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BIOMECHANICS - AIRFLOW IN THE NASAL CAVITY AND THE NASAL SEPTUM PERFORATION

K. Frydrýšek*, S. Drábková, M. Plášek*****

Abstract: *In addition to olfactory, reflective and immune activities, respiration is one of the physiological functions of the nose. The article deals with biomechanical research into the influence of pathological and anatomical effects of the nasal septum perforation on the character of flow during respiration. This is related to subsequent changes of flow in the nasal cavity from predominantly laminar to turbulent flow, i.e. undesirable changes in physiological functions of the nasal cavity occur. The objective of the present study was to examine the influence of the septal perforation and its position. For this purpose, numerical simulation using CFD was carried out on the simplified box model, bringing the comparison of the flow pattern both for an intact and perforated septum. The results can help towards better understanding of the given problem and underlie the further investigation in this field.*

Keywords: Respiration, Nasal airflow, Septal perforation, Airflow patterns, Numerical modelling.

1. Introduction

Respiration is one of the basic physiological functions of the nose. Other functions include the olfactory function, as well as reflective activity ensuring protective reflexes (e.g. sneezing) and the immune function. Pathological-anatomical changes, such as the deviation of the nasal septum, septal perforation, hypertrophy of the lower nasal concha, accidents of the external nose, etc., often result in changes in the physiological functions of the nasal cavity, pathophysiological changes in the dynamics and characteristics of airflow in the nasal cavity – from mostly laminar airflow to turbulent flow and the consequent negative effect on the mucous membranes of the nasal cavity. These changes often lead to the drying of the nasal mucosa, formation of nasal crusts, recurrent epistaxis, decreased immunity, pain and obstruction of nasal breathing due to an increase in nasal resistance, with a direct impact on the quality of patients' lives.

Therefore, it is important to address the biomechanics of the problem (i.e., a multidisciplinary medical-engineering view of the flow during respiration in the nasal cavity with a normal and perforated septum). Numerical modelling is performed using the finite volume method (the program ANSYS/Fluent).

2. Anatomy of the Nose and the Nasal Cavity

The external nose has the shape of a triangular pyramid; we distinguish the nasal dorsum (dorzum nasi) which ends in the nasal root (radix nasi) at the top and the nasal tip (apex nasi) at the bottom. Lateral walls of the nose form the nasal wings (alae nasi). In the front part of the nasal wings and nasal septum, cartilages – cartilago alaris major, nasi lateralis and septi nasi – are the basis of the nasal bone. For the nasal dorsum and root, nasal bones and frontal projections of the upper jaw are the osseous base. The lateral, upper and middle wall of the nasal cavity, and simultaneously the base of the anterior cranial fossa and medial wall of the eye socket are formed by the ethmoid bone (os ethmoidale), which is inserted into

* Assoc. Prof. M.Sc. Karel Frydrýšek, Ph.D., ING-PAED IGIP: Department of Applied Mechanics, Faculty of Mechanical Engineering, VSB-Technical University of Ostrava; 17. listopadu 15/2172; 708 33, Ostrava; CZ, karel.frydrysek@vsb.cz

** Assoc. Prof. M.Sc. Sylva Drábková, Ph.D.: Department of Hydromechanics and Hydraulic Equipment, Faculty of Mechanical Engineering, VSB-Technical University of Ostrava; 17. listopadu 15/2172; 708 33, Ostrava; CZ, sylva.drabkova@vsb.cz

*** M.D. Marek Plášek, Department of Otorhinolaryngology, University Hospital Ostrava, Faculty of Medicine, University of Ostrava, 17. listopadu 1790, 708 52 Ostrava, CZ

incisure of the frontal bone. The side wall of the ethmoid bone is supplemented by the upper jaw, lacrimal bones and lower nasal conchae, see Hybášek et al. (2013).

The nasal septum (septum nasi) divides the nasal cavity into two, under physiological conditions, nearly symmetrical halves. The nasal septum that is not deviated has a role in physiological predominantly laminar airflow. It is divided into three parts – the membranous, cartilaginous and osseous part. The base of the cartilaginous part is the cartilago septi nasi; the osseous part consists of the vomer and the vertical lamella of the ethmoid bone (lamina perpendicularis ossis ethmoidalis), see Hybášek et al. (2013) and Kennedy et al. (2012). At the front, the nasal cavity is surrounded by the nostrils, at the transition to the nasopharynx through choanas, in front of the nasal cavity (cavum nasi proprium), the nasal vestibule (vestibulum nasi) is located, which is lined with skin with adnexa. The nasal cavity is lined with respiratory epithelium (double columnar ciliated epithelium), and it is divided by nasal conchae (lower, middle, upper) passing from the lateral nasal wall to the individual nasal passages – the common one (meatus nasi communis) located in the nasal septum, and three side levels – lower, middle and upper nasal passage (meatus nasi inferior, medius and superior), see Hybášek et al. (2013).

3. Physiological Functions of the Nose

The essential function of the nasal cavity is the respiratory function. In the process of breathing, the nasal cavity plays an important part; it has three basic functions – cleaning, heating and humidifying the inhaled air. At rest, air flows through the nasal cavity at the speed of about 5 litres/minute at a load of up to 70 litres/minute. Slot-like cross-section of the nasal cavity shows that it is adapted for the laminar flow of air – a significant role in this process is played by the nasal septum without deviation. The turbulent flow occurs at places of extending the space beyond the narrowed areas, e.g. beyond the rear ends of the nasal conchae, beyond the nasal valve, beyond the deviation of the nasal septum, and also in the area of the perforation of the nasal septum. During respiration, the resistance of the nasal cavity is about 8 - 20 mm of the water column; if increased air exchange is needed, the area of the nasal valve is widened by the external nose muscles by opening the nostrils; if the resistance rises above 40 mm of the water column, we also need to start breathing through the mouth to cover higher claims for air exchange (e.g. in sports). At inspiration, the air temperature is 31 - 36 °C, namely even at sub-zero temperatures of the air of the external environment; this constant temperature significantly protects mucosa of the lower airways. The nasal mucosa moisturizes the air to a value of 75 – 80 % in the nasopharynx; the air is further humidified during the passage through the airways up to 95 – 100 %. The mucous membrane of the nasal cavity is protected from drying by mucus produced by seromucous and cup-shaped cells, see Kennedy et al. (2012). Other functions of the nose are the olfactory and immune function.

4. Septal Perforation

Perforation of the nasal septum, see Fig. 1 is a relatively frequent clinical problem in rhinology. Patients with this disease suffer from dryness of the nasal mucous membranes, increased formation of nasal crusts, recurrent epistaxis, nasal breathing pain and obstruction; an annoying whistling sound often occurs when

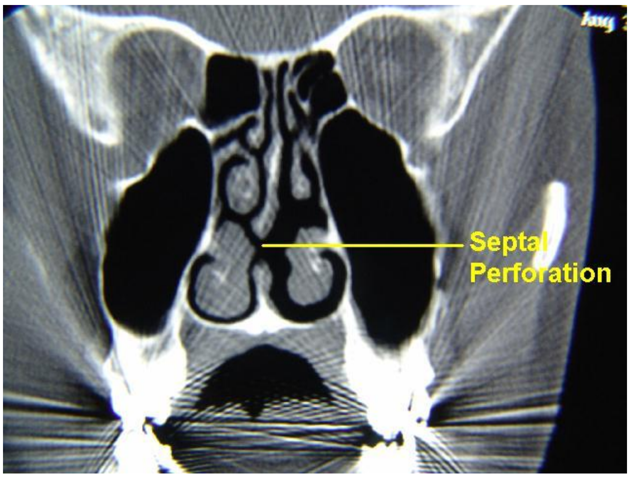

Fig. 1: Septal perforation (CT image in the frontal projection).

breathing in, see Romo et al. (1999). Perforations are often iatrogenic after interventions on the nasal septum (septoplasty, bipolar electrocoagulation). Another cause may be systemic inflammatory diseases (e.g. granulomatosis with polyangiitis), abuse of anemization drops, sprays, cocaine, etc. The cause often remains undetected; these perforations are then idiopathic, see Kharoubi (1998). Generally, the pathophysiologic mechanism of alteration of the nasal mucosa and the development of clinical symptoms is characterized as a change in the laminar flow of air in the nasal cavity to turbulent flow, see Fairbanks (1980).

5. Numerical Modelling

The simplified box model was defined based on a physical experiment presented by Grützenmacher et al. (2005). The basic dimensions of the so-called Mink′s box were: L = 100 mm, w = 30 mm and h = 10 mm. The septum was represented by the partition 80 × 4 mm. Simulations of incompressible transient flow were run in double precision using the two-dimensional turbulent viscous solver ANSYS/Fluent Release 16.2. The discretized Navier–Stokes equations were solved on unstructured meshes using the finite volume approach. The renormalization group (RNG) k-ε model, adapted for turbulent flow of low Reynolds numbers, was applied. Viscosity and density of air were set to 1.7894×10^{-5} kg.m^{-1}.s^{-1} and 1.225 kg.m^{-3}. The walls were modelled as rigid with no-slip boundaries. Pressure condition with zero gauge pressure was defined at inflow and the boundary condition at the exit from the domain was set to mass flow inlet with the desired mass flow rate. Three values of the flow rate were assumed: 50 mls^{-1}, 250 ml.s^{-1} and 500 ml.s^{-1}.

Four series of simulations were carried out, firstly without the septum perforation, followed by three different locations of 15 mm septum perforation illustrated below (see Fig. 2 and Fig. 3). Velocity, pressure field and turbulence parameters were evaluated for each geometry modification.

6. Results

In all cases the flow was symmetrical and turbulence in the domain increased with the increasing flow rate. To illustrate the influence of the perforation, a filled contours plot is presented for the flow rate of 500 ml.s^{-1}. Effective viscosity was evaluated. The laminar viscosity 1.7894×10^{-5} kg.m^{-1}.s^{-1} can be observed at the inflow. In the case of intact septum, the flow along the septum walls exhibits a low value of turbulence. The amplitude of 1.21×10^{-3} kg.m^{-1}.s^{-1} can be observed in the sharp corners at the top of the model.

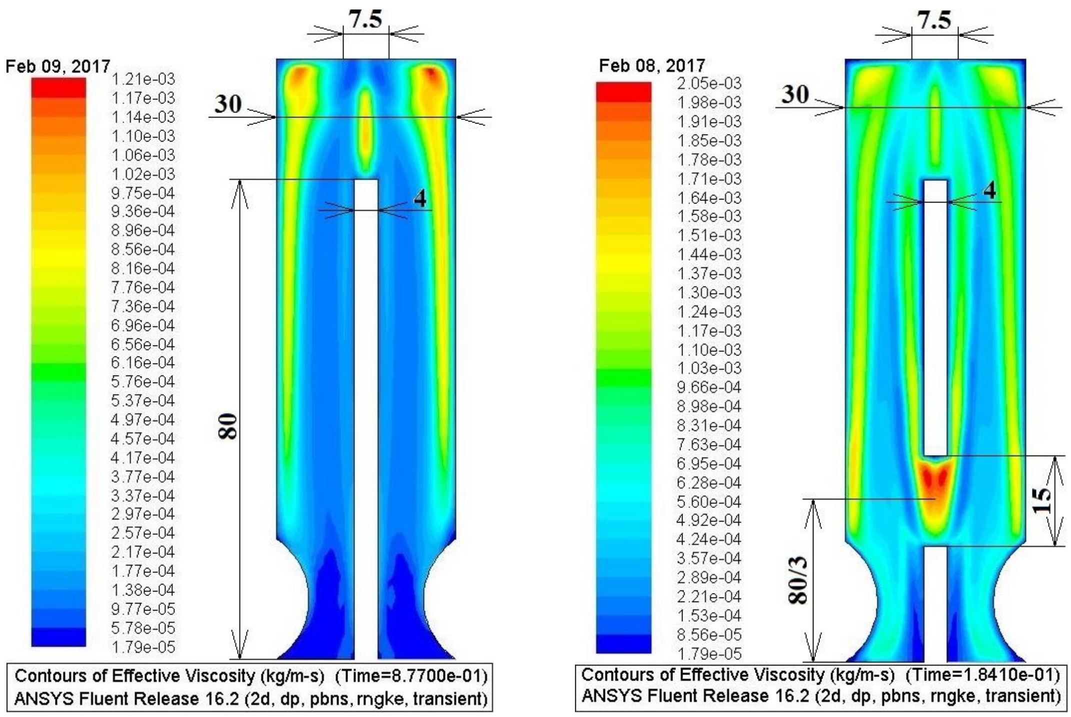

Fig. 2: Evaluation of effective viscosity for: a) intact septum; b) perforation located at 1/3 of septum length.

Effective viscosity distribution and airflow patterns within the model change in the case of perforation. In a gap the flow stagnates and two counter-rotating vortices develop. In the case of perforation, the effective viscosity increases by about 70 %. Turbulence increase can be observed also along the septum walls mainly above the perforation (see Fig. 2b and Fig. 3).

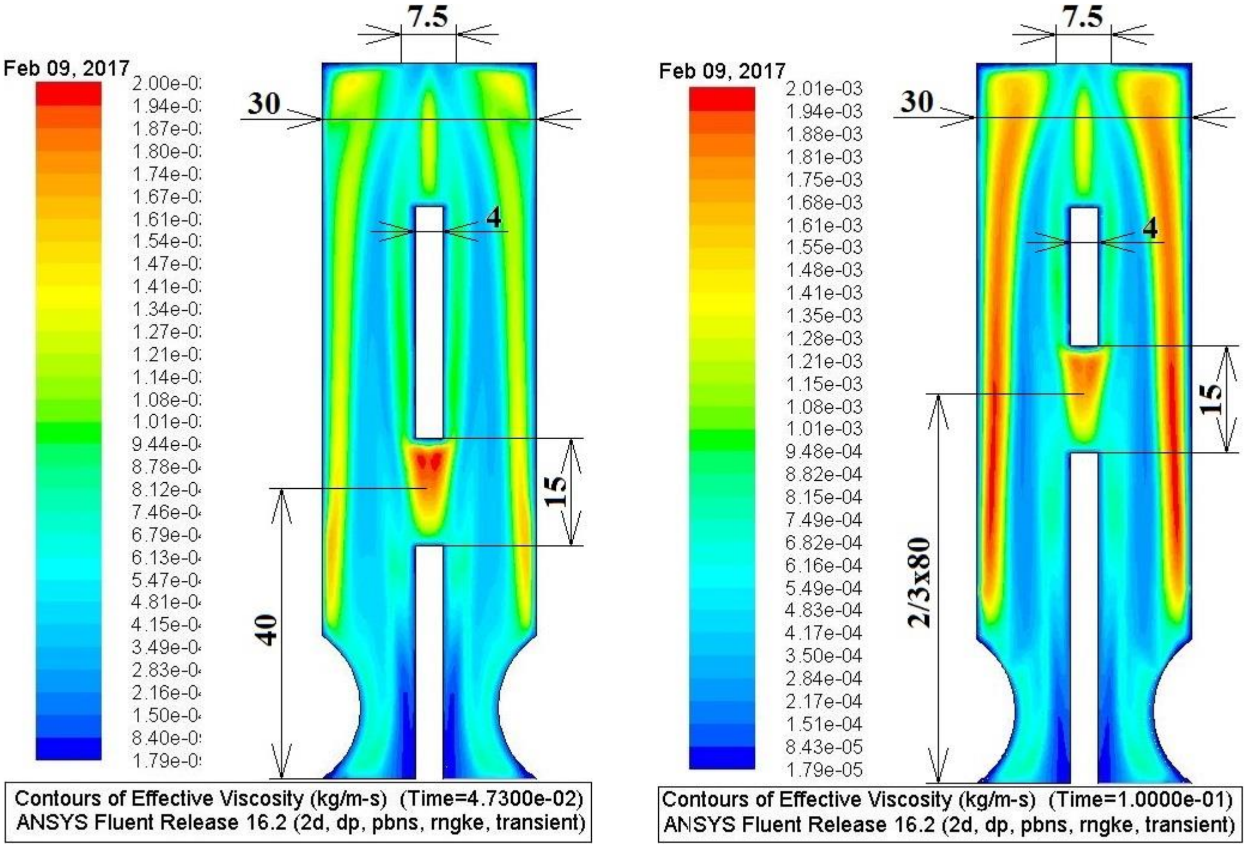

Fig. 3: Evaluation of effective viscosity for perforation located at: a) 1/2 and b) 2/3 of septum length.

7. Conclusions

Septal perforations are avoidable complications of septal surgery, but they can also occur because of a variety of traumatic, iatrogenic, caustic, inflammatory etc. reasons.

The results of numerical modelling of respiration in the nasal cavity show an undesirable increase in effective viscosity by about 70 % in cases of septal perforation. The results can serve as a basis in the decision-making in treating patients.

Acknowledgments

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