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Brief communication (Original)

Computational fluid dynamics study of the effect of posture on airflow characteristics inside the nasal cavity

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Background: Postural changes in nasal airway resistances are of clinical importance when assessing patients with nasal obstruction. Computed tomography (CT) that is used in computational fluid dynamics (CFD) studies is obtained in a supine position, and it is therefore important to identify whether different positions such as supine, prone, and standing/sitting have any influence on flow behavior inside the nasal cavity.

Objectives: To study the effect of posture on modeling nasal airflow and evaluate its influence in determining wall shear stress and other parameters.

Method: A three-dimensional nasal cavity model was constructed based on CT images of a healthy Malaysian adult nose. Navier–Stokes and continuity equations for steady airflow were solved to examine inspiratory nasal flow.

Results: Around a 0.3% change in the average static pressure is observed while changing from a sitting to supine position. A significant drop in velocity was seen while shifting from sitting to supine position.

Conclusion: The gravity effect resulting from postural change influences flow parameters suggesting that future CFD studies should consider posture when conducting analyses. The implication of this study on posture holds importance in future studies of drug delivery though the nasal cavity.

Keywords: CFD, posture, resistance, velocity, wall shear stress

Computational fluid dynamics (CFD) has been used to improve the characterization of airflow inside the nasal cavity [1-4]. CFD modeling involves various simplifications, for example of postural effects, which may affect the outcome of analyses. A three-dimensional (3D) model of the nasal cavity can be developed from magnetic resonance imaging (MRI) or computed tomography (CT). MRI or CT data can currently only be obtained from subjects in a recumbent posture [5]. Postural changes in nasal airway resistances are of clinical importance when assessing patients with nasal obstruction. Mohsenin et al. [6] demonstrated a postural decrease in pharyngeal cross sectional area and more likely occurrence of obstructive sleep apnea (OSA) in supine vs. nonsupine positions. Tvinnereim et al. [7] showed that nasal and pharyngeal resistance doubles upon assumption of a supine posture; however, the difference obtained was not statistically significant. Beaumont et al. [8] found that at sea level, gravity forces that cause the soft palate and tongue to fall back in the supine posture would narrow all upper airways along their length. Matsuzawa et al. [9] observed that MRI obtained in supine, lateral, and prone positions revealed that the upper airway was narrowest in the supine position, and widest in the prone position indicating the anatomical narrowing of the upper airway in the supine position especially in the pharyngeal area.

CFD studies on nasal airflow have provided a detailed understanding of physiological airflow behavior inside the nasal cavity. Moreover, studies of aerosol deposition and nasal drug delivery have improved therapeutic strategies. CT images considered

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in developing 3D models of nasal cavity have been only been obtained in a supine posture. For actions that include walking/running or that involve physical exercise, the intake of air is usually above 15 L/min, and therefore turbulent [1, 4]. This differs from the supine conditions, which is generally the position in which CT or MRI is obtained. Although changes in anatomical geometry because of postural changes may significantly affect analytical outcomes, they have not been taken into account in CFD studies. Change in posture affects airflow and this is related to the direction in which gravity acts. Therefore, it is important to quantify the effect of gravity on nasal airflow as a result of changes in posture.

A 3D nasal cavity model was reconstructed from CT images of a healthy Malaysian woman. A comparative study was conducted for supine, prone, and sitting/standing positions at a laminar flow rate of 15 L/min. The effect of gravity on modeling nasal flow and its effect on wall shear stress and other parameters were examined.

Methods

The study was based on an anatomical model of a normal nasal airway obtained from a CT scan of a healthy 39-year-old Malaysian woman from Universiti Sains Malaysia, Medical Campus Hospital. All necessary ethical clearance was obtained from our institutional ethics review board for the use of a human subject. The scan images were segmented slice-by-slice with an appropriate threshold value using MIMIC software (Materialise, Ann Arbor, Mich, USA). The 3D polyline data of the nasal cavity was processed in CATIA and meshed with unstructured tetrahedral elements using GAMBIT version 2.3.16 (Fluent, Lebanon, NH, USA). An optimized grid with around 500,000 elements was developed from the gradient adaptation technique. As seen in **Figure 1**, a grid independence test has been conducted in the same nasal cavity model using different mesh sizes. Each adaptation resulted in a new mesh and the variation in velocity parameter was noted for different locations until the variations were negligibly small. The findings show that the average velocity values do not change as the mesh resolution increased to 591878. Thus, the mesh with 577010 elements was used for our simulation. This was considered sufficient, taking into account the computational time and system memory.

The simulation was based on the Navier–Stokes equation for 3D airflow. Steady state laminar and turbulent airflow simulations were modeled. The airflow was laminar for flow rates up to 15 L/min as similar to the prediction by Wen et al. [1] and Riazuddin et al. [4]. The flow boundary conditions used were: (1) the nasal wall is rigid, (2) the effect of mucus is negligibly small, and (3) no-slip condition at the airway wall. By describing the mass flow inlet boundary at the nostril inlet and outflow boundary condition at the outlet, numerical simulation was carried out using the commercial CFD solver FLUENT version 6.3.26 (Fluent, Lebanon, PA, USA). A limitation of this study is that, although postural changes effect the anatomical architecture of the nasal cavity, only gravity change has been considered for simulation. This is because it was not possible to obtain CT images of the same subject in the different postures because of limitations associated with the scanner.

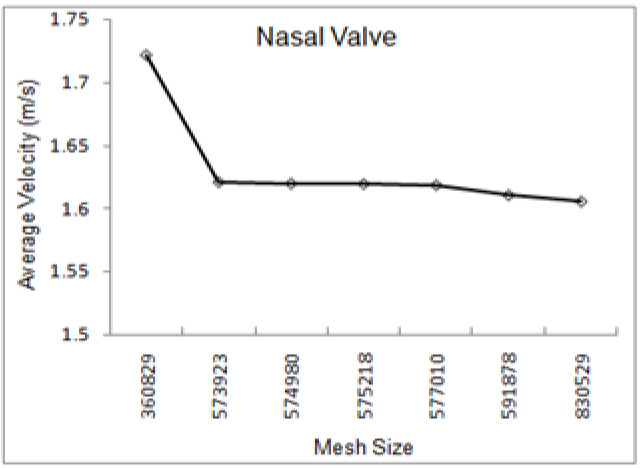

Figure 1. Grid independency study at the nasal valve

Results

Figure 2 shows the variation of average static pressure at different distances from the nostril inlet. Along the middle region the average static pressure decreases as we change position from sitting to supine. Around a 0.3% change in the average static pressure is observed while changing from sitting to supine position. **Figure 3** shows the variation in the maximum velocity beyond the nasal valve region (3.5 cm to 7.5 cm). The effect was more pronounced near the nasopharyngeal region. The change in posture also had significant effect on the wall shear stresses as can be observed from **Figure 4.** Around a 6.6% change in maximum wall shear stress was found just beyond the nasal valve region when subject changed position from sitting to right recumbency. The contours shown in **Figure 5,** clearly highlight the changes incurred in flow separation because of posture variations.

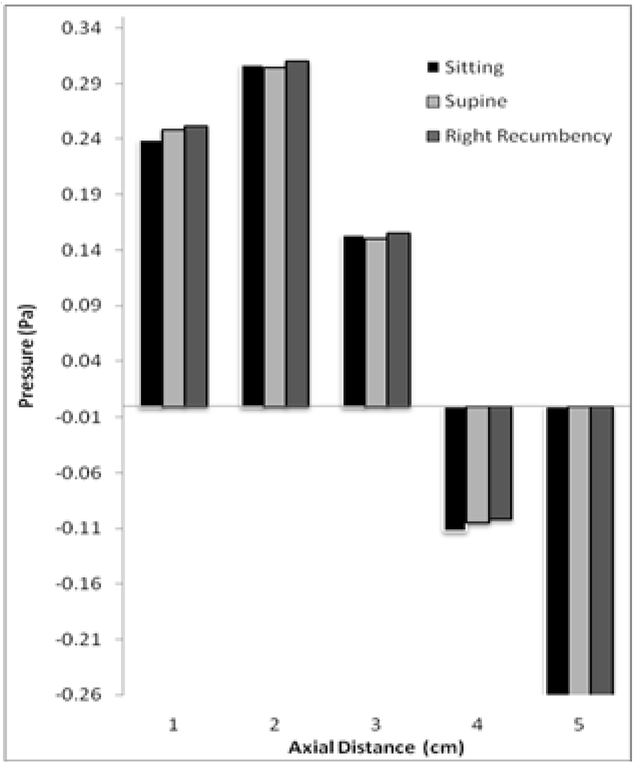

Figure 2. Variation of average static pressure with posture

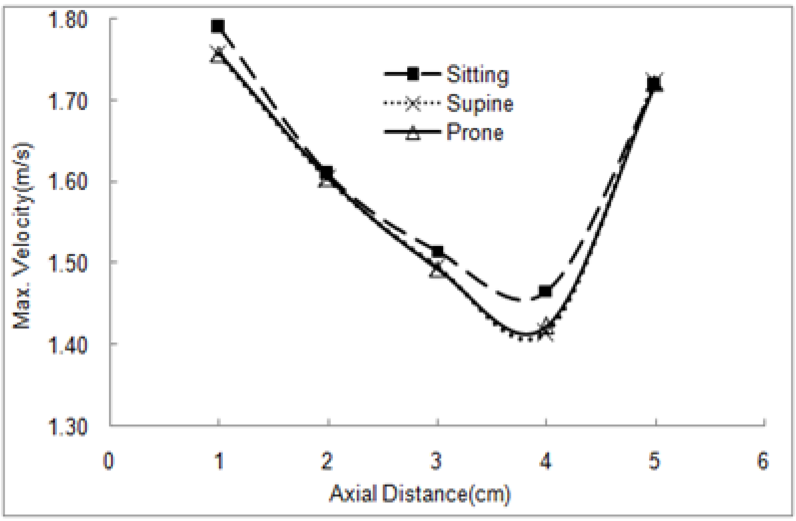

Figure 3. Effect of change of posture on velocity

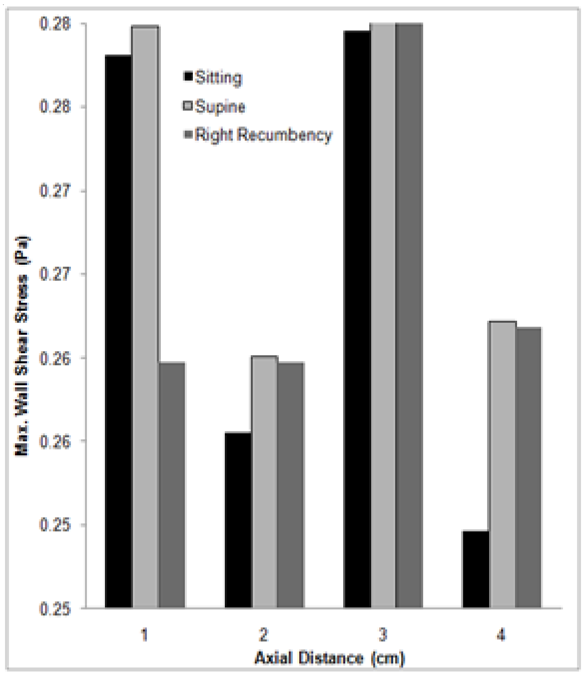

Figure 4. Variation in maximum wall shear stresses with change of posture

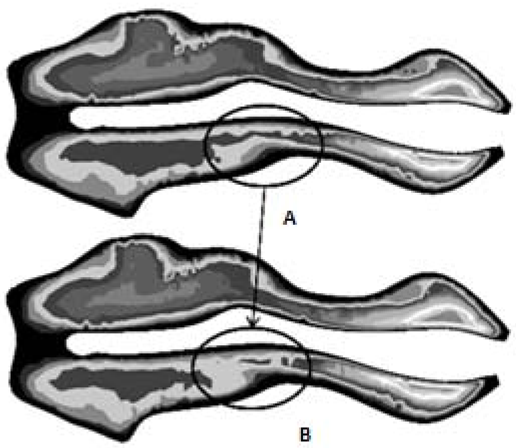

Figure 5. Flow variations along a horizontal plane at middle meatus region (**A**) sitting, (**B**) supine

Discussion

The influence of postural changes on airflow in the nasal cavity has been investigated in this study. Many reasons have been cited for increases in the nasal resistance, from increase in the central venous pressure resulting in congestion of the nasal mucosa, to pressure from body areas resulting in a change in nasal resistance [10]. Thus, postural changes are an important determinant of upper airway dimensions. The aggravating effect of a supine body position on breathing abnormalities during sleep is attributed to the effect of gravity on the upper airway [11]. A recent review by Zubair et al. [12] has emphasized the need to conduct posture modeling because of CT data obtained with subjects in a supine position.

Although the literature cites variation in the pharyngeal area with changes in posture, keeping in mind the ethical issues in procuring the CT data, and the difficulty involved in obtaining CT images of subjects in a sitting posture, only CT data obtained in a supine position has been used to study the effect of posture on airflow. Therefore, this study is limited in that it assumes no changes in the dimensions of the nasal cavity associated with a change in posture.

Nevertheless, the change in the direction in which the gravity acts because of the change of posture is considered for this study. Four postures: sitting, supine, prone, and right recumbent right, were considered. The acceleration because of gravity is taken to be 9.81 m/s^2 at sea level and a body force weighted pressure discretization scheme is adopted that takes into account the discontinuity of explicit body forces (e.g. gravity, swirl).

As seen from **Figure 2**, around a 0.3% change in the average static pressure is observed while changing from a sitting to a supine position. Along the middle region of the nose the average static pressure decreases as we change position from sitting to supine. Significant changes were observed on shifting to a right recumbent position. These results show the influence of gravity associated with the change in posture. **Figure 3** shows the variation in the maximum velocity beyond the nasal valve region (3.5 cm to 7.5 cm). A significant drop in velocity can be seen while shifting from sitting to supine position. Around a 3.6% change in velocity was obtained between sitting and supine position. This variation might also explain the prevalence of snoring among male subjects who demonstrate much smaller posterior nasal regions. However, no much variation in velocity was observed between the supine and the prone position.

The change in posture had significant effect on the wall shear stresses as can be observed from **Figure 4**. Just beyond nasal valve region, around a 6.6% change was observed when subject changed from sitting to right recumbency. However, at the middle section of the nose, change from sitting to supine increased the wall stress under supine position. The contours shown in **Figure 5**, highlight the effect of change of posture on the flow separation. We can observe that the flow along the right nasal cavity decreases when changing posture from sitting to supine. The flow is fully developed in the right nasal cavity in sitting position (Figure 5A) in comparison with a supine posture.

Hence, the numerical modelling associated with posture dynamics has an effect. Posture will affect the type of boundary condition employed in CFD models [13, 14]. Therefore, while applying boundary conditions in the study of nasal flow using CFD; we must take into account the effect of posture and gravity. To our knowledge, none of the previous numerical flow analyses take into account the effect of posture and gravity. Therefore, to accurately predict the flow features inside the nasal airway path, we must specify the posture and apply appropriate boundary conditions.

Conclusion

The gravity effect resulting from changes in posture influences the airflow through the nasal cavity. This study on posture holds importance in the future study of therapeutic drug delivery and determination of an appropriate posture for the drugs to reach desired locations inside the nasal cavity.

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