Journal of Advanced Research in
Numerical Heat Transfer

Journal homepage:
https://semarakilmu.com.my/journals/index.php/arnht/index
ISSN: 2735-0142

Effect of Septum Deviation on the Airflow Distribution for a Patient Specific Model using Numerical Methods

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ARTICLE INFO

Article history:
Received 8 June 2023
Received in revised form 5 July 2023
Accepted 9 August 2023
Available online 30 September 2023

Keywords:
Septal deviation; Nasal cavity; Turbulence Flow; RANS Model; Wall shear stress; ANSYS Fluent

ABSTRACT

Septal deviation (SD) in nasal cavity plays a crucial role in symptoms related to nasal obstruction, aesthetic appearance of the nose, and increase in nasal resistance, and may induce snoring. The aim of the present study was to evaluate the significance of SD on the air flow behaviour and compare its deviation with a healthy nasal cavity by using CFD. A 3D CAD model of subject specific nasal cavity was generated from CT images of patient with septal deviation. The variation of maximum WSS observed in the present study was higher when compared with that of normal subjects. In contrast to the healthy subject, the airflow in the septal deviation models showed asymmetry in bilateral nasal cavities. The maximum velocity inside the nasal cavity exceeded the value that was usually found at the nasal valve region. The findings from this study help understand the basic aerodynamics in a severely deviated septum.

1. Introduction

The recent advances in numerical capability has seen profound enhancements in aerodynamics of air flow in nasal cavity. More than 80 percent of all nasal septum is estimated to be generally off centered and found to have deviation from midline and is shown to be a normal occurrence [1]. The major medical complications are associated with a severely deviated septum which is associated with breathing inconvenience. Some of the other known symptoms for SD ranges from usual known congestion on one side of the nasal cavity to nosebleeds, headaches, pain in facial portion, sinus infections and snoring [2]. Most widely used clinical treatment for SD is septoplasty to correct the deviation and on few occasions, followed by clinical procedure known as Rhinoplasty carried out to modify the morphology in nasal cavity [3-5].

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https://doi.org/10.37934/arnht.14.1.4957

Several studies have reported deterioration of quality of life in patients with nasal obstructive disorders such as septal deviation. The deviated septum often causes olfactory deficiency and higher olfactory thresholds [1-6]. It is also observed that substantial deviation in nasal septal region has impaired the smell sensing ability from the obstructed nostril [4]. Pfaar et al. observed that before there existed clear relationship between odor threshold levels and nasal obstruction, which decreased significantly post septoplasty [7]. The connection between olfaction in humans and nasal anatomy and later changes in structure of upper nasal cavity and also changes in olfactory ability was correlated and established as reported in Ref. [5,6].

Many of the previous studies have explored airflow characteristics of nasal airway using computational fluid dynamics techniques. Zubair *et al.,* [8,9] determined the fundamental flow parameters interior region of nasal cavity. It was established that, low velocity re-circulatory air at the olfactory region helps in retaining the flow for longer duration, which aids the smell perception. This has been experimental validated by their studies carried out using particle image velocimetry [5,6].

Even though previous studies have evaluated effect of septal deviation in terms of airflow in nasal cavity, its effect on airflow distribution over the turbinates are not reported. Also barring some studies by Zubair *et al.,* [9], Zhao *et al.,* [10], and several other investigators [11,12] were unable to correlate the uni-nasal airflow measurements directly and associated olfactory function in SD cases. Enhancement in smell sensing ability can be largely attributed in significantly developing the nasal airflow and thus leading to improve the sensing ability to smell substances. The desired deviations in airflow of individual nasal cavity and intranasal volume can certainly influence to improve the olfactory function. Thus, in the present investigation the outcome in terms of olfactory function of patient specific septal deviation model due to septal deviation was investigated [13].

Present study focus on generation of 3D patient specific model using Computed Tomography (CT) scan images and the influence of septal deviation on the air flow behaviour was investigated. The outcomes were correlated with a control model, a healthy nose without any nasal complications using the same procedure adopted for the SD case study.

2. Methodology

2.1 Theory

Navier-Stokes equations for the continuity and momentum was adopted in the present study for air flow simulation as shown in the Eq. (1):

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

The conservation of mass and momentum for incompressible fluid in three dimensions is given as

$$u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left((v + v_t)\frac{\partial u_i}{\partial x_i}\right) \tag{2}$$

The kinematic viscosity is calculated the using appropriate turbulence model. The behaviour of airflow in nasal cavity is presumed to be steady and incompressible. “Turbulent Flow, SST” Reynolds-averaged Navier–Stokes equations model, is used to capture the air flow velocity fields. This adopted turbulence model has proven to capture and estimate the wall bounded flows with good numerical comparability even in complex flows such as highly flow separated regions. The SST component in this turbulence estimation merges the efficacy of both the $k-\epsilon$ and $k-\omega$ models. The $k-\epsilon$ turbulence model provides a very good near-wall treatment and as a special case, nodes present closer to the boundary vicinity are accumulated without any requirement of function of non-linear damping nature. However, the $k - \omega$ turbulence model is much better and more precise in air flows especially those which involves streamlines curvature.

2.2 Modelling and Analysis

Present investigation focus on numerical simulation carried out on a subject specific septum deviated nasal cavity. The 3D geometrical reconstruction of the septum deviated nasal cavity was developed similar to our previous works presented for a healthy nasal model [13, 14]. Figure 1 provides the axial and coronal view of the patient under consideration for this study. It was found that, the septum deviated towards the extreme left and touched the left wall thereby completely obstructing the flow inside the left cavity. A deviation of more than 25 degree was observed for the present case as shown in the Figure 1B.

(a) (b)

Fig. 1. Septum deviation CT scan: (a) Axial view, (b) coronal view

The segmentation of the CT scan images was carried out using MIMIC (Materialise, Ann Arbor, MI). Appropriate threshold values are required to distinguish the bone from the nasal wall and it differs marginally from case to case. The 3D masked data of the captured nasal cavity was later edited and refined with surface smoothening in CATIA (Dassault Systems,SA). 3D CAD geometry of nasal cavity was meshed using hybrid mesh technique having unstructured tetrahedral elements at the core and prism layers at the wall maintaining a y+ <3. Pilot study to evaluate the airflow at a flow rate of 20 L/min was carried out on an initial meshed model comprising of 106,393 cells. The optimized grid was obtained through grid independency test comprising of 500,000 elements for the septum deviated case. The numerical simulation was carried out using the ANSYS FLUENT solver.

The numerical simulation in present study was performed on the solution strategy based on Navier-Stokes equation used for solving 3D incompressible flow and viscous fluids in accordance with previous studies [5, 8, 10, 11]. The SST k-ω turbulence model, a two-equation turbulence model was adopted and Mylavarapu *et al.,* [12] have experimentally validated the suitability of the SST k-ω model. The concept of plug flow method was adopted to apply the boundary conditions as observed in the previous studies [8, 10, 11]. The presence of mucus in was ignored in the present numerical simulation and complete boundary of nasal cavity was assumed to be rigid. Exterior region of nasal cavity was applied with no-slip boundary condition, and mechanism of inspiration was applied at the nostril inlet using concept of mass flow inlet boundary. However, outflow boundary condition was applied at the outlet. Mass flow boundary values were adopted to define the expiration using nasopharynx region with nostrils considering pressure outlet boundary values. The turbulence intensity factor of 10% was adopted in the present numerical simulation at inlet. Also, the y+ value of well less than 5 was assumed at wall region. The wall functions were completely ignored during modelling the effects of viscous flow. Laminar flow during steady state was considered along with the turbulent airflow during modelling and simulations. At nostril inlet for different flow rates such as 15 L/min and 20 L/min, estimated Reynolds number was found to be 1600 and 3100 respectively. Therefore, the airflow was considered to be laminar for flow rates up to 15 L/min and turbulent beyond 15 L/min. This observation is similar to the previous studies who investigated the laminar flow behaviour for flow rate less than 15 L/min [13,14]. Flow properties were assumed to be having constant air density of 1.217 kg/m^3 and viscosity of 1.87×10^{-5} kg/m/s. The numerical simulation is carried out using ANSYS Fluent solver on a high end workstation with IBM platform, Intel, Xenon(R) CPU, 16 GB RAM and duration of two days for the complete simulation.

3. Results and Discussion

In the present study, significant changes in inspiratory airflow pattern in nasal cavity model with severe SD was investigated. The cross-section of passage in nasal cavity at different distances from the nostril is shown in the Figure 2. The encircled area highlights the deviated section of the nasal airway due to septum disorientation. It is observed that the major deviation was located in the main airway position which is very close to the middle turbinates. The region of SD as noticed in the Figure 2 starts at distance of 45 mm from the nose tip, further reducing the area of the nasal airway and the septum region is gradually shifted to the right side.

The limit of septal deviation from the midline portion is clearly observed from the Figure 2 and later undergoes an abrupt and sharp deviation of approximately 25 degree far from the midline region. This steep deviation has resulted in obstructing the formation of middle turbinates in the right cavity as observed from Figure 3 at a distance of 40 cm and 50 cm. Moreover, when compared to the normal nasal cavity on left side, the middle turbinates region is not visible even up to a distance of 58 mm as observed from the nostril tip. Further, deviated septum almost reached the lateral side of right nasal cavity and thereby impeding the flow passage completely in that vicinity. Later, the deviation terminates at the starting portion of the nasopharynx region [15].

For extrapolating the findings, the mid-section of the nasal cavity was divided into zone 1 and zone 2 as observed from the Figure 3. The volumetric flow rate in terms of percentage value was evaluated considering the total flow in the whole nasal cavity and tabulated in Table 1. It is clearly observed that flow variables in Table 1, especially the right side in zone 2 has been severely affected due to SD as observed in the Figure 3. Out of total flow, only 41% of flow was located in the left zone 2 region, whereas the similar zone on right side had only 19% of flow passing through that section. The SD has significantly influenced the changes in form of the asymmetry flow pattern caused due to anatomical deviation. This observation of airflow will certainly influence the volume of flow that reaches the olfactory region.

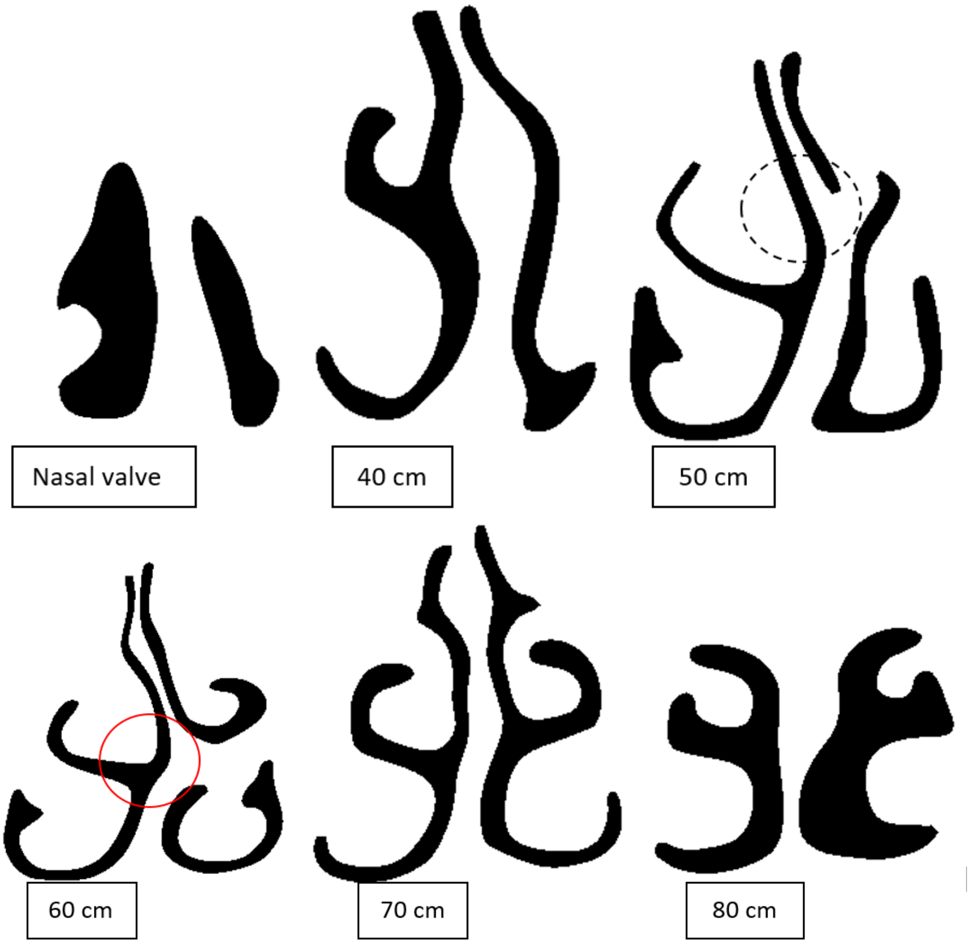

Fig. 2. Nasal coronal cross sections at various distances from nostril. Black area represents the airway passage. Circled area highlights the deviated section of the airway due to septum disorientation

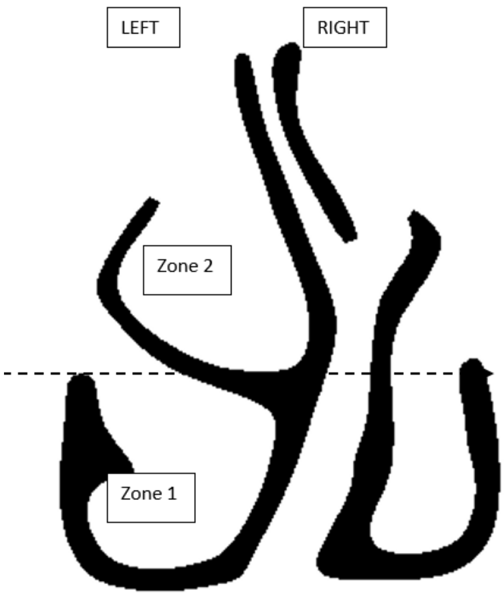

Fig. 3. A schematic diagram of a cross sectional plane depicting zone 1 and zone 2

Table 1
Description of comparative flow between right and left half of the nasal cavity

Region	Left Zone 1	Right Zone 1	Left Zone 2	Right Zone 2
% Flow	17.69	22.10	40.58	19.63
Maximum velocity (m/s)	2.0	2.78	2.19	3.0

Flow velocity distribution across the sagittal plane is as shown in the Figure 4. Velocity pattern has significantly increased in the entire anterior portion of nasal cavity on the right side as the flow pattern is affected by septum deviation. Nature of flow in form of jet is observed in this location due to limited flow in nasal cavity on right side with deviated septum. The maximum velocity observed at the anterior portion of nasal cavity on right side and nasal valve region is similar. Also, location of maximum velocity in particular is at the constricted region of nasal valve. However, as observed in the case of SD, the maximum air flow velocity was found to be located in the maximum septum deviation region of the nasal cavity on right half side. This abnormal behaviour in air flow pattern has resulted in severe affected comfortable breathing pattern. This behaviour is further established in form of cluster of maximum flow velocity as observed in the Figure 5, in anterior portion of middle-turbinate section on right side nasal cavity.

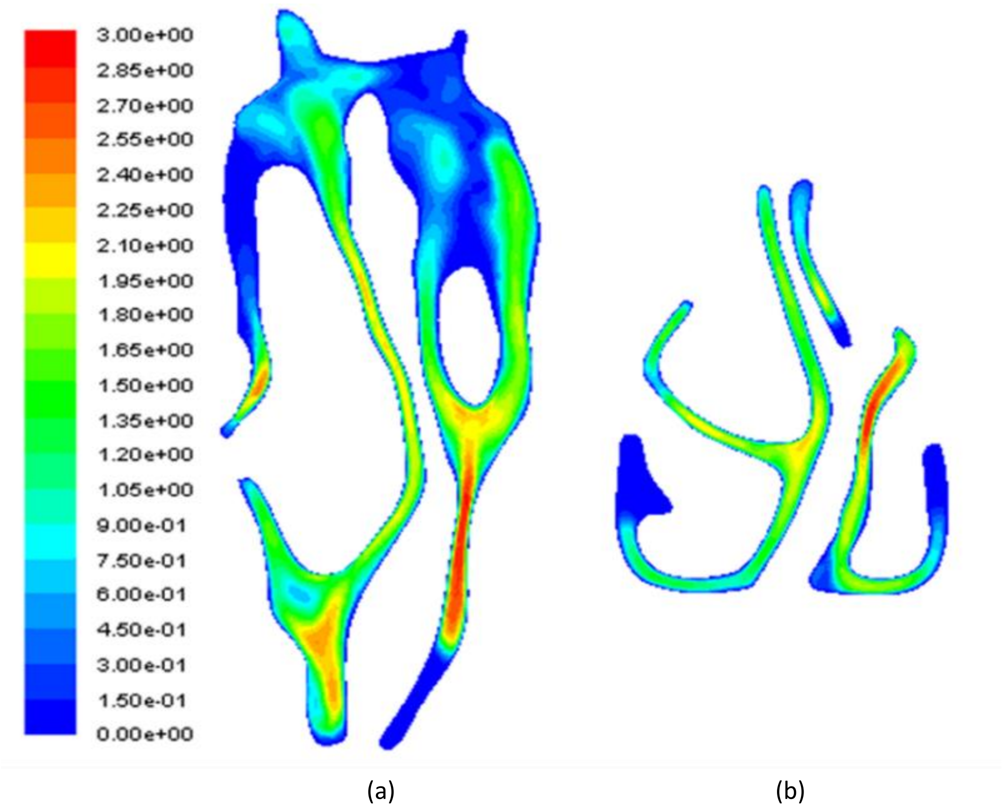

Fig. 4. Velocity contours for SD case: (a) sagital plane, (b) coronal plane at 50 mm from nostril

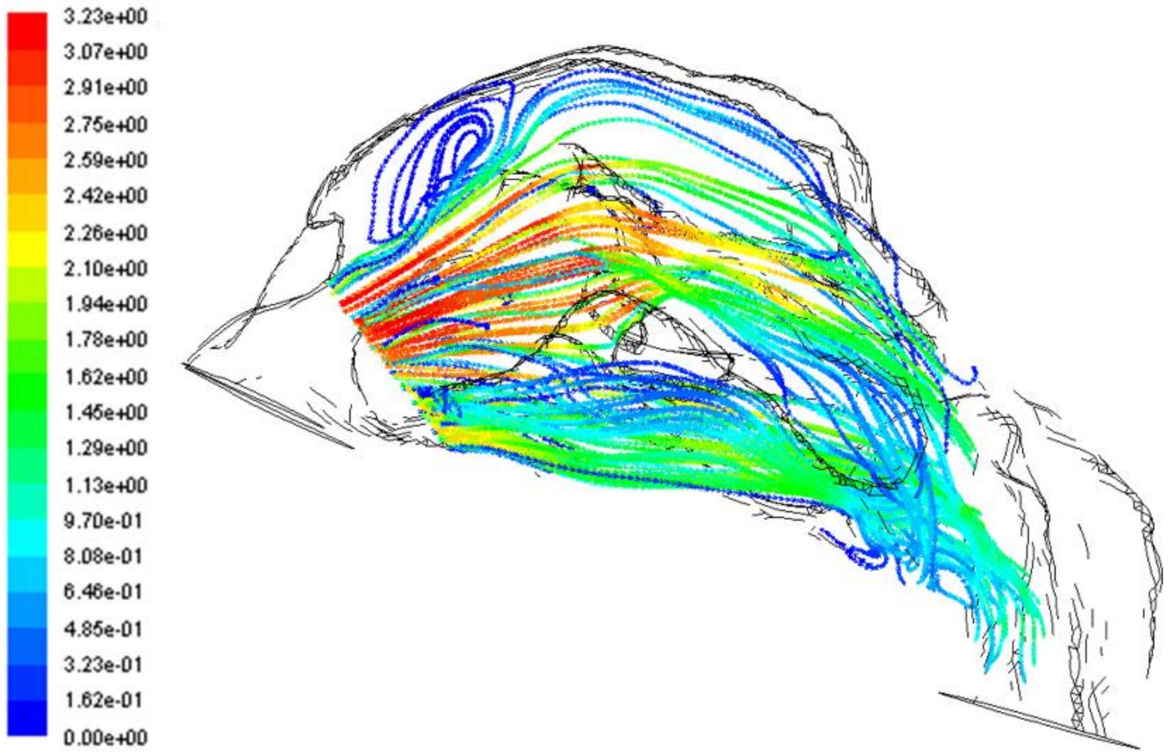

Fig. 5. Velocity streamline plot indicating maximum air flow velocity at the anterior side of middle turbinate portion on the right side nasal cavity due to deviated septum

Moreover, the occurrence of maximum velocity has resulted in severe WSS especially located along the deviated septum which is prominent along the walls of nasal cavity region. The effect of septal deviation is well established on the boundary wall of the nasal cavity as observed from Figure 6. There is an increased WSS as observed on the right nasal cavity walls especially on deviated side. This significant changes in WSS can be harmful to the normal and healthy breathing through nose because blood vessels can rupture under the influence of extremely high flow rates [16,17]. In addition to these flow rate fluctuations, cells associated with nerves in the close vicinity will also be affected. Perhaps this might be the one of the reason for recurrent symptoms of headaches as observed in severe SD cases [18]. Clinical doctors such as otolaryngologists will be highly benefitted in understanding the friction distribution pattern in interior region of the nasal passage of SD cases. Considering the air flow parameters, as investigated in this present study, the maximum value was found to be higher than that observed in normal subjects without any septum deviation. These major changes observed agrees well with the previous investigations and from clinical perspective, it can be correlated that the epistaxis (nose bleeding) is found to be more relevant as observed clinically in more cases who are diagnosed with deviation in septum region [19,20]. In the present investigation of numerical nasal cavity model with severe SD, the major changes were observed in the pattern of inspiratory airflow. In addition, the variation of WSS, was also established quantitatively and qualitatively. This CFD based study shall provide comprehensive fundamental understanding of the aerodynamic effects in septal deviation focusing on nasal airflow patterns considering related physiological functions.

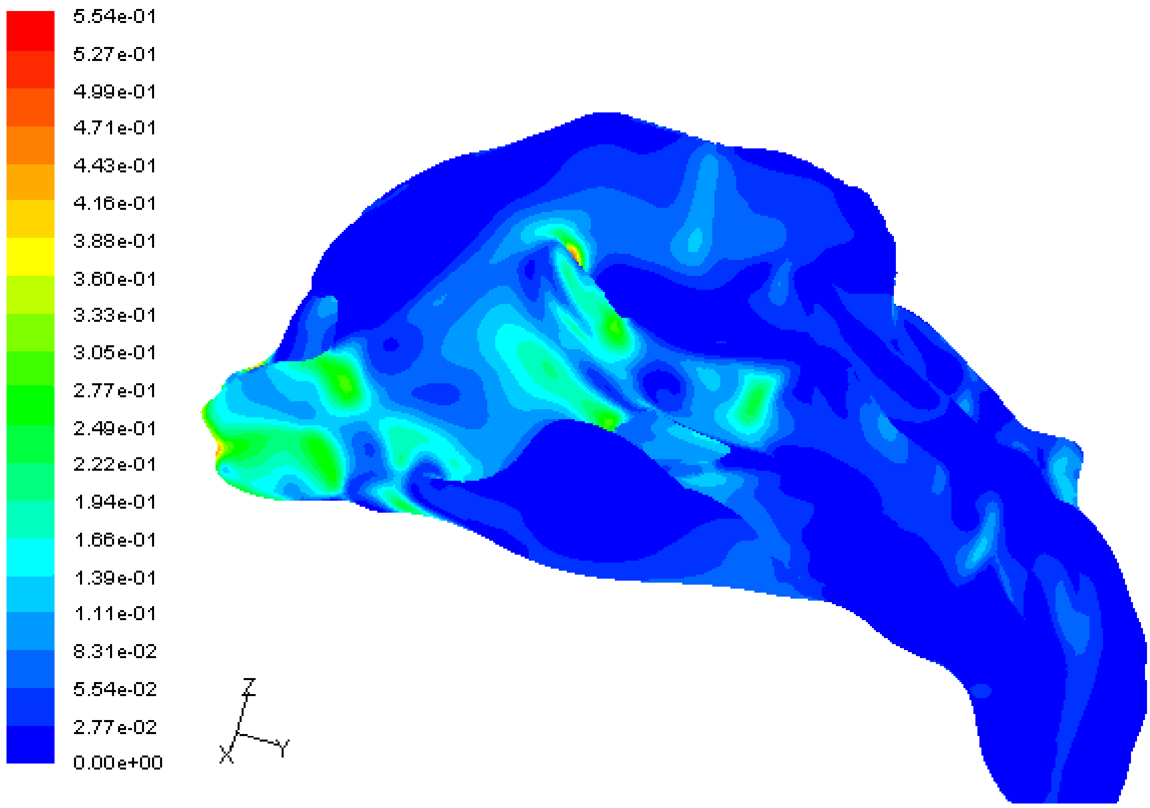

Fig. 6. Wall shear stress distribution for SD case

4. Conclusions

In the present study, a 3D patient specific model was generated using computed tomography (CT) scan data and the effects of deviation in septum region on the air flow behaviour was investigated using CFD. During investigation, it was observed that right side zone-2 was found to be severely affected due to SD. However, the left side of zone-2 section could permit only 41% of the total air flow, whereas the right side in this zone had only 19% of the total air flow through that section. The effected SD is pronounced in the asymmetry in the flow pattern that has generated due to anatomical deviation.

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