A Review on Numerical simulations of the nasal cavity for understanding the nasal structure

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Abstract - To perform, close to perfect and accurate surgeries on either the inner or outer portion of our body, doctors need to have a very good understanding of the working and behavior of that organ or the muscle. In this paper, we try to present different methods brought forward in research which prove mathematically that the nasal cavity is affected highly on the outside sources and conditions in which the person is living. It is then supported with a solid foundation of simulation done on the software; simulation techniques strengthened the mathematical methods by exploring the better results. The result concludes the dependency on the environmental conditions in which one person lives with the nasal cavity.

Keywords – Experimental data, Nasal Cavity, Numerical Simulation, Navier-Stokes Equation, work-bench.

I. INTRODUCTION

Our nose structure is very delicate; it acts as a defense for our respiratory system. It acts like one filter to separate the dust from the air we breathe in. So far medical science to get benefits from mathematics and computational modelling for a better understanding of this precious organ we tried to review the most edge research among the airflow simulation and statistical approach throughout this paper. When we take unusually hot air through our respiratory tracts they get damaged, which is a huge problem for people who work under extreme conditions like fire workers, miners, and factory workers, it is explained how do these affect our windpipes and nasal tracts, using HRT (Hormone Replacement Therapy) model and computational fluid dynamics. To create an image for these case researchers used Magnetic resource imaging (MRI) and computer axial tomography (CAT) and then analyzed it. In one study TanJ et.al (2012), researchers have tried to diversify their understanding of nasal cavity and to do so they have taken twenty-six samples from Northeast China randomly and evaluating them through rhinoscopy and endoscopy they designed a computational model using software named ANSYS and some methods from previous researches for this so that to get the best possible outcome[1]. In another research, R. Möges (2010), the researcher used Grid Pro software and particle image velocity methods combined into a single model for numerically simulating the noses' airflow and making certain calculations of the air passing through the nose to get the understanding of the muscular movement inside of the nose while inhaling and exhaling this was done by taking the bone model and muscular model combined and then evaluating the flux and Reynolds number value[10]. In this part authors divided the nasal structure into two different parts one being Partial Removal Middle Turbinate (PRMT), Partial Removal of Inferior Turbinate (PRIT) these were sampled over twenty-six people. Using this, statistical data
research was conducted on the study of the distribution of heat throughout the nose while inhaling and exhaling, flux changed on several different parameters. These researches provide high value for making a better and easy understanding of complex structures in medical science to junior doctors and nurses also.

II MATERIALS

To calculate the dependency of flux, heat, dust and many other factors to the flow of air in the nasal cavity, researchers applied different statistical models and mathematical equations. The most used equation by the researchers in this nasal cavity domain was Navier Stokes Equation. This is because it works on the principle of conservation of mass, energy, and momentum in an object.

\[
\frac{\partial u}{\partial t} + u \cdot \nabla u = -\frac{\nabla p}{\rho} + \partial \nabla^2 u
\]

It is also called continuity equations and since authors are modelling the flow of heat inside the respiratory tract, an equation that worked on the conservation of energy was required. Next to the Navier Stokesequation a five-step Runge–Kutta method of the second accuracy in temporal integration was used and the coefficients were optimized for a central scheme. The expression for this method shows the calculation for inviscid fluxes \( F_d \) which then gets split into convective and a pressure term the final expression will be having one parameter as \( c \) which is the speed of sound – \( c \).

\[
F_d^l = F_d^c + F_d^p = \frac{u_a}{c} \left( \frac{\rho c}{\rho c(E + p/\rho)} \right) + \left( \frac{0}{p} \right)
\]

Breaking the equation as :

The generalized frame of references, \( \xi_a = \xi_a(x_\beta) (\beta = 1, 2, 3); (\alpha = 1, 2, 3) \). \( \mu_\beta \) and \( U_a \) are quantities that represent Cartesian and the contravariant velocity component which is \( U_a = u_\beta \frac{\partial x_a}{\partial x_\beta} \), where \( \frac{\partial x_a}{\partial x_\beta} \) is the Numerical flux on the single-cell face was calculated as

\[
F_d^c = \frac{1}{2} \left[ M_a^+ + M_a^- \left( f_d^c+ + f_d^c- \right) \right] + \frac{M_a^+ + M_a^-}{2} \left( f_d^c+ - f_d^c- \right)
\]

Where \( f_d^c \) are flux and Mach number determined by left and right interpolated variables that are obtained using a Monotonic Upstream Centred Schemes for ConservationLaws to approach for the primitive variables.

Jun Zhanget.al (2009) used a part of Navier stokes equation by giving their own parameter according to the research output they wanted. Here authors analysed their method completely with different data points. \( \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0 \) \( \frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + u_y \frac{\partial u_x}{\partial y} + u_z \frac{\partial u_x}{\partial z} = \frac{1}{\rho} \frac{\partial p}{\partial x} + f_x + \nabla^2 u_x \)

Where, \( u_x, u_y, u_z \) are the speed variables, \( p \) is pressure, \( \rho \) is the mass-density of air and \( v \) is its dynamic viscosity coefficient[13].

The nostril was made directly open to the atmosphere with certain pressure boundary condition \( P\Omega_l = 101325 \)Pa. The non-slip boundary condition: \( u_0 = 0 \) was chosen on the inner wall. Velocity boundary condition was given at the top cut of the oropharynx. The regular inspiratory capacity for a relaxed, steady inhalation/exhalation is 400–600 ml per time, with an inspiratory rate of 15-25 breath /minutes, using the higher value in calculations 600ml[11]. An assumption was taken as defining the inhalation and exhalation period to be for 3 seconds and also that the airflow speed changes linearly with time at exhalation as shown in Fig.2; The vertical axis showed airflow flux (cm²/ s) and the horizontal axis showed time( s ).
Point ‘a’ shows the highest value of airflow flux in the inhaling period. Point ‘b’ shows the highest value of airflow flux in the exhalation period. At the exit section the peak flowing speed is calculated through $u = \frac{Q}{0.75S}$, where $Q$ is the tidal volume; $S$ is the cross-sectional area at the exit [9]. The airflow was explained as transient-state turbulence flow by the governing equations (1) and (2).

To understand the effect of heat on the different part of the nasal cavity inside the nose was studied by another group of researchers for with their choice of methods which was using the $\Delta T$ method for the differences in the parts of the nose,

$$\Delta T = \alpha \times f \text{ where } 1.5 < f < 3,$$

Where parameter.

$$f = (\log l/\log V)$$

This was used to explain the way our nose geometry and airflow flux works, where $S$ and $l$ are the surface area and length of the nasal cavity and $V$ and $Q$ are the volumes of the nasal cavity and airflow flux. The temperature contrast($\Delta T$) under nostril was used to show the nasal capacity [4]. It can be considered static or linear relationship approximately between parameter $f$ and temperature when $1.5 < f < 3$, shown as the correlation coefficient $\rho$ was 0.51 respectively, related to the two fitting curves [8].

### III METHODS

With the word on the nasal structure we searched the most viewed articles on online and in journals. We analysed the open access journals; the passage of air on the nose. Most of the researchers used the common available libraries and software for making calculations and simulations on the data points collected through the statistical sampling of data on several different classes of people [3]. Software like ANSYS with CFD (Computational Fluid Dynamics) libraries. It is a powerful software for simulating dynamic models or machine parts and allows perform several tests on that model like crashing of system, and pressure tests. It consists of a workbench which is the most commonly used version used by researchers for the simulation. The model is generally constructed using an MRI scans of a group of volunteers. The model is then run through a series of iterations (200 or greater) depending upon requirement [12].
Figure 3. Sagittal views of the normal cavity model and its two variants.

Figure 4. The velocity (left), pressure (middle) and vector (right) plot at the moment of point ‘b’.

Figure 5. Extraction position of characteristic dimensions

Airflow distribution in the nasal cavity. Fig 4 is a simulation of female nose structure. One part was selected to show the velocity distribution (Fig. 4.left) and speed (Fig. 4.right) vectors show the airflow path in the nose model at particular point of ‘b’. The symmetrical pressure drop is shown in Fig. 4 middle. At the point of ‘b’ shows the exhalation airflow flux and the pressure drop at their highest value[5]. The drastically high airflow velocity was recorded in the region of nasal valve however it is not always like this instance, many representative of speed distribution graphs are shown in Fig. 5. This figure explained how the air distribution and air flux in one side of nasal cavity is different from other side. Taking the result there are 3 different nasal airways:
1. In which air passed through the common nasal meatus and little passed through centre and inner nasal meatus (shown in Figure 5 left). In it airflow flux that passed through common meatus was about 56.6%

2. Main air passes through inner nasal meatus and common nasal meatus (shown in Fig 5 middle). Airflow flux is about 60.5%

3. Air passes through centre nasal meatus and common meatus (shown in Fig 5 right). Airflow flux is about 77.0%.

In the 30 experiments, 7 followed the first mode, 7 followed the second mode, 16 followed third the mode. In these samples airflow region was about 3cm wide and resulted in 50.5%~77.8% nasal airway resistance.

IV ANALYSIS

The most commonly used equation in the reviewed papers is the Navier-Stokes equation which governs most of the computations of fluid dynamics. This equation enable us the better understanding in flow of air inside our nasal cavity as it deals with Lagrangian calculation of fluid motion is based on closely keeping track of a fluid particle which is huge so that it’s properties can be detected. Between the initial points at time $t_0$ and points of the same particle at time $t_1$ hundred thousand of separate particles have to be precisely calculated through the path that is difficult or impossible to follow. In the Eulerian method, any specific particle across the path is not followed, whereas the velocity field as a function of time and position is calculated[6]. This equation can be used with parameters which defines the law of mass and momentum conservation which makes it very efficient.

These papers failed to consider the deposition of hazardous particles along the tract during oronasal breathing while simulating the model. Also the extent of the damage to the upper respiratory tract was not clear in the simulation models, although these issues can be topics of further research. A group of researchers modelled the flow of air in the nasal cavity using AUSM and compared it with experimental data to find a good similarity in results of both approaches. The finding revealed that the flow inside the nostril is laminar and steady with Reynolds number of 1560 and 1230 at inspiration and expiration respectively[7]. Unlike most, here the results of both approaches are compared and hence verified. The research fails to acknowledge the flow obstructions caused due to impurities in the air, bodily fluids and tissues. The entire cavity is assumed to be a single piece of bone which is misleading.

Kambiz Farahmand et.al. (2012) used 30 volunteers who belonged to Northeast China in an effort to observe the change in airflow rate, pressure drops and velocity distribution in the nasal cavity[2]. The research can be of immense medical usage when considering medical treatment of people belonging to different nations or regions. The nasal vestibule, valve, and nasopharynx were assumed quadrilateral and the meatuses were simplified as corners. CT scans were used over any other scans because each coronal image could be linked together form a 3D model. This method provides a good way to model nasal cavities as per region of birth and can be used repetitively to model various regions in a country.

V CONCLUSIONS

The human nasal cavity and the entire respiratory tract are essential parts of the human body and therefore the knowledge of human airflow is important. The main airflow passes through a wider portion i.e. the common nasal meatus or the intersection of common nasal meatus and middle nasal meatus. The temperature analysis of the upper HRT shows that the temperature decreases as the heat is absorbed when air travels further down in the respiratory tract. The information extracted via CFD analysis of HRT is important in preventing injuries and in development of devices which can cool the inhaling air to a normal range.

In understanding the operations of the nasal cavity, it was important to observe the effects of surface area, length, and the volume of nasal cavity on the airflow flux. Since specific geometries of images were chosen above others, an accurate model of the heat exchange process was constructed wherein the conservation of heat and mass were prime objectives. The calculations and simulations are worthless in their entirety if they are not juxtaposed against experimental data. Hence, numerically simulated data at inspiration and expiration was compared with the experimental data to find a satisfactory similarity which strengthens our understanding of the nasal cavity and the human respiratory tract.
VI  FUTURE WORK AND APPLICATIONS

The entire research on airflow patterns in the nasal cavity has immense potential for further work. Medicine and healthcare still have a long way to go and since human respiratory tract is an important segment of the human body, it is imperative that continuous research must take place. The preliminary tests as summarised above have revealed that multiple areas in the system like heat transfer, demographic analysis, etc are major topics of research.

Applications

- Development of a flow solver used to analyze the flow of air and gases within the nasal cavity. Useful for surgeons in improving the breathing capacity of patients.
- Improved respiratory devices to cool down the air inhaled by firemen and miners to protect the inner tissues. Further research might include the effects of hazardous particles inhaled during breathing on the respiratory system.
- Creation of different models as per the demographic origin of the people. It can be useful to treat patients belonging to different nations with utmost precision and customised care.

References