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Computer Simulations of Pressure and Velocity fields in Human Upper Airway during Sneezing

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Abstract

In this paper, the airflow field including the velocity, pressure and turbulence intensity distributions during sneezing of a female subject was simulated using a computational fluid dynamics model of realistic upper airways including both oral and nasal cavities. The effects of variation of reaction of the subject during sneezing were also investigated. That is, the impacts of holding the nose or closing the mouth during sneezing on the pressure and velocity distributions were studied. Few works have studied the sneeze and therefore different aspects of this phenomenon have remained unknown. To cover more possibilities about the inlet condition of trachea in different sneeze scenarios, it was assumed that the suppressed sneeze happens with either the same inlet pressure or the same flow rate as the normal sneeze. The simulation results showed that during a normal sneeze, the pressure in the trachea reaches about 7000 Pa, which is much higher than the pressure level of about 200 Pa during the high activity exhalation. In addition, the results showed that, suppressing the sneeze by holding the nose or mouth leads to a

noticeable increase in pressure difference in the tract. This increase was about 5 to 24 times of that during a normal sneeze. This significant rise in the pressure can justify some reported damages due to suppressing a sneeze.

Key words: CFD, Flow field, Oral cavity, Realistic airway model, Sneeze

1. Introduction

Sneezing is a semi-autonomous defending mechanism of the body used to drain the stimulants entering the nose. When the nasal mucosa is stimulated by the foreign particles, the sensitive nerve cells of the nose are irritated and they send a signal to a part of the brain named the sneeze centre. The brain responds through sending a signal to the chest muscles, contracting the lung muscles and a number of other organs, so that a large amount of air flows out impulsively from the lung. The explosive airflow then exits from the respiratory tract through the nose and mouth outlets at high speeds to remove the foreign particles from the airways.

There is a significant number of investigations in the literature which focused on different aspects of normal breathing and also coughing. Zhang and Lessmann (1996), Cebral and Summers (2004), Zhang and Kleinstreuer (2002) and Nowak et al. (2003) among others used an simplified geometry of the airways for the simulation of airflow. On the other hand, some other researchers used the CT-scan or MRI images to develop more realistic models of the respiratory system to study the normal breathing condition (Nithiarasu et al., 2008; Liu et al., 2002; Moghadas et al., 2011; Vinchurkar et al., 2012; Abouali et al., 2012; Tavakoli et al., 2012; Faramarzi et al., 2014; Naseri et al., 2014; Borojeni et al., 2014).

Malve et al. (2010) studied the unsteady turbulent airflow in the trachea using the FSI (Fluid Solid Interaction) technique during coughing. Recently, Chen et al. (2014) visualized the exhaled airflow during coughing while the mouth of the subject was covered with various methods by which people usually reduce the exposure of exhaled droplets to the environment. They also investigated the effect of a covered mouth on the receptor's exposure to exhaled particles by numerical simulations. According to their observations, covering a cough with a tissue, hand, or elbow can markedly reduce the particle velocity. Zhu et al., (2006) also measured the maximum airflow velocity exiting from mouth during coughing and reported a value of 22 m/s. Mavle et al. (2010) numerically computed the velocity profile in trachea in a cough and Tang et al. (2008) obtained a velocity map during coughing by image analysis. They observed that the maximum surrounding air speed reaches 8 m/s. Most of previous works performed a velocity measurement during coughing and there are significant differences among the reported airflow rates during a cough by different researchers. However, addressing the air flow rate of a cough, Gupta et al. (2009) carried out an experimental study on different subjects and concluded that airflow rate of an adult human during coughing is in the range of 2 to 8 L/s. Nunn and Gregg (1989) also carried out a study with experimental data to reach new regression equations for predicting peak expiratory flow in adults.

As mentioned above, although some researchers studied the respiratory system during coughing, there is still an inconsistency between the reported data. The story becomes worse when we turn to the other important phenomenon, sneeze, which has not been investigated very much in detail. Some researches (Gao and Niu, 2006; Gao, 2007) cited the work of Badeau et al. (2002) for an estimate of the airflow of 250 L/min during sneezing. But, in fact, Badeau and colleagues studied the cough flow rate and that of sneeze was not discussed in their work. It seems that there is no accurate data on the airflow rate during sneezing reported in the literature. Wells (1955) reported that the velocity of exhaled air in sneeze can reach 100 m/s and Xie et al. (2007) reported that the velocity of expelled large droplets which are carried by exhaled air during sneezing can be as high as 50 m/s. According to the experimental observations of Jennison and Edgerton (1940) and Jennison (1942), the velocity of exiting droplets in a sneeze is about 46 m/s. Nishimura et al. (2013) studied the sneeze by taking images of a subject during a sneeze using a digital high speed video system and reported that the initial velocity of the outlet particles or their clusters is greater than 6 m/s. Bourouiba et al. (2014) presented the results of a combined experimental and theoretical investigation of the fluid dynamics of sneezing and coughing events and developed continuous models of droplet fallout from the cloud. They demonstrated that violent flows in such conditions are turbulent and multiphase puffs. Tang et al. (2013) also reported that the maximum velocity of fluid in the environment due to sneezing is about 4.5 m/s. Mentioned studies depict that a large variation exists for the air or particle velocity expelled during sneezing. The intranasal pressure during a normal sneeze in healthy volunteers was measured by Gwaltney et al. (2000) and it was reported that the pressure value is about 612±505 Pa.

Few researchers investigated the effects of sneezing with closed airway on the health of humans. Faden et al. (2011) reported the effect of the closed-airway sneezing on the laryngeal fracture which was due to increased intraluminal pressure. This increased pressure may cause undesirable outcomes such as cervicofacial emphysema and pneumomediastinum (Tewfik et al., 2006). Also a case of fracture of the thyroid cartilage, odynophagia, neck pain and dysphonia after an episode of sneezing was reported by Martinez et al. (2007). It is conjectured that the main reason for these damages is the pressure built up in the respiratory tract during sneezing that is not allowed to be naturally released from nose or mouth. This indicates the importance of studying the pressure rise due to a suppressed sneeze.

In this paper, a computational model of a realistic model of human upper airway including both oral and nasal cavities was developed using the CT scan images of an adult female subject. The airflow, pressure and turbulence intensity field during sneezing under various conditions were simulated and compared. One important feature of the present study is the inclusion of the oral cavity in the model. The presence of both oral and nasal cavities in the computational domain was not considered in the previous works, possibly due to the significant geometric complexity. This feature in the current work provides the opportunity to analyze various sneezing scenarios. In addition to normal sneezing for which both nostrils and mouth are open, simulations results are presented for the stifled sneezes by holding the nose or closing the mouth. The simulation results for different cases were compared with those for the normal sneezing and discussed. The presented numerical simulation results shed light on the airflow velocity and pressure fields in the respiratory tract during various sneezing scenarios.

2. Numerical Methods

2.1. Computational model of the upper airways

The human upper respiratory tract including the nasal cavity investigated in this paper has the same configuration as that used in our previous studies (Farhadi Ghalati et al., 2012; Dastan et al., 2014; Ghahramani et al., 2014). However, in the present work the oral cavity is also included into the computational domain to generate a more realistic representation of the complete respiratory airways during sneezing. The patient was a 24-year old non-smoking female subject. The process for constructing the geometry of the airway passage from the CT scan images was presented in details in the work of Farhadi Ghalati et al. (2012), and therefore is not repeated here for the sake of brevity. The distances between consecutive CT scan images used in the present research for imaging process passage was 0.625 mm. It should be noted that the inflation level of the patient during CT scan was unknown. Lung volume during sneezing is different from normal situations and this might affect the geometry of trachea or some other parts of the upper airway. The glottal opening level may also have an impact on the pressure field during the expelling of air. To the best knowledge, no reliable experimental data about these parameters is available in the literature and therefore, their possible effects were ignored in the present research.

Figure 1 shows the schematic view of the upper airways investigated in the present study. Moving from the lower parts to the upper regions, the upper airway consists of trachea, larynx, oropharynx, oral cavity, nasopharynx and nasal cavity. Some coronal and transverse planes shown in Fig. 1 were used to present the airflow field simulation results for different parts of the tract. Some of these planes are also the boundaries between different regions of the investigated airway passages. For example, plane **c** is located between trachea and larynx, plane **d** is at the end of nasopharynx, and plane **f** is at the end of nasal cavity. Table 1 lists the information about the locations and the cross section areas of plane sections shown in Fig. 1. Figure 2 also gives more information about the cross sectional area of the geometry. The areas at oral and nasal cavities were measured on coronal planes, while those of trachea, larynx and a part of nasopharynx were associated to transverse planes. The area at nasal cavity is sum of the left and right passages and the details of each can be found in the work of Dastan et al. (2014). As it can be seen, the oral cavity is narrower than the nasal cavity for most of their length. However, it should be noted that the complicated geometry of the nasal cavity, particularly within the narrow nasal valve and main airway, causes the hydraulic diameter of the passage to considerably drop and, therefore, the resistance of the airway to the air flow increases due to more friction with the walls of nasal cavity.

A hybrid mesh scheme was used for grid generation. To properly capture the interaction between the airflow and the walls of the rather complex respiratory passages (Dastan et al., 2014), 15 layers of prismatic elements were produced adjacent to the wall regions, while the inner domain was filled with the tetrahedral elements. A series of grid sensitivity study was performed for 4 different grids with 2.4, 3.2, 3.8 and 5.2 million elements and the velocity and pressure distribution over some selected lines in different regions of the airway model were compared. The results for the grid sizes of 3.8 and 5.2 million were almost the same and finally the former was selected as the most suitable grid having accuracy as well as efficiency. This grid with 3.8 million elements was used for the rest of simulations. The height of the first prismatic layer adjacent to the walls was 0.047 mm and the exponentially growth perpendicular to wall led to 15-layer prismatic cells with total height of 1.5 mm. Figure 3 shows some views of the selected grid. The maximum y^+ of the first grid adjacent to the walls in the trachea, nasal cavity, and oral cavity are, respectively, 7, 3 and 2 in normal sneeze for flow rate of 470 L/min (see section 3.1).

2.2. Governing equations and boundary conditions

A sneeze is a rapid drain of a large amount of air from the respiratory outlets. That is, the air flows in the airways for about less than a second and hence, the nature of the sneezing is strongly unsteady (Gwaltney et al., 2000). Since there is no available experimental data in the literature on the flow rate profile during a sneeze, in this work, as the first attempt to study the airflow velocity and pressure fields during sneezing, the simulation is performed in a quasi-steady manner. This means that a steady flow simulation with an estimated flow rate for a sneeze is carried out. To be sure that this assumption does not lead to unreasonable results, a comparison between the unsteady simulation of a cough, which is another unsteady drain of air, and its associated steady one was performed (the results are not presented here). The exhalation airflow rate profile, being similar to one used by Malve et al. (2010) for cough simulation, was applied on the present upper airway model. Steady simulation data at a particular flow rate had a good agreement with the unsteady data at that flow rate. This suggests that the quasi-steady simulation should be a good estimation for the real unsteady situation.

The flow field is assumed to be steady, compressible and turbulent. The reason for using a compressible model is the high velocity of the airflow in the studied sneeze case which will be shown in the results section. The walls were assumed to be rigid. This approximation can change the pressure and velocity distribution in the airway, as the elastic behavior of the real human airway tissues may damp the high pressure waves. However, this effect is out of scope of current work and left for a future study. The extra opening of the mouth during the sneeze was also neglected which may have some effects on the exit air velocity.

Due to the high airflow rate during sneezing, the flow is turbulent in certain areas of the airways. It should be emphasized that the turbulence modeling is a major challenge for CFD studies especially for such complicated geometries of the human upper airway. To choose a suitable turbulence model for present computational work, a series of numerical simulations was performed and the results were compared with experimental measurements of Mylavarapu et al. (2009). In this reference, both simulations and experiments were performed on a double-size physical model of human upper airway at a peak expiratory flow rate of 200 L/min. They measured pressure and velocity in different parts of the physical model. In order to have a valid comparison, the airway model in the present work was scaled up to have generally similar size to that of the experimental model in the work of Mylavarapu et al. (2009). Different turbulence models available in Fluent commercial software (standard k-ω, transient flow k-ω, SST k-ω, low-Reynolds k-ε and k-ε with enhanced wall treatment) were applied. The details of the turbulence models were discussed in FLUENT Users' Manual and hence are not repeated here for the sake of brevity. The trends of the results were similar to those obtained in the study of Mylavarapu et al. (2009). In general, a turbulence model could not be selected with confidence, as each model had a low accuracy for some points in the model where the experimental data are available. However, the results obtained by SST k-ω had a lower error. Zubair et al. (2012) in reviewing of the CFD studies in airway models also concluded the same result and, although, no single turbulence model is universally accepted for solving all class of problems, they suggested that SST k-ω has been found to be suitable in many related studies. In conclusion, the SST k-ω turbulent model was used for the simulations performed in the current research.

As noted in the introduction, there are considerable uncertainties on the airflow rate of a sneeze for different subjects. For a rough estimate the results of Nunn and Gregg (1989) were used. They carried out an experimental study for predicting peak expiratory flow in adults. For a normal female subject of age 24, the average peak expiratory flow rate was reported to be about 470 L/min. Therefore, the volume flow rate of 470 L/min is considered as the main case for the sneeze expiratory flow rate in the present work. In the normal sneeze, by applying the constant gauge pressure at the trachea inlet, the volume flow rate of 470 L/min was achieved. Also the experimental data Nunn and Gregg (1989) depict that by considering a 90% confidence interval, the flow rate falls between 400 and 570 L/min. Therefore, two different volume flow rates of 400 and 570 L/min are also investigated to evaluate the effect of variation in the flow rates. It should be emphasized as we have a compressible model here; hence the specified flow rates refer to the inlet of trachea.

Due to lack of reliable data for the details of the sneezing process, and also to provide a reasonable comparison between different cases of sneeze habits, two different inlet boundary conditions are considered. In the first case, a constant total gauge pressure is used as the boundary condition of the inlet plane for different cases of sneeze (normal and suppressed sneezes) while in the second case a constant normal velocity is imposed on the inlet plane at trachea and therefore the airflow rate is fixed for normal and stifled cases. In a normal sneeze, both the mouth and nose outlets are open and hence a constant zero gauge pressure condition is assumed at the nostril and the mouth outlet. To investigate the effect of suppressing a sneeze when a person blocks the nose or mouth by his/her hands, the closed outlet boundary is changed to wall, while the open one is left as the pressure outlet boundary condition with zero gauge pressure.

The numerical procedure for solving the governing equations and applying the boundary conditions were discussed in our previous works (Ghahramani et al., 2014), and hence it is not repeated here. However, as the flow field in the current simulation is compressible, in addition to the continuity and momentum equations, the energy equation is also solved. The ideal gas law is used to correlate the pressure, density and temperature. The detail of the governing equations can be found in FLUENT Users' Manual. No-slip boundary condition is applied on all walls of the respiratory passages. The temperature of the walls and the inlet air was assumed to be 37º C. The accuracy of the present computational model predictions was also verified in our earlier works for the range of normal breathing flow rates. As noted before, to the best of authors' knowledge, there is no study in the literature on the velocity field inside the upper respiratory tract during sneezing but there is some data for the pressure which will be compared with the present numerical data.

3. Results

3.1. Normal sneeze

As noted before, airflow and pressure during sneezing are investigated in the present work for different conditions.

Here, both the mouth and nose outlets are open and the air leaves the airways from both oral and nasal cavities. The portion of the airflow through oral and nasal passages depends on the geometric features of these airways. In a trial and error procedure, it was found that by applying a total pressure of 8000 Pa at the trachea inlet, the airflow rate at the airway inlet would be 470 L/min. This pressure is used in the subsequent sections for simulation of different sneezing scenarios such as holding the nose or blocking the mouth.

Figure 4 shows the lateral view of pressure contours on the airway walls. The contour plot shows the distribution of pressure in color bands and lines between color bands are Isopleths. It is seen that along the flow direction from trachea to the outlets, the pressure decreases relatively smoothly, except after the oropharynx in which a pressure recovery due to the deceleration of fluid occurs. Figure 4 also shows that the range of pressure variation in the domain is between -4340 Pa and 8000 Pa implying that there is a relatively large pressure difference of about 12.3 kPa. Figure 5 presents the velocity magnitude contours on the sections specified in Fig. 1. It should be emphasized that the plane sections are not with the same scale and are drawn from the view of an observer at the back or top sides. As expected, the high velocity regions are on the sections that the airway narrows. The relatively low cross section area at the nasopharynx in the nasal cavity passage causes more blockage for the exiting air and therefore only 239 L/min drains from the nostril, while the mouth flow rate is 261 L/min. Figure 5 shows that the maximum velocity in the tract happens on plane **d**. As seen, the velocity in the trachea also reaches more than 100 m/s.

Table 2 presents the average values of velocity magnitude, turbulence intensity and static pressure on different planes of the airways for a normal sneeze with volume flow rate of 470 L/min. The turbulence intensity is defined as:

$$I = \sqrt{2k/3}\Big/U \tag{1}$$

Where I is the turbulence intensity (%), k is the turbulent kinetic energy, and U is the mean local velocity magnitude. The higher the turbulence intensity, the more turbulent the flow is in that region. As stated in Table 2, the turbulence intensity increases to the maximum value of about 38.9% at the oral cavity and then decreases at the outlets.

The data reported in the literature on the peak expiratory flow rate suggest a wide range of variations. To assess the effect of variations in the airflow rate and according to the data from investigations by Nunn and Gregg (1989) for peak expiratory flow, flow rates of 400 L/min and 570 L/min were also investigated in the present work. Figure 6 compares the pressure distribution in the upper airways for different studied inlet flow rates. As expected, the increase of airflow rate led to an increase in the total pressure drop across the airway. For the flow rate of 570 L/min, the pressure drop was about 19 kPa which is 2.1 times greater than that for the flow rate of 400 L/min. For the normal sneezing conditions, Table 3 presents the values of the parameters similar to those shown in Table 2, but for different volume flow rates. The average air velocity in trachea and nasopharynx reaches more than 110 m/s for the total flow rate of 570 L/min. Data of Table 2 and 3 depict that the relation between the average velocity and pressure and the airflow rate is approximately linear, while the turbulence intensity seems to be more dependent on the location of the measurements and not on the airflow rate in the investigated range.

In the next sections, the important results for the cases of suppressed sneeze with closed nose and closed mouth are reported and the results for two different inlet conditions are compared.

3.2. Sneeze with blocked nose

In this section, the simulation results for airflow velocity and pressure conditions during a steady sneezing with closed nose are presented. This part of the study shows the effect of blocking the nostril during sneezing on the increase of pressure difference in the upper airways. To perform these simulations, the nostril outlet in the computational model is simply changed to the wall; therefore, the air is forced to exit through the oral cavity.

3.2.1 The same trachea inlet pressure as the normal sneeze

Figure 7 (I) shows the pressure distribution on the airway walls during the sneezing with closed nose while a constant inlet total pressure of 8000 Pa is applied at the inlet of trachea. This pressure is the same as that in the normal sneeze which led to the inlet airflow rate of 470 L/min. In this case, the outlet airflow rate from the mouth was 308 L/min. For the normal sneeze case that was described earlier, the airflow rate through the mouth was 261 L/min (with a flow rate of 239 L/min exiting through the nostril). Therefore in the case of closed nose and the same pressure boundary condition as the normal sneeze, the outlet airflow rate flowing through the upper airway system decreases about 38.4%, while the oral cavity flow rate increases by 18.0%. The minimum and maximum pressure values in the domain were respectively -1820 and 8000 Pa. The absolute value of the sub-ambient pressure in this case was about 2.5 kPa smaller than that associated with the normal sneeze. As shown in the Fig. 7, the pressure decreases in the inlet of the oral cavity where the passage is narrowed. Figure 8 (I) illustrates velocity contours on different planes in a sneeze with closed nose while the pressure of 8000 Pa was applied on the trachea inlet. The maximum velocity in this case reached 118 m/s and occurred at the beginning of oral cavity. It should be noted that the coronal plane **e** has an angle with the flow direction; therefore, the effective cross section area perpendicular to the airflow is less than what is stated in Table 1. Table 4 also gives information about the average flow field data in the case of a sneeze with closed nose. The reduction of pressure due to the fluid acceleration in the plane **e** (beginning of the oral cavity) is clearly seen in Table 4.

3.2.2. The same volume flow rate as the normal sneeze

The simulation results for the inlet airflow rate of 470 L/min during sneezing with the closed nose are plotted in Figure 7 and described in this section. Figure 7 (II) shows that the minimum and maximum pressures under this condition were respectively -5880 and 27500 Pa. The pressure difference in the upper airway in a sneeze with closed nose is approximately 2.7 times as much as that during a normal sneezing with open mouth and nose. It is also seen that the pressure inside the nasal passage was approximately constant with the value of about 21.8 kPa. This value is about 18 times as much value as the maximum nasal pressure during the normal sneeze. This pressure is very high compared to normal breathing and even normal sneeze and explains some suggested precautions for the sneeze with closed nose as discussed before. Velocity contours on different planes are shown in Figure 8 (II). The maximum velocity in this case reached 202 m/s that happened at the beginning of the oral cavity. As table 4 depicts, the average velocity of the exiting air from the mouth during sneezing with closed nose for inlet volume flow rate of 470 L/min is approximately 1.8 times greater than that in the case with the pressure of 8000 at inlet of trachea. The turbulence intensity in the nasopharynx (section **d**) reaches the value of about 51.5% which is higher than that in the normal sneeze.

3.3. Sneeze with closed mouth

3.3.1. The same trachea inlet pressure as the normal sneeze

The results of the simulation of a sneeze with closed mouth are presented in this part assuming that the inlet total pressure of trachea is the same as that in a normal sneeze. The procedure for analysis was similar to the other cases. The corresponding pressure contours on the walls of the airway are presented in Fig. 9 (I). It is seen that the pressure variation along the nasal cavities was very small being about 700 Pa compared with the pressure change in the neck of nasopharynx due to its small passage cross section. The range of pressure in the airway during the sneezing with closed mouth was between -7090 and 8000 Pa. Thus, the pressure difference in this case was 2.7 kPa larger than that of the normal sneeze. The pressure in the oral cavity is about 6200 Pa which is about 4 times as much as that in the normal sneeze and the pressure in the nose is below 1800 Pa, which is slightly lower than the normal sneeze and about one-fourth of that in a sneeze with closed nose for similar inlet pressure.

The corresponding velocity contours on different planes are shown in the Fig. 10 (I). The maximum velocity occurred in plane **d** at the beginning of nasopharynx. The maximum velocity magnitude in the airway in this case was 147 m/s. Table 5 presents the average simulation results for the sneeze with closed mouth while the inlet total pressure of 8000 was applied on trachea inlet. The average outlet velocity of air from the nose in this case was about 35.5 m/s. This is roughly the exit velocity for the removed particles and droplets from the nasal airway during sneezing. Here the outlet volume flow rate is 282 L/min, which is less than the exit flow rate from mouth for the case of sneeze with a closed nose. The maximum turbulence intensity occurs in section **e** with the value of about 44.4%.

3.3.2. The same volume flow rate as the normal sneeze

The results of the simulation of a sneeze with closed mouth and inlet flow rate of 470 L/min are presented in this section. As shown in Fig. 9 (II), the pressure difference is surprisingly high (about 84 kPa) and the range of pressure values for this sneezing with closed mouth is between -37.3 and 47 kPa. The pressure difference in this case is about 6.8 times as much as that of normal sneezing. The pressure in the oral cavity is about 39 kPa which is about 6 times as much as that in the case of closed mouth sneeze with the inlet pressure boundary condition. The oral cavity pressure is about 24 times as much as that in a normal sneeze. The value of pressure in the nose is lower than 8000 Pa which is about 6.1 times as much as the associated pressure in the normal sneeze and 0.4 of that in a sneeze with closed nose and the same inlet flow rate boundary condition.

Fig. 10 (II) shows the velocity contours for different sections shown in Fig. 1. The maximum value of the velocity magnitude in the domain in this case is 338 m/s. This velocity is very high and near to sonic velocity and it shows how the air can be accelerated if the mouth is being blocked during a sneeze. According to Table 5, the average outlet velocity of air through the nose in this case is about 84.6 m/s, which is 2.8 times as much as that in a normal sneeze.

4. Discussion

Due to the high airflow velocity and the resultant high pressure differences between the different parts of the respiratory tract and also the pressure difference between inside and outside of the tract during sneezing, understanding of the airflow field in the human airways is of great importance. It is believed that if the normal sneeze is suppressed, the resulting force and airflow velocity can damage the blood vessels in the head, causing injury to the diaphragm and possibly lead to hearing loss. The excess pressure might force the air through the Eustachian tubes, which connect the nasopharynx to the middle ear, into the ears and cause an injury to the inner ear or a ruptured the ear drum causing the hearing loss and/or vertigo. Suppressing a sneeze may also send infectious viruses carried by particles/droplets into the sinuses, spreading infection. Although the risks of the above noted events are low, they have been reported for some cases (www.uamshealth.com and Binns, 2010). The results presented in the last section shed light on the pressure and velocity distribution inside the upper airway for normal and blocked sneezes by giving some quantitative information.

According to the measurements done by Gwaltney et al. (2000), the intranasal pressure during a normal sneeze is about 4.6$\pm$3.8 mmHg (612$\pm$ 505 Pa). As seen, the present simulation results predicted a mean pressure of about 850 Pa in the nasal cavity (average of sections **f** and **h,** Table 2**)** which is in agreement with the measured value. While the main pressure drop during sneezing is due to the wall friction, the reason for generation of sub-ambient pressure in the pharynx is the acceleration of the air as the result of the change in effective cross section of the flow passage. Due to the bend-shape geometry of the nasopharynx and the beginning of the oral cavity, the airflow is directed to the outer bend, top of the cavities, and therefore the high velocity regions are located near the top of the cavities (in planes **f** and **g,** Figure 5**)**. The left and right nasal cavities of the current respiratory tract have a geometric difference and an asymmetry is observed between them. Dastan et al. (2014) measured the cross section areas of the right and left cavities of this respiratory model and showed that the right passage is slightly more patent. It is not quite clear whether this small difference in the area is due to the function of nasal cycle or a permanent geometrical difference exists for this particular subject. However, when air passes through the nasal cavity in either inhalation or exhalation, it is easier to pass through the patent passage, due to more resistance to the flow experienced in the digested one. This was seen in our previous work in the range of normal breathing by observing larger pressure drop for the congested passage (left cavity) at fixed flow rate, and this observation was also repeated in the current work for a very high flow rate exhalation. Here, the airflow is not partitioned symmetrically into both cavities and the air flow draining from the right cavity is slightly larger. In addition, the inter-subject differences may also play a role on the air flow field during sneezing. These differences include the physiological variation and also the flow rate generated by individuals. Although we expect that the qualitative results achieved here can be generalized to other subjects, this needs to be studied further in future works.

It should be pointed out that due to the uncertainty on the physiology of a suppressed sneeze (by closing the nose or mouth), two different conditions were simulated. In the first case, it was assumed that the contraction of the chest muscles and deformation of diaphragm produce a lung pressure which leads to a pressure at trachea inlet similar to that for a normal sneeze. In the second case, it is assumed that the airflow rate for suppressed sneeze is still equal to the volume flow rate for the normal sneeze. The real physiological situation is unknown and needs *in-vivo* measurements. We believe that the real condition is somewhere between these two extremes, but much closer to the assumption of constant pressure boundary condition.

When the sneeze is being suppressed by closing the nose, the pressure field mainly changes in the oral cavity. The pressure drops markedly as the air enters to the oro-pharynx. The minimum pressure in the upper airway with this sneeze habit occurs around the Uvula and soft palate. The pressure is recovered again in the oral cavity due to increase of the cross section size. It then decreases as it travels in the cavity till it reaches the zero gauge pressure at the outlet. Comparing the data of Tables 2 and 4 reveals interesting information. Since there is no noticeable airflow in the nasal cavity for sneeze with closed nose, the pressure inside the nasal passage is nearly constant at about 7000 Pa, while in a normal sneeze the pressure in the nasal airway is lower than 1200 Pa. It is concluded that when the nasal airway is closed, there is roughly six-fold increase in the pressure in the nasal cavity. This observation can explain some cautions for a stifled sneeze. The situation becomes worse, if a higher pressure in the lung occurs for the case of suppressed sneeze. If we assume that the same airflow rate occurs for both normal and closed nose sneezing, about 18-fold increase of pressure in the nasal cavity could occur. This suppressing could also affect the condition of the exhaled air and droplets through the mouth. The average velocity of the exiting air from the mouth in the case of sneezing with closed nose with inlet flow rate of 470 L/min is approximately 2.1 times greater than that in the normal sneeze. This higher speed may lead to an increase in the distance that the droplets or particles disperse in the environment. Also higher pressure in the trachea is another concern. A comparison between the simulation results presented in Tables 2 and 4 reveals that the pressure in the trachea for the case of stifled sneeze with closed nose is about 1.5 times as much as that in the normal sneeze even when a similar inlet pressure exists at the inlet of trachea for both cases. As Faden et al. (2011) reported, this increased intraluminal pressure may cause the laryngeal fracture or undesirable results such as cervicofacial emphysema and pneumomediastinum (Tewfik et al., 2006).

As it was expected, if the same flow rate happens during both blocked and normal sneeze conditions, the flow velocity fields in the trachea and larynx would be almost the same, but the airflow velocities in the oral and nasal cavities and also the pressures for all parts are markedly different (Table 2, 4 and 5). The results for the sneeze with blocked nose showed higher pressure in the nasal cavity compared with that in normal sneeze. The high air pressure could cause some medical problems in certain subjects. It should be pointed out that closing of the nose alters the main function of a sneeze, which is the removal of foreign particles from the nasal passage.

The situation of a sneeze with blocked mouth was also studied. For the same inlet trachea pressure, the flow rate through the nose is lower compared with that through the mouth in a closed nose sneezing. It is due to the higher hydraulic resistance of the nasal airway (smaller effective cross section area in the investigated respiratory airway) compared with that in oral cavity.

The reported high pressures in some parts of the respiratory tract and very low pressure in high velocity regions during a suppressed sneeze could explain the reasons for some observed sneezing injuries such as laryngeal fracture, cervicofacial emphysema, pneumomediastinum, fracture of thyroid cartilage, injury to the diaphragm, and damage of the sinuses or middle ear. According to the results, the average intranasal pressure in the case of suppressed sneeze with closed nose, may reach 21.8 kPa which is comparable with the values of pressure reported by Gwaltney et al. (2000), where both nose and mouth were closed with a tissue (17.4±5.9 kPa). Taking a look at table 5, the pressure in the oral cavity even can become significantly larger in the case of closed mouth (39.0 kPa).

It should be noted that some controversial issues have been presented for the exit of airflow during sneezing. Although it is mentioned in most of physiology textbooks that the depression of the uvula while sneezing causes a quickly pass of a large amount of air through the nasal passages in order to clear the foreign matter (Hall and Guyton, 2010; Forleo, 2008), but Burke (2012) and Birch (1959) claimed that little or no air exits from the nose due to blocking of the nasopharyngeal junction under normal sneezing. Performing an FSI simulation is being suggested for a future work to shed light on these controversial issues about sneeze. In addition, having a more accurate and real model for describing the behavior of soft and elastic material of the upper airway can be more helpful in studying the sneeze effects on the respiratory tract. The consequences of high pressure on the geometry of the airway by influencing on more compliant regions, which spans the space being available for the travelling of the air, should be emphasized. This may damp the pressure reported in the current study. Another limitation of the present work is the truncation of airway model at the bottom of the trachea. This model ignores the effect of secondary flow due to the confluence of left and right main bronchi on the flow field in the trachea and upper airway. This might have an effect especially on the flow field in entrance region of the trachea, although, unlike with inhaled airflow dynamics, the branching of the bronchi below the level of the trachea does not matter too much in expelled airflow (like the sneeze) and this may not be such a significant limitation. The glottal opening level during expiration was also ignored in the present study which should be considered in details in the future works.

5. Conclusions

In the present paper, the quasi-steady flow field in a realistic human upper airway model during sneezing was simulated. The airway computational model included both oral and nasal cavities. Three different sneezing conditions including normal sneezing with both open nose and mouth, suppressed sneezes with the closed nose or closed mouth were studied. Two different inlet conditions (at the trachea) were investigated for the normal and suppressed sneezing conditions. For the first case it was assumed that the inlet pressure of the trachea during the normal and suppressed sneezing remains the same and for the second case it was assumed that the inlet volume flow rate is similar.

The case of normal sneezing was studied for three different airflow rates. The simulation results for normal sneeze with a volume flow rate of 470 L/min showed that the pressure in the trachea reached more than 7500 Pa and inside the nasal and oral cavities was less than 2000 Pa. The maximum velocity reached more than 123 m/s in trachea and nasopharynx. The average outlet velocities through the mouth and nose were about 48 and 30 m/s, respectively.

The simulations for the suppressed sneeze were performed for two cases of sneezing with closed nose or closed mouth. For each case, two conditions of inlet pressure and inlet airflow rate identical to those for the normal sneezing with open mouth and nose were studied. The results showed that a blocked sneezing condition markedly changed the airflow and pressure fields in the upper airway. If the sneezing occurs with blocked nostril, the pressure increases significantly in the nasal cavity. For the same inlet pressure as the normal sneeze, the pressure in the nasal cavity in a sneeze with blocked nose increased to around 7 kPa. For the condition of the same flow rate as the normal sneeze, the nasal cavity pressure reached about 21.8 kPa. This five to eighteen fold increase in the nasal cavity pressure in a blocked sneeze compared with that in a normal sneeze, scientifically confirms the global medical community recommendation about not suppressing the sneeze.

For the sneeze with a closed mouth, the pressure increased markedly in the oral cavity to about 6000 Pa for the same trachea inlet pressure, and to 39.0 kPa for the same flow rate condition as the normal sneeze. In this case, the change in pressure along the nasal cavity was not noticeable.

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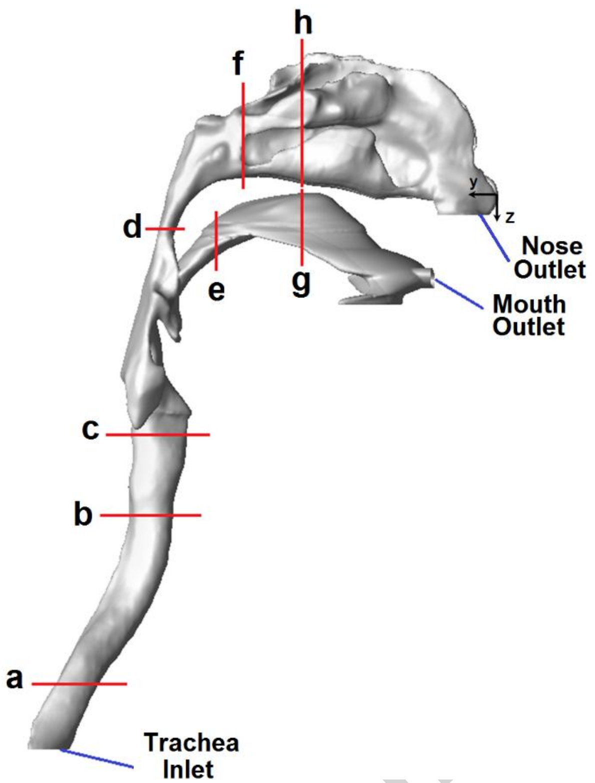

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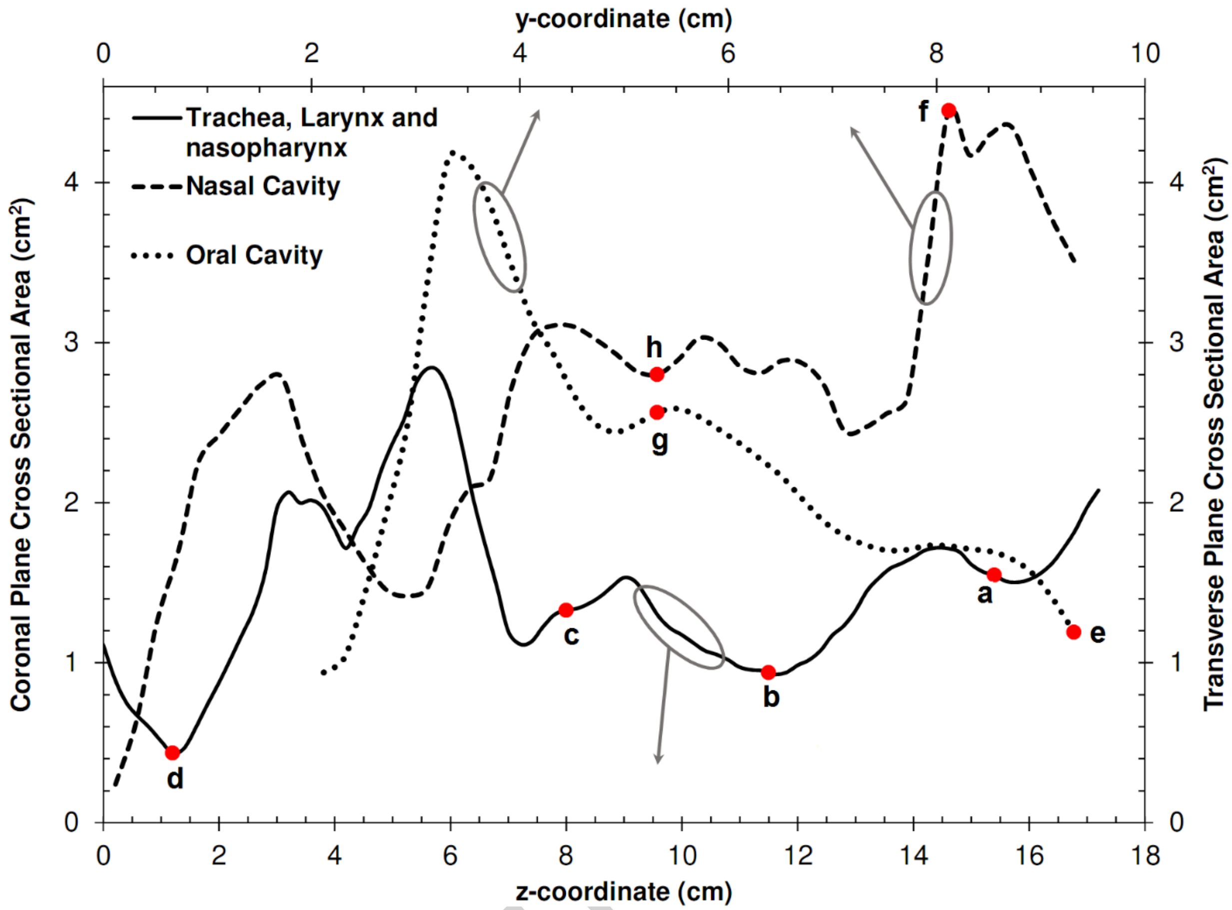

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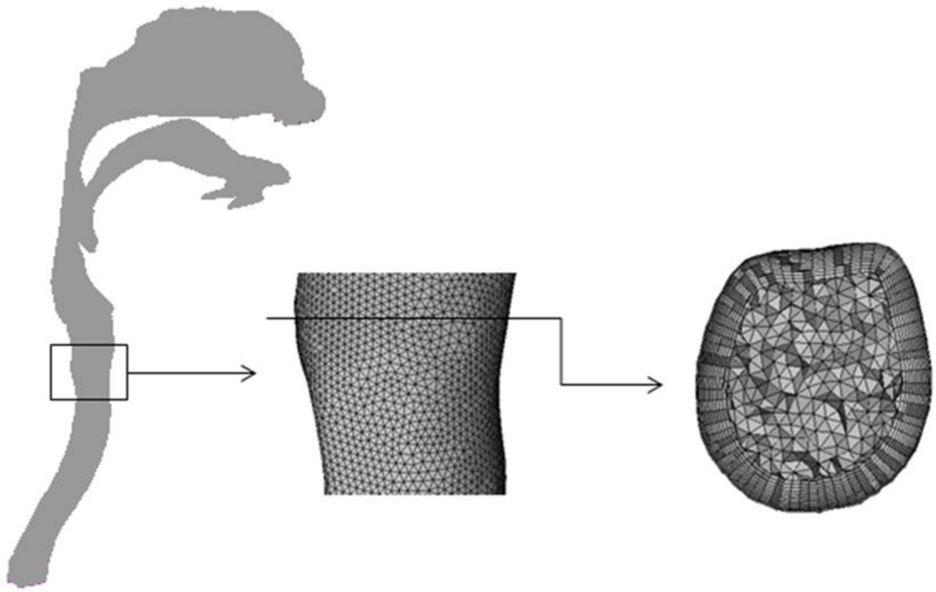

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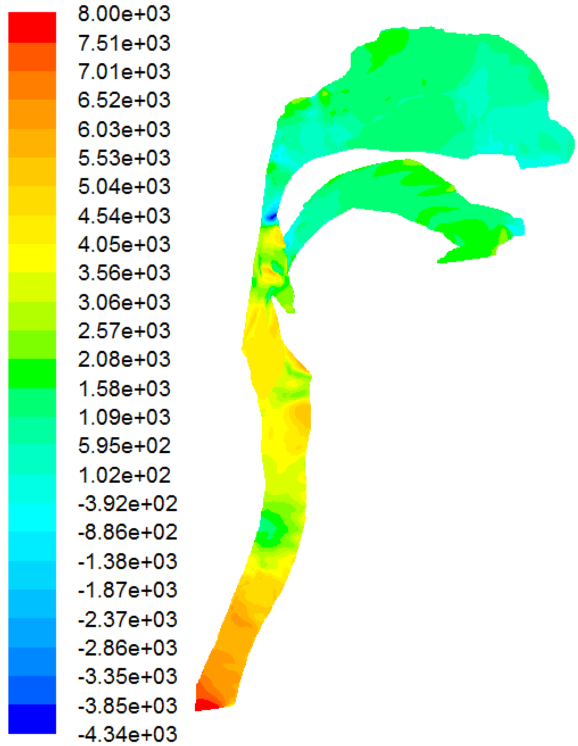

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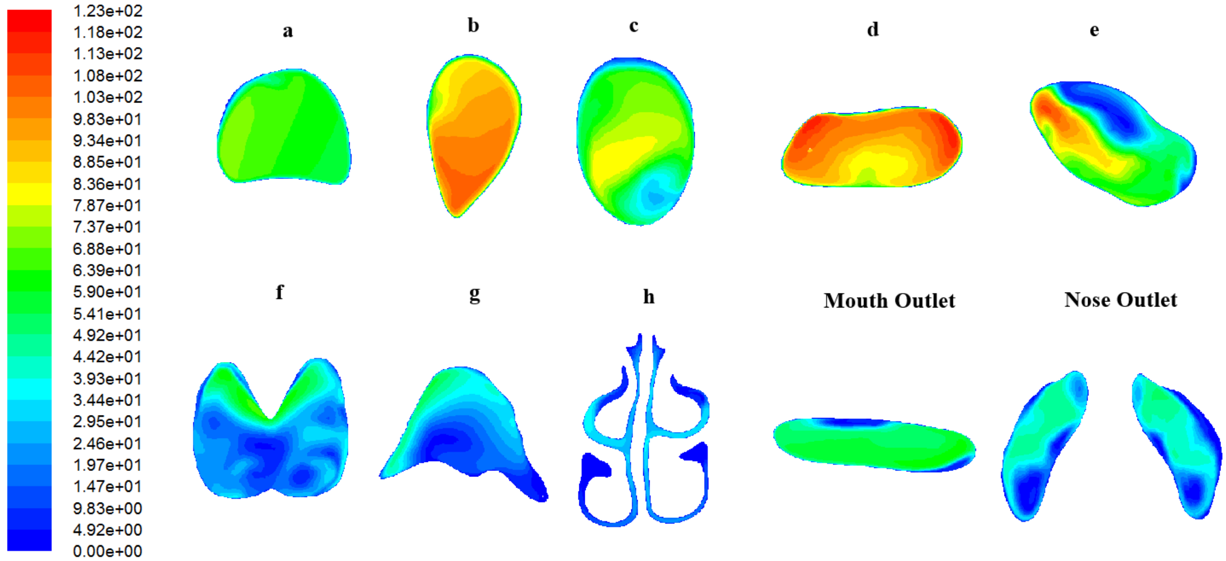

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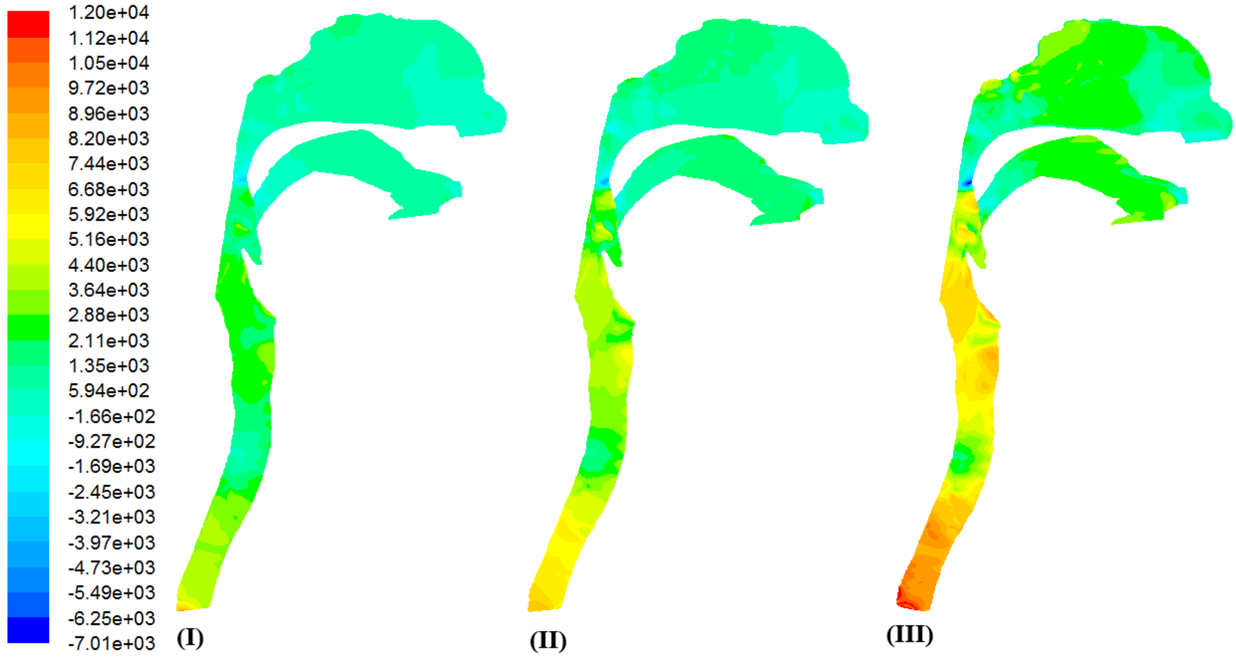

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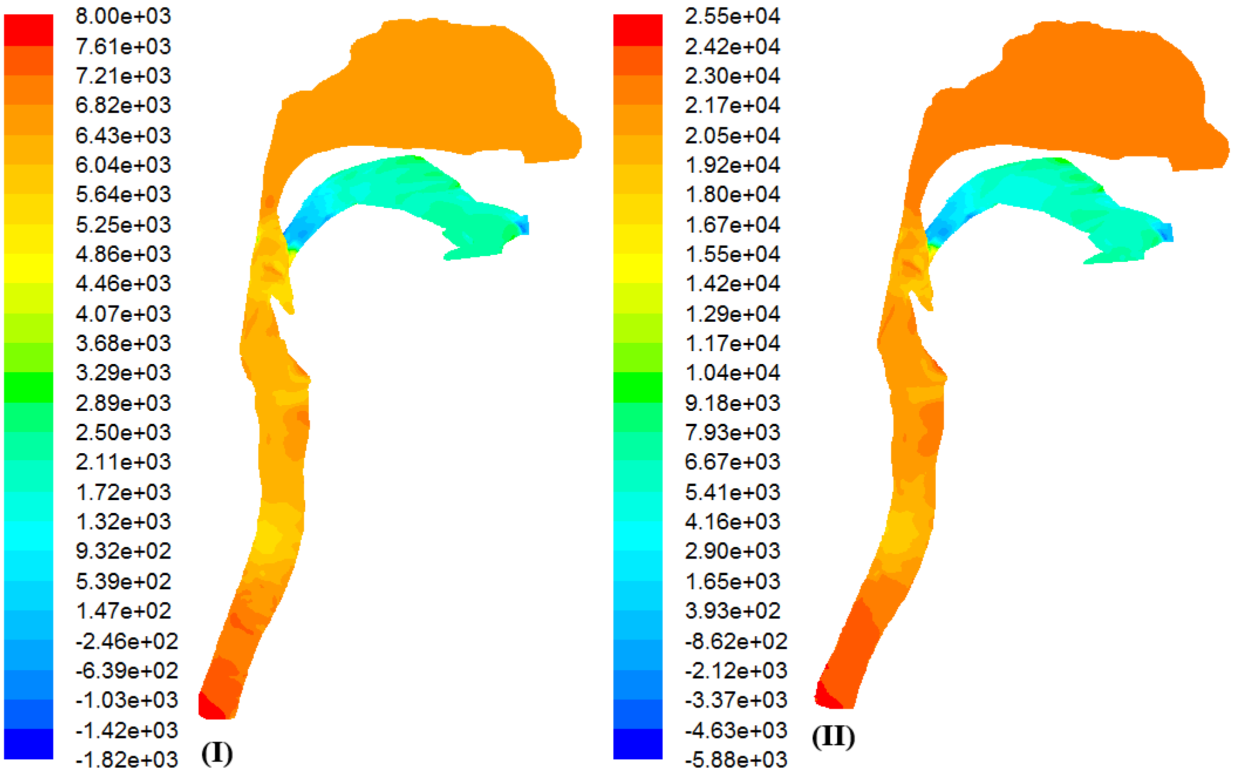

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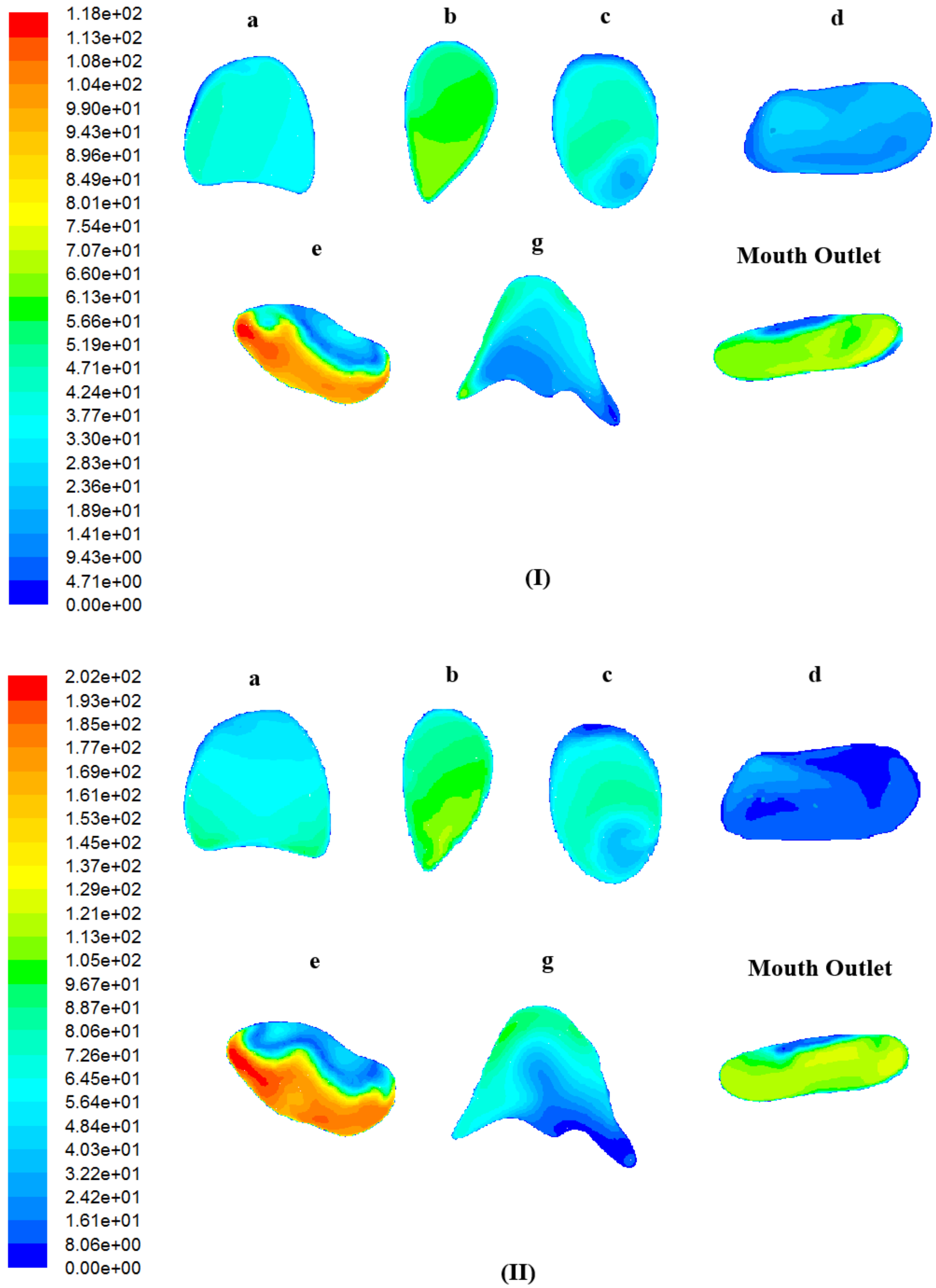

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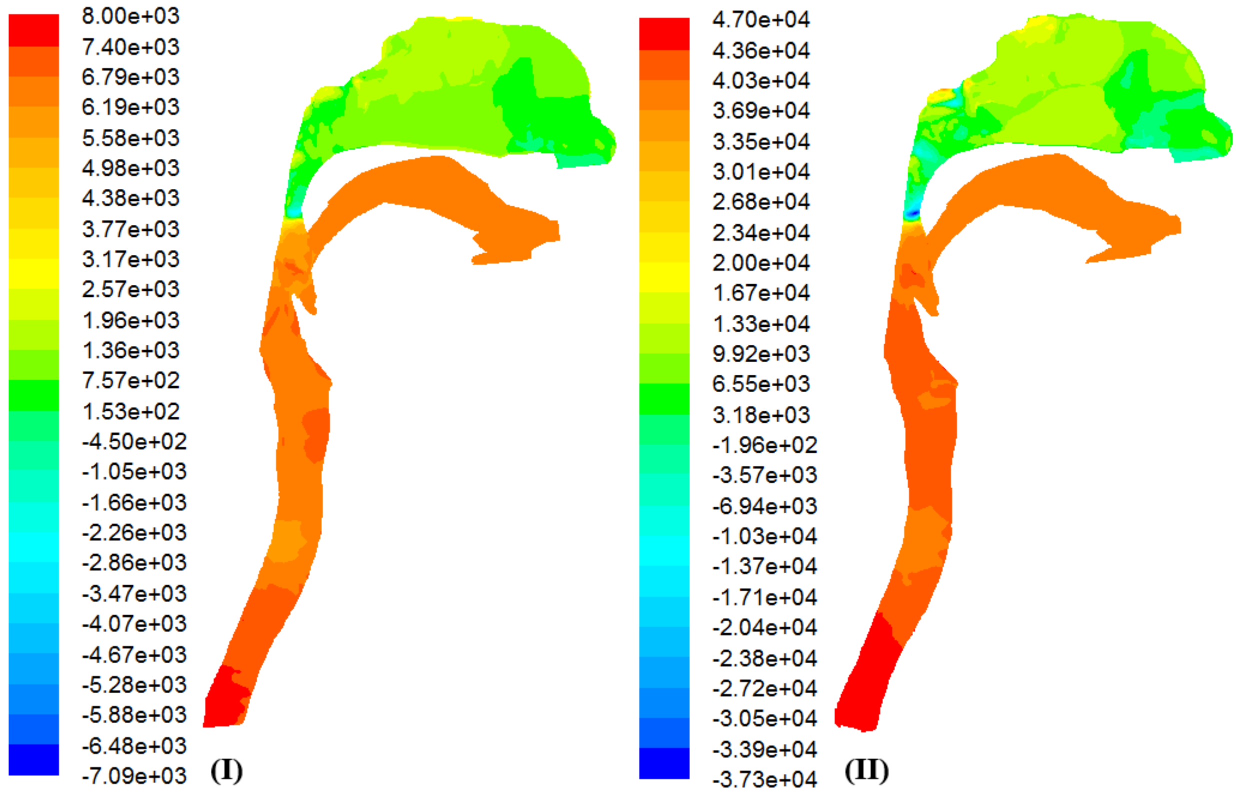

Fig. 9. Static pressure contours (Pa) on the walls of the upper airway in a suppressed sneeze with closed mouth. I) Inlet pressure similar to normal sneeze (8000 Pa). II) Inlet volume flow rate similar to normal sneeze (470 L/min).

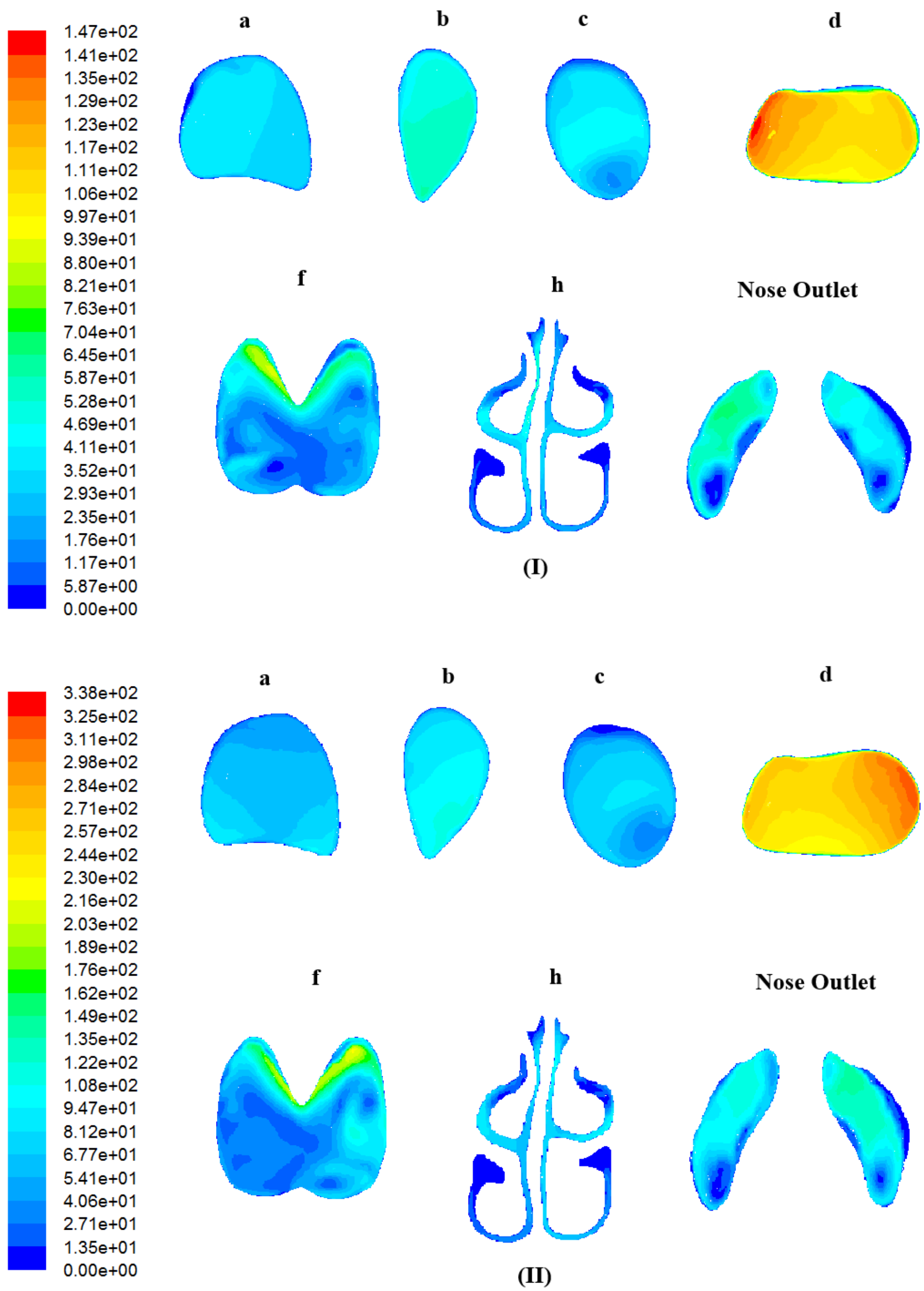

Fig. 10. Velocity magnitude contours (m/s) on different planes specified in Fig. 1 in a sneeze with closed mouth. I) Inlet pressure similar to normal sneeze (8000 Pa). II) Inlet volume flow rate similar to normal sneeze (470 L/min).

Table 1. Location and cross sectional area of the planes shown in Fig. 1

Plane Name	Location	Area (cm^2)
Inlet	Beginning of the trachea	2.078
a	Trachea	1.548
b	Minimum cross section area in trachea	0.938
c	Boundary of trachea and larynx	1.327
d	Boundary of nasopharynx and oropharynx	0.438
e	Oral cavity	1.188
f	Boundary of nasal cavity and nasopharynx	4.449
g	Oral cavity	2.565
h	Nasal cavity (main airway)	2.800
Mouth Outlet	-	0.935
Nose Outlet	-	1.630

Table 2. Average values of flow field data on different planes of the domain in a normal sneeze for the flow rate of 470 L/min (pressure at trachea inlet, 8000 Pa).

Plane Name	**Average Velocity (m/s)**	**Average Turbulence Intensity (%)**	**Average Static Pressure (Pa)**
Inlet	37.5	0.01	7013.0
a	61.2	2.4	5472.5
b	90.8	3.3	2280.2
c	60.6	9.6	4382.6
d	93.3	9.6	-701.1
e	55.0	37.2	282.9
f	26.7	36.9	559.2
g	23.6	38.9	1562.3
h	16.4	25.7	1151.0
Mouth Outlet	48.3	14.5	0.0
Nose Outlet	30.2	15.9	0.0

Table 3. Average values of flow field data on different planes of the domain in a normal sneeze.

		Average Velocity (m/s)		Average Turbulence Intensity (%)		Average Static Pressure (Pa)	
	Flow Rate (L/min)	**400**	**570**	**400**	**570**	**400**	**570**
Plane name	Inlet	32.2	45.7	0.01	0.01	4901.4	11644.8
	a	53.0	76.0	2.4	2.0	3465.3	8543.7
	b	77.8	113.8	3.8	3.2	1178.3	3410.4
	c	52.5	75.5	13.1	10.4	2639.6	6828.7
	d	79.6	117.4	9.8	8.9	-849.9	-1096.9
	e	46.0	68.7	36.4	48.3	-195.4	194.3
	f	20.5	29.2	42.8	42.6	635.3	1040.2
	g	17.3	27.8	30.8	33.5	1000.2	2518.9
	h	13.2	19.1	24.3	27.2	905.8	1866.7
	Mouth Outlet	39.9	61.8	13.3	13.8	0.0	0.0
	Nose Outlet	25.3	37.5	15.4	14.3	0.0	0.0

Table 4. Average values of flow field data on different planes of the domain in a suppressed sneeze with closed nose.

		Average Velocity (m/s)		Average Turbulence Intensity (%)		Average Static Pressure (Pa)	
Boundary Condition		Pressure Similar to Normal Sneeze (8000 Pa)	Volume Flow Rate similar to Normal Sneeze (470 L/min)	Pressure Similar to Normal Sneeze (8000 Pa)	Volume Flow Rate Similar to Normal Sneeze (470 L/min)	Pressure Similar to Normal Sneeze (8000 Pa)	Volume Flow Rate Similar to Normal Sneeze (470 L/min)
Plane name	Inlet	24.2	37.5	0.01	0.4	7948.6	25250.1
	a	37.4	61.8	1.9	2.0	7021.5	22942.9
	b	55.0	91.4	3.6	3.4	5796.5	19266.4
	c	37.0	61.0	10.0	11.8	6523.4	21695.2
	d	18.0	12.3	29.2	51.5	6562.9	21669.4
	e	67.0	116.9	37.0	36.4	-39.1	28.4
	f	1.5	1.1	43.7	44.1	6740.6	21826.3
	g	26.0	48.3	32.5	36.2	2180.5	6659.7
	h	0.1	0.1	1.0	10.7	6742.3	21828.7
	Mouth Outlet	57.4	104.6	14.5	12.0	0.0	0.0
	Nose Outlet	0.0	0.0	-	-	6742.6	21829.2

Table 5. Average values of flow field data on different planes of the domain in a sneeze with closed mouth.

		Average Velocity (m/s)		Average Turbulence Intensity (%)		Average Static Pressure (Pa)	
Boundary Condition		Pressure Similar to Normal Sneeze (8000 Pa)	Volume Flow Rate Similar to Normal Sneeze (470 L/min)	Pressure Similar to Normal Sneeze (8000 Pa)	Volume Flow Rate Similar to Normal Sneeze (470 L/min)	Pressure Similar to Normal Sneeze (8000 Pa)	Volume Flow Rate Similar to Normal Sneeze (470 L/min)
Plane Name	Inlet	21.1	37.6	0.01	0.4	7688.4	46567.1
	a	34.0	62.0	2.0	1.9	7185.7	43810.3
	b	50.0	91.9	3.5	3.2	6211.0	39232.9
	c	33.6	61.3	9.8	10.5	6849.1	42056.6
	d	108.3	258.1	7.1	4.9	-825.2	-6969.1
	e	6.9	14.2	44.4	33.1	6245.7	39498.0
	f	27.3	64.6	44.0	43.8	849.8	4116.5
	g	3.1	6.7	41.3	37.0	6278.7	39680.5
	h	19.3	43.6	24.3	24.2	1625.5	8381.0
	Mouth Outlet	0.0	0.0	-	-	6285.3	39765.0
	Nose Outlet	35.3	84.6	17.6	15.8	0.0	0.0

Conflict of interest statement

All the authors declare that there is no potential conflict of interest including any financial, personal or other relationships with other people or organizations within that could inappropriately influence (bias) this work.

Highlights

- A computational study of velocity and pressure fields during a sneeze was performed.
- Both normal and suppressed sneezes were investigated.
- Air pressure along the airway during a sneeze is much higher than normal breathing.
- Suppressing the sneeze increases the pressure in the respiratory tract markedly.
- The increased pressure can explain the reasons of reported injuries during a sneeze.