrane to the left (2), chronic rhinosinusitis (3): (R) – rhinomanometric, (N) – natural, (T) – theoretical data.

When the nasal membrane is curved (case (2) in Figure 5), the coefficients of aerodynamic nasal resistance are the largest (about 2 kPa•s/l) than in other cases, while the theoretical (*T*) and real-world simulation data (*N*) are significantly lower than the rhinomanometric ones, which shows the impossibility of a more adequate consideration of turbulence in the mathematical model (*T*) and the generalized smaller effect of friction losses during studies of the natural model (*N*). are low enough and amount to about 0.3 kPa•s/l, and the experimental data obtained by the full-scale model are lower than the rhinomanometric and theoretical ones, which is due to the properties of the surface of the full-scale model and insufficient consideration of small local resistances in the mathematical model.

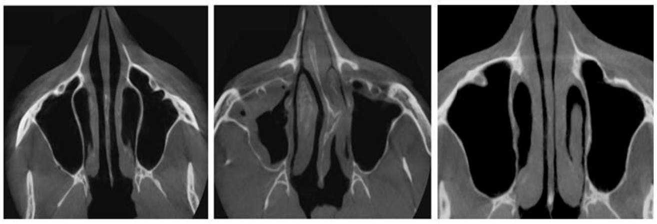

Fig. 6. Axial computer tomograms of patients with: a) conventional norm; b) bleeding of the nasal membrane to the left; c) chronic rhinosinusitis.

In case of chronic rhinosinusitis (case (3) in Figure 5), the coefficients of aerodynamic nasal resistance are also quite high (about 1.6 kPa·s/l), while the data of natural modeling (*N*) are relatively the largest, which is caused by the possible influence of the nasal cycle during rhinomanometry (*R*), as well as the lack of influence of local resistances in the model during theoretical calculations (*T*).

Thus, based on the obtained data of aerodynamic nose drag coefficients in the considered examples of typical pathologies and the conventional norm, it can be concluded that the theoretical model has a systematic error in the direction of decrease, which can be somewhat eliminated. But, this needs further research with sets of statistical data.

V. Conclusions

In the paper, three methods of obtaining data on the coefficient of aerodynamic nose drag are considered and their comparative analysis is carried out. Thus, according to the one-dimensional air flow model, it is possible to obtain theoretical results regarding this coefficient, taking into account local resistances and friction costs against the wall of the nasal cavity. According to the results of experimental tests of the full-scale model, which is obtained by the 3D printing method, it is possible to calculate the value of the aerodynamic nose drag coefficient by obtaining the pressure drop values - total losses at the corresponding specified air flow rates. The initial data for both models are segmented tomographic sections of the configuration of the nasal cavity. It is possible to verify the obtained data by performing rhinomanometry studies directly on real patients.

The adequacy of the models is determined by comparing the values of the coefficient of aerodynamic nose drag, which are obtained from model data with the results of rhinomanometry.

The discrepancy in the values of the coefficients of aerodynamic nasal resistance did not exceed 15% and is explained by methodical errors associated with the approaches to the calculations of the aerodynamic model of the nasal cavity, in particular, the failure to take into account all local disturbances and their mutual influence, and the properties of the plastic surface of the air channels of the full-scale model at experimental tests.

Nevertheless, the obtained data can be useful for planning surgical interventions with virtual and real-life modeling of changes in the configuration of the nasal cavity and corresponding prediction of changes in aerodynamic nasal drag coefficients.

The perspective of the work is the statistical processing of data sets to determine the reliability of the obtained results and the improvement of model representations of the nasal cavity due to the development of mathematical apparatus and prototyping materials.

Acknowledgment

The exchange program with East European Countries funded by DAAD (Ostpartnerschaften, project number 54364768) and joint Ukraine-Germany project MESU-BMBF 2019-2021 “3D-Model - Implementation of rapid prototyping to design and model the upper respiratory tract in normal and typical pathologies”.

References

[1] O. G. Avrunin, M. Y. Tymkovych, H. F. I.Saed, A.V. Loburets, I.A. Krivoruchko, A. Smolarz, S. Kalimoldayeva, “Application of 3D printing technologies in building patient-specific training systems for computing planning in rhinology“, Paper presented at the Information Technology in Medical Diagnostics II - Proceedings of the International Scientific Internet Conference on Computer Graphics and Image Processing and 48th International Scientific and Practical Conference on Application of Lasers in Medicine and Biology, 2018, 1-8. doi:10.1201/9780429057618-1

[2] O. Avrunin, M. Tymkovych, J. Drauil, “Automatized technique for three-dimensional reconstruction of cranial implant based on symmetry”, Paper presented at the 2015 Information Technologies in Innovation Business Conference, ITIB 2015, Proceedings, 39-42. doi:10.1109/ITIB.2015.7355070

[3] O. G. Avrunin, Y. V. Nosova, N. O. Shuhlyapina, S. M. Zlepko, S. V. Tymchyk, O. Hotra, . . . A. Mussabekova, “Principles of computer planning in the functional nasal surgery” [Zasady planowania komputerowego w czynnościowej chirurgii nosa] Przeglad Elektrotechniczny, 2017, 93(3), 140-143. doi:10.15199/48.2017.03.32

[4] O.G. Avrunin, Y.V. Nosova, S.V. Pavlov, N.O. Shushliapina and etc. “Research Active Posterior Rhinomanometry Tomography Method for Nasal Breathing Determining Violations”, Sensors 2021, 21, 8508. doi: 10.3390/s21248508

[5] H. Tang, J. Y. Tu, H. F. Li, B. Au-Hijleh, C. C. Xue, & C. G. Li, “Dynamic analysis of airflow features in a 3D real-anatomical geometry of the human nasal cavity”, In Proceedings of the 15th Australasian Fluid Mechanics Conference, 2004, December, pp. 80-83.

[6] Y. V. Nosova, K. I. Faruk, & O. G. Avrunin, “A tool for researching respiratory and olfaction disorders” Telecommunications and Radio Engineering (English Translation of Elektrosvyaz and Radiotekhnika), 2018, 77(15), 1389-1395. doi:10.1615/telecomradeng.v77.i15.90

[7] P. A. Clements, & F.Gortds, “Standardisation Committee on Objective Assessment of the Nasal Airway, IRS, and ERS Consensus report on acoustic rhinometry and rhinomanometry”, 2005, Rhynology, 43(3), 169-179.

[8] K. Vogt, A. A. Jalowayski, W. Althaus, C. Cao, D. Han, W. Hasse, ... & P. Zaporoshenko, “4-Phase-Rhinomanometry (4PR) --basics and practice”, 2010, Rhinology. Supplement, 21, 1-50.

[9] H. P. Lee, & B. R. Gordon, “Impacts of fluid dynamics simulation in study of nasal airflow physiology and pathophysiology in realistic human three-dimensional nose models” Clinical and experimental otorhinolaryngology, *5*(4), 2012, 181.

[10] S. E. Churchill, L. L. Shackelford, J. N. Georgi, & M. T. Black, “Morphological variation and airflow dynamics in the human nose”

American Journal of Human Biology: The Official Journal of the Human Biology Association, 2004, 16(6), 625-638.

[11] J. Van Strien, K.Shrestha, S. Gabriel, P. Lappas, D. F.Fletcher, N. Singh & K. Inthavong, "Pressure distribution and flow dynamics in a nasal airway using a scale resolving simulation", Physics of Fluids, 2021, 33(1) doi:10.1063/5.0036095

[12] H. Calmet, K. Inthavong, H. Owen, D. Dosimont, O. Lehmkuhl, G. Houzeaux, & M. Vázquez, "Computational modelling of nasal respiratory flow", Computer Methods in Biomechanics and Biomedical Engineering, 2020, doi:10.1080/10255842.2020.1833865

[13] M. G. Moghaddam, G. J. M. Garcia, D. O. Frank-Ito, J. S. Kimbell, & J. S. Rhee, "Virtual septoplasty: A method to predict surgical outcomes for patients with nasal airway obstruction". International Journal of Computer Assisted Radiology and Surgery, 2020, 15(4), 725-735. doi:10.1007/s11548-020-02124-z

[14] M. Berger, A. I. Giotakis, M.Pillei, A. Mehrle, M. Kraxner, F. Kral, , . . . W. Freysinger, "Agreement between rhinomanometry and computed tomography-based computational fluid dynamics". International Journal of Computer Assisted Radiology and Surgery, 2021, 16(4), 629-638. doi:10.1007/s11548-021-02332-1

[15] A.Aras, M. C. Akay, I. Çukurova, T. Günbay, E. Işıksal, & I. Aras, "Dimensional changes of the nasal cavity after transpalatal distraction using bone-borne distractor: an acoustic rhinometry and computed tomography evaluation", Journal of oral and maxillofacial surgery, 2010, 68(7), 1487-1497.

[16] G. Mlynski, S. Grützenmacher, S. Plontke, B. Mlynski & C. Lang, "Correlation of nasal morphology and respiratory function", 2001, Rhinology, 39(4), 197-201.

[17] G. H. Zhang, R. S. Fenton, R. Rival, P. Solomon, P. Cole & Y. Li, "Correlation between subjective assessment and objective measurement of nasal obstruction", Zhonghua er bi yan hou tou Jing wai ke za Chinese Journal of Otorhinolaryngology Head and Neck Surgery, 2008, 43(7), 484-489.

[18] H. F. I. Saied, A. K. Al-Omari & O. G. Avrunin, "An attempt of the determination of aerodynamic characteristics of nasal airways", Image Processing and Communications Challenges 3. Springer, Berlin, Heidelberg, 2011. p. 311-322. doi:10.1007/978-3-642-23154-4_35

[19] G. H. Zhang, R. S. Fenton, R. Rival, P. Solomon, P. Cole & Y. Li, "Correlation between subjective assessment and objective measurement of nasal obstruction", Zhonghua er bi yan hou tou Jing wai ke za Chinese Journal of Otorhinolaryngology Head and Neck Surgery, 43(7), 2008, 484-489.

[20] V. Filatov, & A. Kovalenko, "Fuzzy systems in data mining tasks". In Advances in Spatio-Temporal Segmentation of Visual Data, Springer, Cham, 2020, pp. 243-274..