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RESEARCH ARTICLE



Computational investigation of dust mite allergens in a realistic human nasal cavity

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ABSTRACT

Aim: Inhaled allergens from house dust mite (HDM) are a major source of allergic disease such as allergic rhinitis and asthma. It has been a challenge to properly evaluate health risks caused by HDM related allergens including mite bodies, eggs and fecal pellets. This paper presents a numerical study on particle deposition of dust mite allergens in a human nasal cavity.

Materials and methods: A realistic nasal cavity model was reconstructed from CT scans and a Computational Fluid Dynamics analysis of steady airflow was simulated. The discrete phase model was used to trace particle trajectories of three dust mite related particles.

Results: The flow and particle model were validated by comparing with nasal resistance measurement and previous literature respectively. Aerodynamic characteristics and deposition of dust mite allergens in the nasal cavity were analyzed under different breathing conditions including rest and exercising conditions.

Conclusions: The numerical results revealed the roles of different nasal cavity regions in filtering various types of dust mite allergens with consideration of breathing conditions.

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KEYWORDS

Human nasal cavity; inhaled allergens; house dust mite; particle deposition

Introduction

House dust mites (HDM) live in common furniture such as beds and carpets and produce allergens including their fecal pellets, eggs and bodies (dust mite allergens). As the world's largest source of allergens, HDM feces play a major role in allergic disease, especially in allergic rhinitis and bronchial asthma (Colloff 2009). It's estimated that people spend approximately 90% of their time in indoor environments (Ge Q et al. 2013) and roughly 1–2% of the world population (65–130 million people) suffer from dust mite allergens (Colloff 2009) as a result of dusting, vacuuming, bed making, and other domestic activities that re-disperse settled dust into the air.

Dust mite allergens suspended in the air are inhaled into respiratory tract through the nasal cavity. As a principal channel of entry into the human body for aerosols, the nasal cavity has a significant role in respiratory defense by filtering allergen particles, thus serving as the first barrier to prevent inhaled dust mites. The nasal cavity is a complex organ with multiple functions including olfaction, and air conditioning (e.g. humidifying, warming, and filtering) of inhaled air. The nose serves as a 'scrubbing tower' that removes inhaled pathogens that may be harmful to the more sensitive epithelial tissues in the lower tracheobronchial airways and pulmonary parenchyma (Morris and Shusterman 2016).

Therefore, to evaluate the health risks caused by dust mite allergens, it's crucial to investigate the allergen particle deposition in the nasal passage and its interaction with airflow patterns under different breathing conditions.

In the past, conventional plastination of cadaver noses were used to study general characteristics of nasal airflow (Cheng et al. 1999). Such models however, were inaccurate due to shrinkage of mucous membranes or insertion of casting materials, and limited outcomes were shown in view of a patient-specific approach. Acoustic rhinometry is an effective, noninvasive test, for revealing the variation in cross-sectional area of the airways as a function of the distance from the nares. However, rhinomanometry is difficult to analyze details of the flow especially in crucial region of the inferior and middle meatus and only provides a general assessment depicted from a complex fluid dynamics pattern.

In recent years, with the rapid development of manufacturing, computer technology and medical imaging, nasal cavity casts and computational fluid dynamics (CFD) methods are widely used as powerful tools for performing virtual surgery to achieve optimal outcomes. Experimental and numerical study of the flow dynamics and the particle deposition in the nasal cavity has been the subject of many researches. Work by Zachow et al. (2006), Tian et al. (2007),

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Inthavong et al. (2013a), Patel et al. (2015), Shang et al. (2017) and Dong et al. (2018) are examples of some recent numerical studies for the airflow in the physiological perspective. The work of Garcia et al. (2007) and Wakayama et al. (2016) are examples of some recent numerical studies for the airflow in the pathological perspective. Rhinologists used this approach to simulate surgeries for nasal septum deviation, turbinate surgery, maxillary sinus ventilation and nasal septum perforation repair (Morgan and Monticello 1990; Chen et al. 2011; Xiong et al. 2011; Ge QJ et al. 2012; Zhou et al. 2013; Kumar et al. 2016; Lee et al. 2016). Results indicate that CFD is a promising research method compatible with precision medicine. Research performed by Zamankhan et al. (2006), Xi and Longest (2008), Inthavong et al. (2008), Wang et al. (2009), King Se et al. (2010) and Shang et al. (2015) presented numerical results for the micro/nanoparticle deposition in the nasal cavity.

To date, none of these studies investigated the deposition of the allergens derived from house dust mites in the respiratory tract. In previous CFD simulations, due to restricted quality of CT-scanning, over-simplified nasal cavity models were widely used by neglecting sinuses due to difficulty during airway segmentation. Previous studies mostly demonstrated the applicability of the numerical models but missing the detailed analysis in aspects of clinical applications, especially for the dust mite particles. Therefore, research about the allergic particle deposition of dust mite in the nasal cavity is of great importance in both risk evaluation of allergic particles and aerosol therapy.

In this paper, CFD simulation was performed on a realistic nasal cavity model reconstructed from high quality CT-scan datasets acquired by a Siemens Dual Source CT machine. The airflow velocity fields were validated by comparing nasal resistance that was measured by a commercial rhinomanometry. Particle trajectories and deposition locations in the nasal cavity wall were recorded for three types of dust mite allergens, e. g. mite bodies, eggs and fecal pellets. The flow characteristics of fluid phases were then analyzed in detail to better understand the deposition of dust mite allergens at the anterior-middle turbinates and their projections on the thickened nasal septum mucosa called nasal swell body. Finally, the effects caused by variations in inhalation flow rate and change in body positions were discussed.

Methods

Realistic nasal cavity reconstruction

This research was approved by the institutional review board at the second affiliated hospital of the Xi'an Jiaotong University (Shaanxi Province, China), and informed consent was obtained from the volunteer. The realistic nasal cavity geometry was reconstructed from high-quality CT scans of a healthy 25-year-old, Asian female (161 cm height, 53 kg mass, without nasal septum deviation, turbinate hypertrophy and sinusitis) at rest condition. The CT data was scanned by the Siemens Dual Source CT Machine and parameters of CT images were 0.39×0.39 mm in pixel size, 512×512 in image dimension and 0.5 mm in slice thickness.

The nasal cavity model was reconstructed in two steps. Firstly, CT data in DICOM format was segmented in an open-source software 3D-Slicer (Version 4.10, developed by Fedorov et al. (2012) and Kikinis et al. (2014)). The nasal passages and all paranasal sinuses including maxillary, ethmoid, frontal and sphenoid sinuses, were segmented. Previous research has shown that the existence of facial features significantly affects airflow entrance at the nostrils (Anthony et al. 2004; Inthavong, Wen, et al. 2009; Yidan et al. 2015). Therefore, the geometry of face was retained and a hemisphere with a diameter of 200 mm was attached in front of the face. An 80 mm extension was added to the nasopharynx to ensure a fully developed flow at the outlet. The surface boundaries were exported to the reverse-engineering software Geomagic Wrap (Version 2017, 3D Systems, Rock Hill) for surface optimization and separating anatomical regions.

Figure 1 shows surface geometry and anatomy inside the model through two sagittal (a, b) and two coronal (c, d) cross-sectional slices. The cross-sections show locations of characteristic nasal structures including inferior/middle turbinates, inferior/middle meatus, nasal vestibule and all the paranasal sinuses. Cross-section b also reveals the nasal swell body, which is a key structure to protect nasal cavity from inhaled allergens.

The nose is divided into the left and right chambers by the septum; the nasal turbinates further separate each nasal chamber into three passages, namely the inferior meatus (IM), middle meatus (MM) and superior meatus (SM). The paranasal sinuses (maxillary, sphenoid, ethmoid and frontal) are air-filled spaces connected to the nasal cavity by narrow passageways called ostia. Detailed geometry data is given in Table 1 for key anatomy is used in the analysis for its role in filtering dust mite allergens.

Mathematical model description

Steady-state, inspiratory flow was modeled in Fluent 19.2 (ANSYS Inc) using a laminar model for a flow rate of 15 L/min and a $k-\omega$ -SST turbulence model for a flow rate of 30 L/min. Due to low particle concentration in the airflow, the effect of particle motion on the flow was neglected and the one-way coupled Lagrangian method to track particle trajectories was used. In this method, the airflow field was simulated first and then the trajectories of individual particles were calculated. For the nano-particles, the deposition is mainly affected by Brownian diffusion. But for the micron ranged particles, typically larger than $1 \mu\text{m}$, deposition by inertial impaction becomes dominant and the effect of Brownian diffusion becomes negligible (Inthavong, Wen, et al. 2009; Shang et al. 2015). In this study, only the gravity and the drag force were considered for tracking the dust mite particles. The motion of particles in Cartesian coordinates was given as:

$$\frac{du_p^i}{dt} = F_D(u_i^g - u_p^i) + g_i \left(1 - \frac{\rho^g}{\rho^p}\right) \quad (1)$$

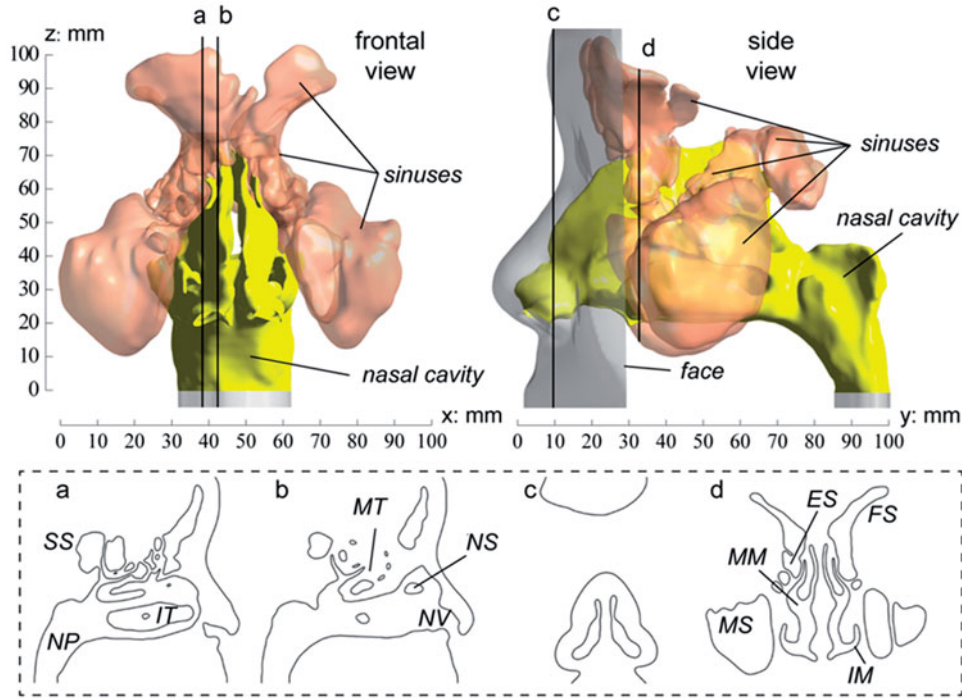


Figure 1. Nasal cavity geometry and inner anatomy of the nasal airway model: frontal view (left); side view (right). Planar slices in the sagittal (slice-a and b) and coronal planes (slice c and d) are given. The abbreviations are: NP: nasopharynx; IT: inferior turbinate; SS: sphenoid sinus; MT: middle turbinate; NV: nasal vestibule; NS: nasal swell body; MM: middle meatus; IM: inferior meatus; MS: maxillary sinus; FS: frontal sinus; ES: ethmoid sinus.

Table 1. Geometric information of some key nasal anatomy.

	Nasal vestibules	Inferior turbinates	Middle turbinates	Nasal septum	Nasopharynx	Maxillary sinus
Range in x-axis (mm)	35–45 (right), 50–60 (left)	30–40 (right), 52–62 (left)	38–44 (right), 50–57 (left)	42–50	32–61	0–30 (right) 60–91 (left)
Range in y-axis (mm)	0–20	20–63	30–68	10–70	70–100	25–67
Range in z-axis (mm)	28–42	32–43	45–55	30–70	0–30	18–63

The drag force F_D is dependent on the drag coefficient C_D , which was defined in Morsi and Alexander (1972)'s work:

$$C_D = \frac{F_D}{\frac{1}{2} \rho^f (u^f - u^p)^2 A} = a_1 + \frac{a_2}{Re} + \frac{a_3}{Re^2} \quad (2)$$

Where, a_1 , a_2 and a_3 are empirical constants for smooth spherical particle over several ranges of droplet Reynolds number.

Dust mite allergens are usually suspended in the air or found on the bed. In the particle tracking simulation, particles were released at the nostrils. Shapes of dust mite allergens can be characterized using a shape factor ϕ to determine particles' equivalent aerodynamic diameters:

$$\phi = S_{\text{sphere}} / S_{\text{ellipsoid}} \quad (3)$$

Where, $S_{\text{ellipsoid}}$ is the actual surface area of the dust mite body or the mite egg, and S_{sphere} is the equivalent surface area of a sphere that has the same volume. Detailed shape factors of dust mite bodies, mite eggs and fecal pellets are listed in Table 2. Haider and Levenspiel (1989) developed a model to define the C_D as a function of particle Reynold's number and shape factor. However, Gabitto and Tsouris

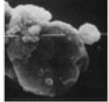
(2008) reported that the model is not a propriate method to predict non-spherical transport with small shape factors.

Tran-Cong et al. (2004) experimentally investigated aggregated particles and developed a novel model by using three parameters: nominal diameter ($d_n = \sqrt{6V/\pi^3}$), surface equivalent sphere diameter ($d_A = \sqrt{A_{\text{proj}}/\pi}$) and circularity ($c = \pi(d_A/P_{\text{proj}})$). A_{proj} and P_{proj} are projected area and perimeter in particle's direction of motion. The correlation for the drag coefficient was empirically modified as,

$$C_D = \frac{24}{Re_p} \frac{d_A}{d_n} \left[1 + \frac{0.15}{\sqrt{c}} \left(\frac{d_A}{d_n} Re_p \right)^{0.687} \right] + \frac{0.42 \left(\frac{d_A}{d_n} \right)}{\sqrt{c} \left[1 + 42,500 \left(\frac{d_A}{d_n} Re_p \right)^{-1.16} \right]} \quad (4)$$

This correlation was experimentally fitted from measurements on falling fibers using spherical aggregate particles clustered into a cylindrical bar configuration. The implementation of this correlation into FLUENT user-defined functions were the same with authors' previous studies (Inthavong et al. 2008; Inthavong et al. 2013b).

Table 2. Shapes images of dust mite bodies, mite eggs and fecal pellets.

Shape	Typical size range	Density	Real image		Shape factor	d_{ae}
Ellipsoid	Dust mite body length: 230 – 515 μm , width: 150 – 340 μm p110, Colloff (2009)	1000 kg/m ³		$a = 186 \mu\text{m}$ $b = 123 \mu\text{m}$	0.97	280 μm
Ellipsoid	Mite eggs length: 160 – 180 μm , width: 70 – 90 μm p216, Colloff (2009)	1000 kg/m ³		$a = 85 \mu\text{m}$ $b = 40 \mu\text{m}$	0.92	100 μm
Sphere	Fecal pellets (single) Diameter: 10 μm p54, Colloff (2009)	1000 kg/m ³		$a = b = 5 \mu\text{m}$	1.0	10 μm

Another popular correlation for the equivalent aerodynamic diameter (d_{ae}) was developed by Stöber (1972) to normalize the non-spherical particle size,

$$d_{ae} = d_{ve} \sqrt{\rho / (1000\kappa)} \quad (5)$$

Where, d_{ve} is the volume equivalent diameter, ρ is the particle density and κ is the dynamic shape factor introduced by the orientation of the non-spherical particle. For random orientated particles, the dynamic shape factor is determined by a perpendicular sub-factor $\kappa_{\perp}$ and a parallel sub-factor $\kappa_{\parallel}$ (Kulkarni et al. 2011),

$$\frac{1}{\kappa} = \frac{1}{3\kappa_{\parallel}} + \frac{2}{3\kappa_{\perp}} \quad (6)$$

$$\kappa_{\perp} = \frac{8}{3} \frac{(\beta^2 - 1)\beta^{-1/3}}{(2\beta^2 - 1) \ln(\beta + \sqrt{\beta^2 - 1}) + \beta} \quad (7)$$

$$\kappa_{\parallel} = \frac{4}{3} \frac{(\beta^2 - 1)\beta^{-1/3}}{(2\beta^2 - 3) \ln(\beta + \sqrt{\beta^2 - 1}) - \beta} \quad (8)$$

Where, β is the aspect ratio calculated by the ratio of particle length to diameter. Corresponding aerodynamic sizes are listed in Table 2 for comparison.

Mesh generation, boundary conditions and simulation setup

The nasal cavity model was imported into Fluent-Meshing (Version 19.2) for mesh grid generation. A polyhedral mesh with three prism layers was created to achieve more reliable discretization quality for the complex nasal geometry compared to a tetrahedral mesh (Figure 2).

Mesh independence test was performed by comparing velocity on a characteristic line under 15 L/min flow rate with coarse, medium and fine tetrahedral meshes. The characteristic line started from the tip of the right nostril and ended at the nasopharynx along the y -axis. The average velocity change was less than 1% when increasing mesh size

from 1.5 million to 4.0 million (Figure 3). As a result, the medium mesh with approximately 2.8 million cells was chosen for airflow simulation.

Boundary conditions were set as follows: (1) pressure in the ambient environment was set 0 Pa, (2) non-slip boundary conditions for nasal walls, and (3) outlet pressure was set to a value that resulted in 15 L/min of bilateral airflow, corresponding to adult breathing at rest, and a value that resulted in 30 L/min of bilateral airflow, corresponding adult breathing at exercise.

Hahn et al. (1993) and Kelly J et al. (2000)'s experimental work, as well as Keyhani et al. (1997)'s simulation suggested that airflow can be considered as laminar flow up to a rate of 24 L/min. Thus, laminar model was used for resting condition and k- ω transitional SST turbulence model was used for exercise condition.

Results and discussion

Model validation

The CFD results for pressure drop in the nasal geometry model was compared against rhinomanometry (Equipment Model NR6, GM Instruments) measurements for different flow rates. When measuring the pressure drop, the left nostril was blocked so that no air flowed through the left cavity, leading to the pressure of left nostril equivalent to the pressure at the choanae. A pressure probe was placed inside the left nasal cavity and the pressure drop between right nostril and choanae was calculated by subtracting probe pressure from environmental pressure. The measurement was performed 5 min before CT scanning. The reconstructed nasal cavity model was assumed consistent with the nasal geometry for pressure drop measurement. Figure 4(a) shows pressure drop against air flow rate comparison between numerical and experimental results plotted in the inspiration phase. The simulation results show good agreement with the experimental data.

For particle deposition, the inertial parameter $I = Qd_{ae}^2$ has been widely used for determining particle deposition rate by considering both particle sizes and flow rates, where

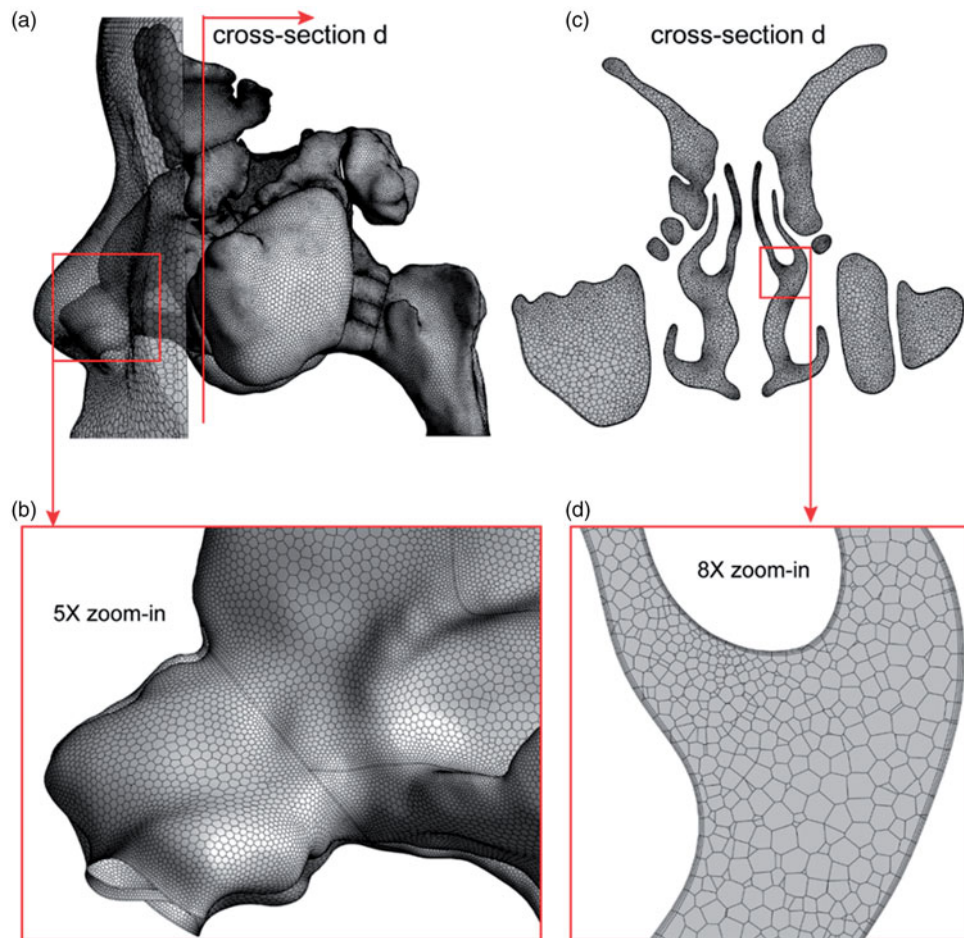


Figure 2. The nasal cavity model was discretized by polyhedral mesh created in Fluent-Meshing. (a and b) Show the surface mesh and (c and d) show the volume mesh on a cross-section that reveals major anatomical regions including nasal passages, maxillary, ethmoid and frontal sinuses.

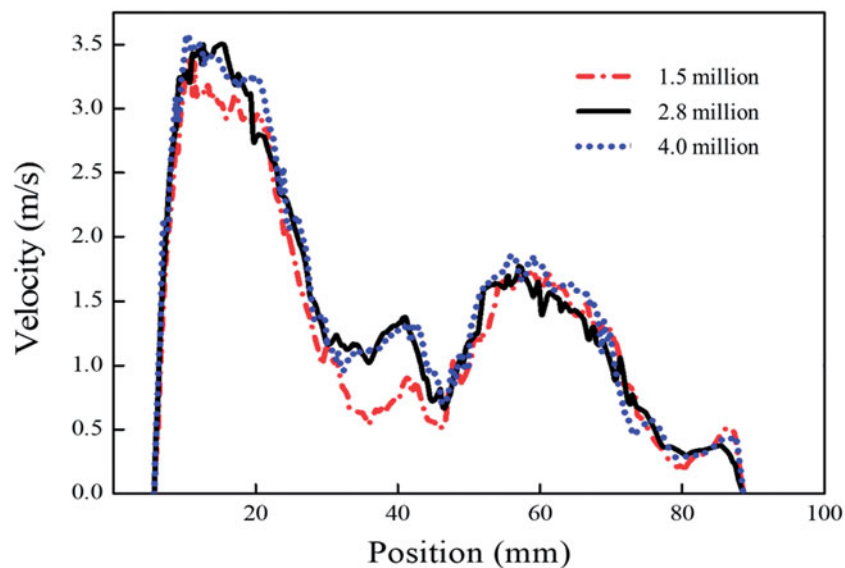


Figure 3. Mesh independent test. Velocity along a characteristic line from right nostril to nasopharynx along y-axis are plotted for coarse, medium and fine meshes. The final mesh selected for computation was the medium mesh that contains 2.8 M cells, 15.5 M faces and 11.0 M nodes.

Q is the air flow rate and d_{ae} is the aerodynamic equivalent diameter. Figure 4(b) shows deposition of micro-particles ranging from 1 to 30 μm for flow rates from 7.5 to 15 L/min increased as the inertial parameter increased. It can be

observed that the simulation results in this paper agreed well with Shi et al. (2007), and Schroeter et al. (2011)'s reported data for the inertial parameter less than 10,000 $\mu\text{m}^2\text{cm}^3/\text{s}$. The trend of the simulation results

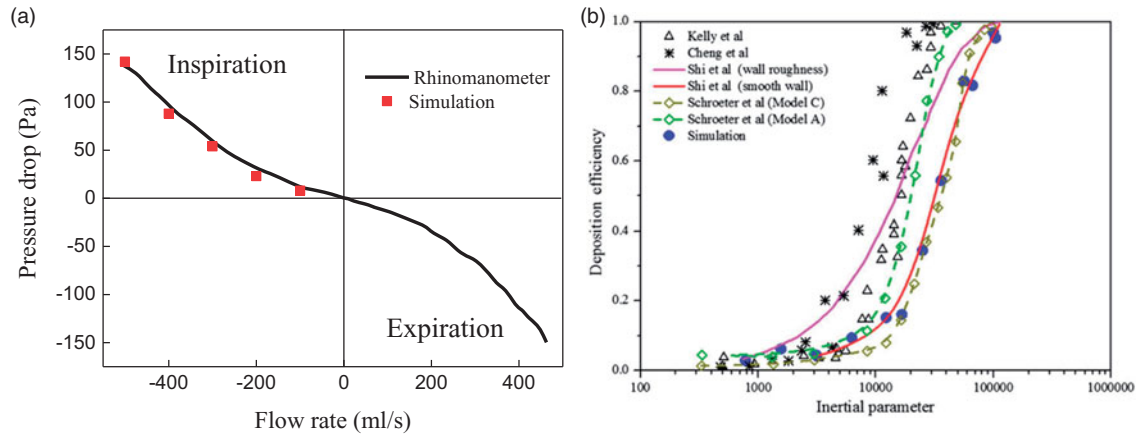


Figure 4. (a) Comparison of nasal resistances in right nasal cavity numerical red point, and experimental results. (b) Total deposition of particles between 1 and 30 μm with flow rate from 7.5 to 15 L/min as a function of inertial.

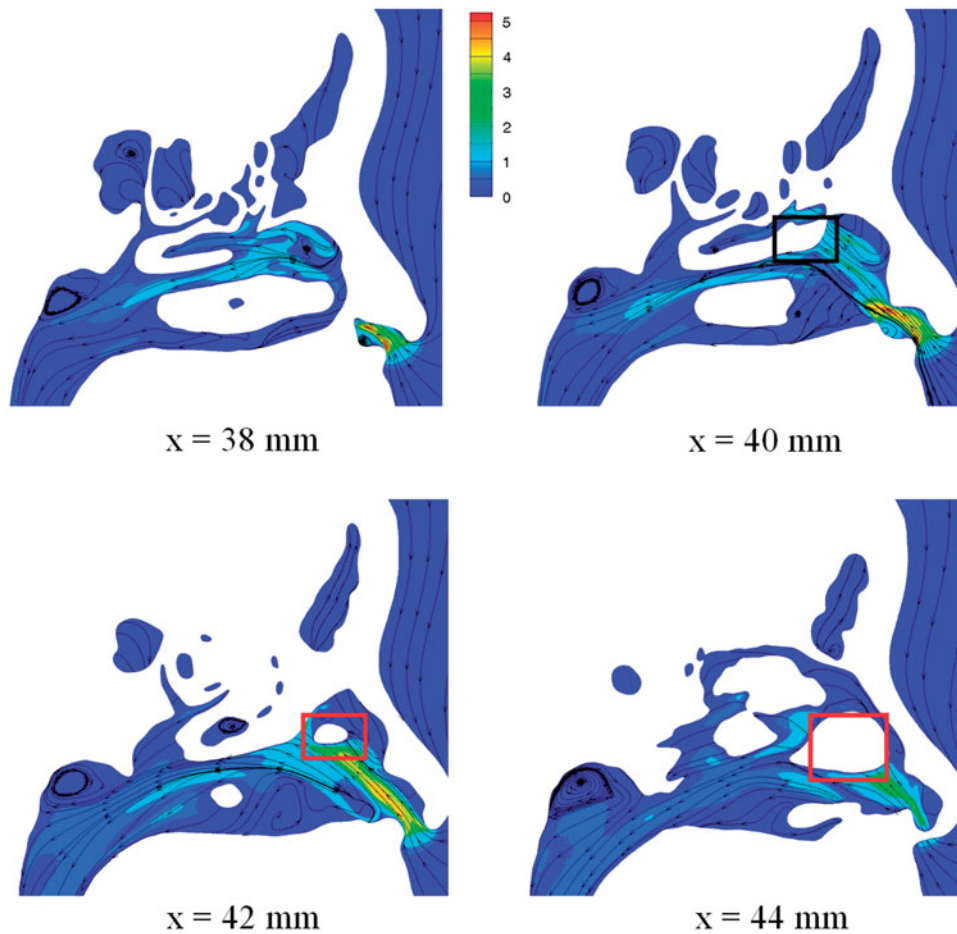


Figure 5. Velocity (m/s) contours and streamlines in x plane 38–42 mm under normal breathing conditions (the black square is the head of middle turbinates, the red squares are the nasal swell body).

matches Kelly JT et al. (2004), Cheng et al. (2001) and Shi et al. (2007)'s data although the value is considerably lower due to individual variations.

Characteristic of gas and particle flow

Airflow behavior

Flow streamlines were calculated from the left and right nostrils to reveal flow patterns on four sagittal planes,

located at $x = 38$ mm, 40 mm, 42 mm and 44 mm. Airflow enters uniformly from the nostril into the turbinate region and then experiences almost a 45° turn. This turn occurs due to two structures, the nasal swell body just beside the vestibule and the anterior part of middle turbinates (see slices $x = 40$ mm, $x = 42$ mm, Figure 5), changing the flow direction from 45° upward to a horizontal direction. The streamlines (Figure 5) and the velocity vectors (Figure 6) around these two structures show the airflow encounters the

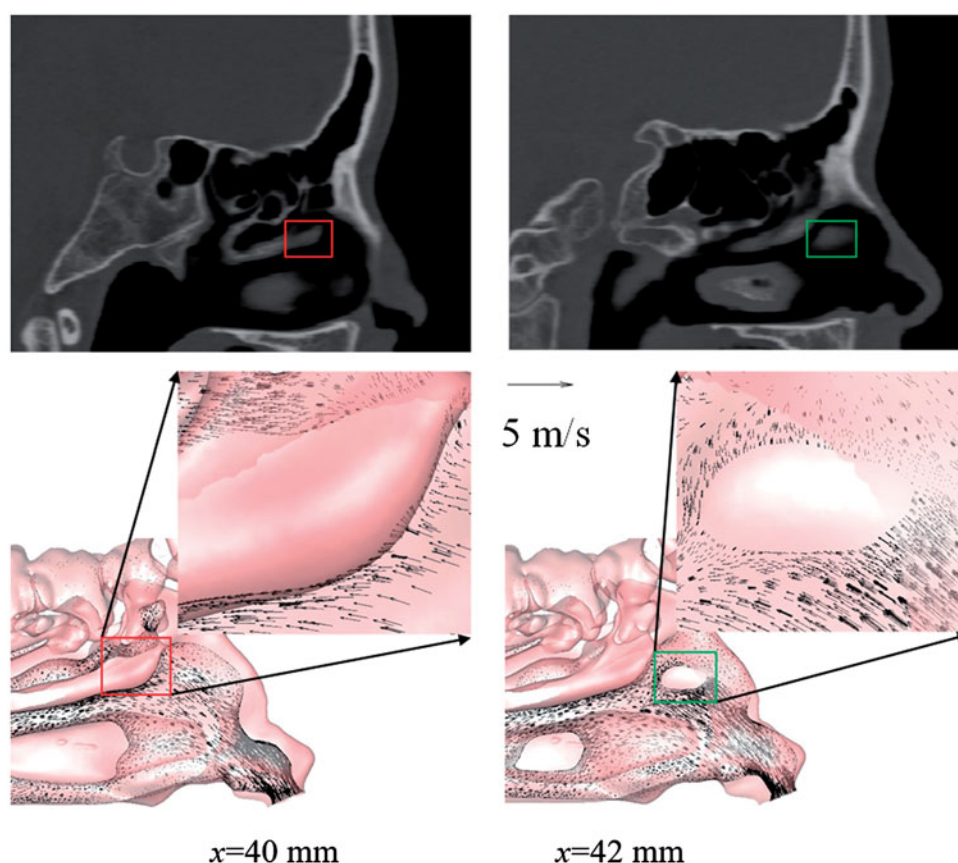


Figure 6. CT scans and velocity (m/s) vectors in x plane 40, 42 mm under normal breathing conditions (red square is the head of middle turbinates, and green square is the nasal swell body).

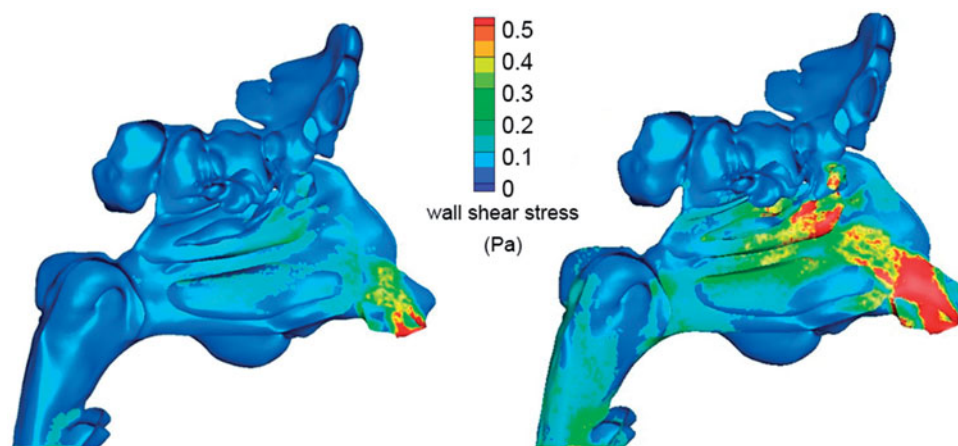


Figure 7. Comparison of mucosal wall shear stress contours under (a) normal breathing, 15 L/min and (b) exercising breathing, 30 L/min conditions.

nasal swell body with a relatively high velocity of 4 m/s suggesting high possibility of inhaled particles to deposit in this region.

Mucosal wall shear stress

Wall shear stress (WSS) is the tangential shearing force produced by air passing over the mucosal surface. It is a function of the velocity gradient of air at the mucosal surface. Figure 7 shows high WSS is concentrated at the antero-inferior part of the nasal septum (also referred to as Little's area,

which is an anastomosis of blood vessels over the nasal septum). The Little's area is susceptible to epistaxis (Supriya et al. 2010; Nitek et al. 2011). Studies based on CFD modeling have demonstrated a much higher shear stress over the Little's area, thus contributing to its propensity for spontaneous epistaxis (Bailie et al. 2009; Cannon et al. 2013). High shear stress was also found at the anterior regions of the middle turbinates that confront the oncoming airflow. The anterior middle turbinates exhibited higher wall shear than the anterior inferior turbinates. It was evident that the higher the flow rate, the larger area of high shear force appeared.

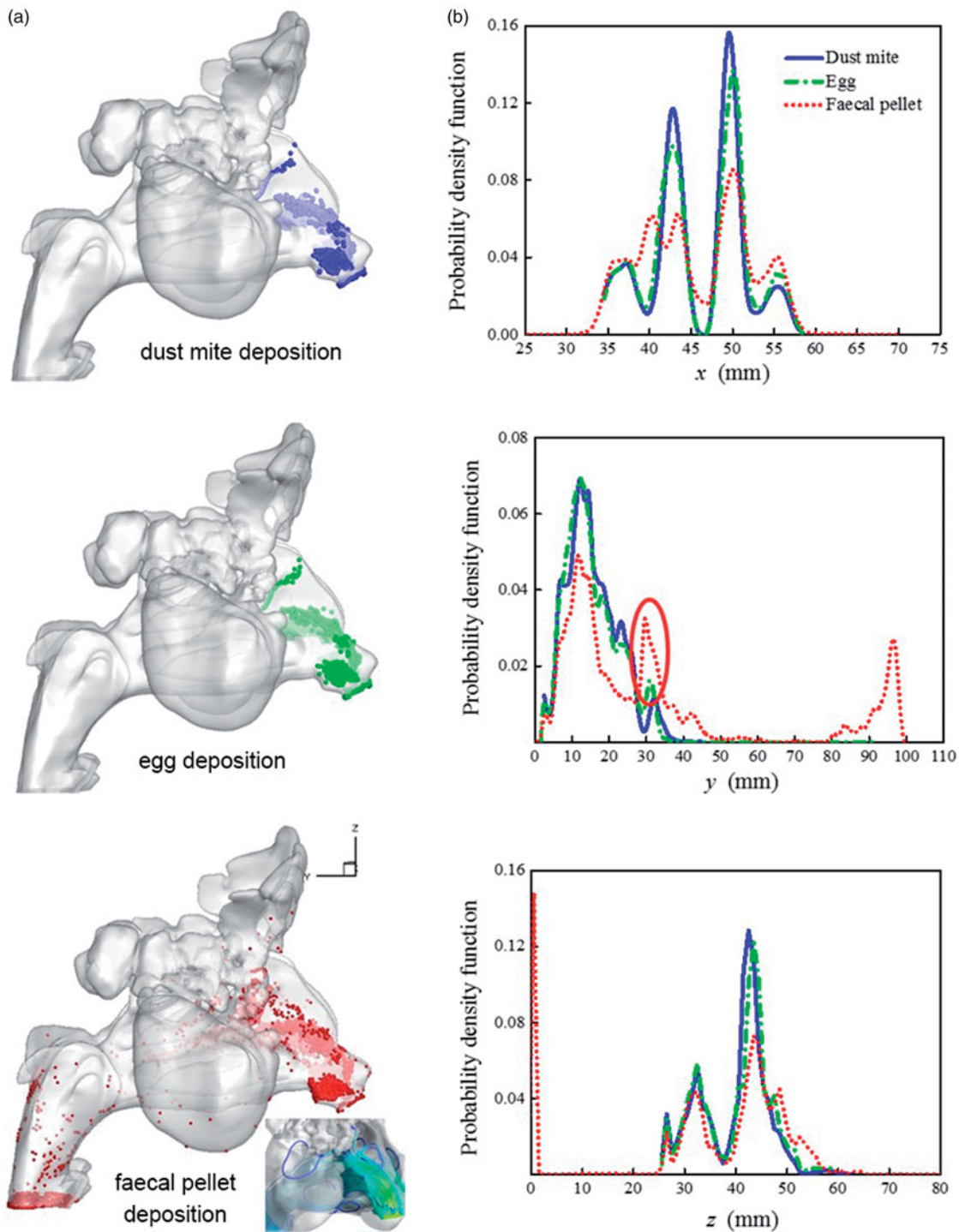


Figure 8. (a) Surface deposition of dust mite allergens with different particle sizes (blue for dust mite; yellow for the eggs; and red for the faecal pellets) under normal inspiratory conditions. (b) Probability density function (PDF) deposition profiles in x (sagittal), y (coronal) and z (transverse) axis.

Particle deposition

Particle deposition in the nasal cavity can occur by four mechanisms: inertial impaction, Brownian diffusion, and to a lesser extent, gravitational sedimentation and interception. For micron particles, larger than $1\ \mu\text{m}$, the effect of particle inertia becomes important and deposition by inertial impaction becomes dominant. Inertial impaction occurs due to the particles departing from the air streamlines, thus moving more tangentially and more likely to deposit on the near wall (Inthavong, Tu, et al. 2009). Studies have shown that

the sharp curvatures in the nasal cavity airway that change the airflow direction are responsible for inertial deposition of micron particles (Inthavong et al. 2011). This is particularly significant at the entrance to the main nasal passage and at the nasopharynx where the flow exhibits 90° curvatures.

To gain insight into the spatial distribution of inhaled dust mite bodies and eggs, deposited particle locations were plotted as probability distribution function (PDF) lines along X (sagittal axis), Y (coronal axis), and Z (transverse

axis) directions. Figure 8 shows the distribution profiles of the dust mite body (blue markers) and egg (green markers) are generally almost the same. The main deposition region was found at the anterior region, at $y=35$ mm from the nostril. Xi et al. (2014) also found a similar phenomenon for $30\mu\text{m}$ and larger particles that generally were filtered out before passing through the nasal valve. The first deposition peak was found in the nasal vestibule in both nasal chambers, where the cross-sectional area changed from narrow to wide and then back to narrow. The airflow in Figure 5 ($x=38$ mm) showed a high velocity impacting onto the outer vestibule wall, suggesting it serves as an impaction collector to filter allergens. The second highest concentration region for the deposited dust mite body and egg particle occurred at the anterior middle turbinates and the nasal swell body where the main airflow changed directions from 45° vertical, to a horizontal direction. These critical locations combined with high-velocity flow impacting onto the surface walls, and sharp directional flow changes, effectively captured the inhaled particles.

To date, there are only a few CFD studies which investigated particle deposition through the nasal cavity taking the paranasal sinuses into consideration (Zachow et al. 2007; Abouali et al. 2012; Ge QJ et al. 2012). However, these studies either over simplified the nasal vestibular structure, or overlooked the real nostril anatomical shape and its opening, making it difficult to observe the deposition of particles on the outside of the nasal vestibule, as well as the accurate representation of the inhaled inlet condition.

Most small particles (fecal pellets) deposited in the frontal but deeper zone of the nose and were able to penetrate into the maxillary sinus and pass through the nasopharynx (Figure 8). About one-third of human nasal cavities have an accessory ostium maxilare, but none of the previous

investigations described its function with CFD results. The fecal pellet deposition within the sinuses or around the ostia is important due to their potential clinical consequences. The airflow was observed to enter the maxillary sinus from the ostium maxilare and out of it from the accessory ostium maxilare. This offers a flow path which fecal pellets could enter the maxillary sinus while a single-ostium sinus can be considered a reservoir of fluid attached to the nose. The resulting flow through the right ostium-sinus was $4.205 \times 10^{-6} \text{ m}^3/\text{s}$, with the average flow rate being 0.1199 m/s . These findings contradict the report by (Ge QJ et al. 2012) and (Hood et al. 2009) that ostium sinus ventilation is limited (unless the ostium is very large) and that the gas exchange of nitric oxide between the air in the maxillary sinus and the nasal air does not contribute greatly to the overall nitric oxide concentration. However, this study's result showed that the existence of the accessory ostium maxilare structure enhances the flow into the maxillary sinus.

Effects of variables

Different airflow

To better understand the behavior of mite particles under different flowrates, an increased airflow of 30LPM (litres per min) was simulated representing exercising or deep breath condition, and the deposition results are given in Figures 9 and 10.

Figure 9 shows dust mite peak deposition occurring at 7–14 mm in y -axis and 28–35 mm in the z -axis which increase for 30LPM due to increased deposition rate in the nasal vestibule. The deepest position which mites penetrated into the nasal cavity in the y -axis was from 30 to 45 mm (Ghalati et al. 2012). For fecal pellet particles, the deposition

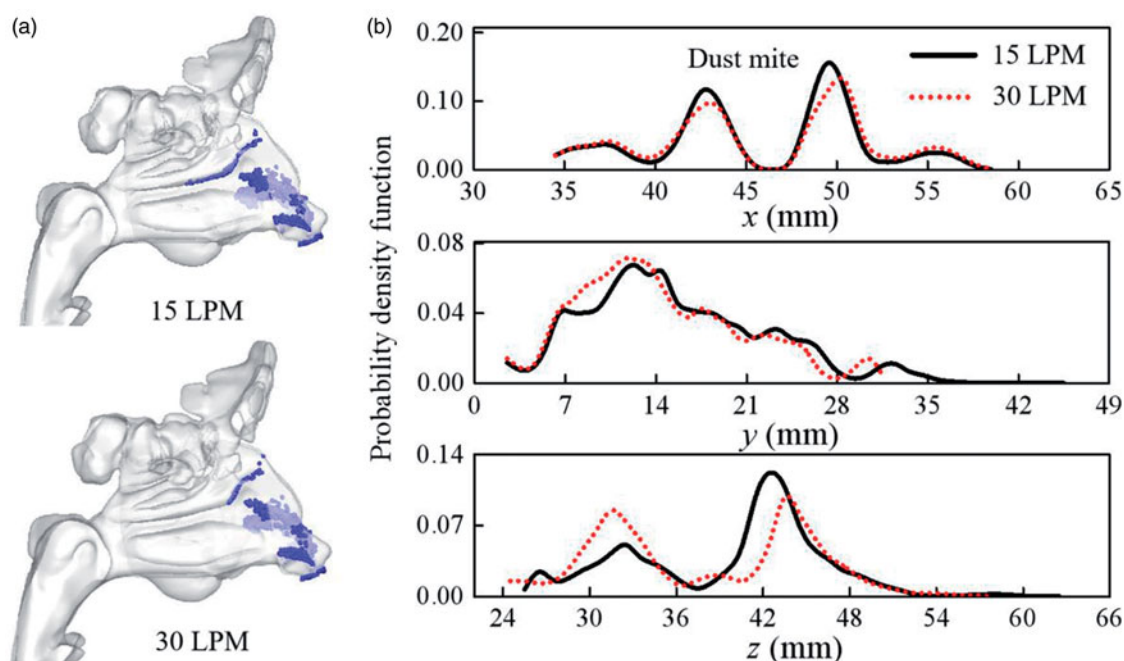


Figure 9. (a) Surface deposition of dust mite body from $x=36$ to 48 mm under the normal inspiratory condition and exercising inspiratory condition. (b) Probability density function (PDF) deposition profiles in x (sagittal), y (coronal) and z (transverse) axis.

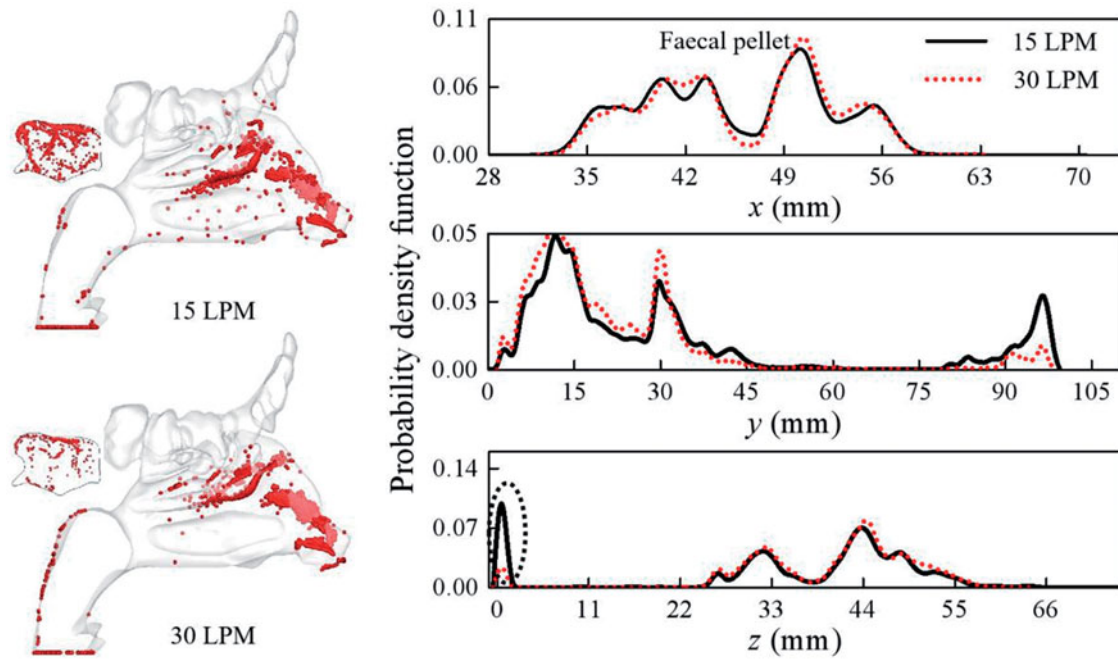


Figure 10. Left: surface deposition of fecal pellet from $x=36$ to 48 mm under the normal inspiratory condition and exercising inspiratory condition. Right: the density function (PDF) of the fecal pellet in x , y and z -axis.

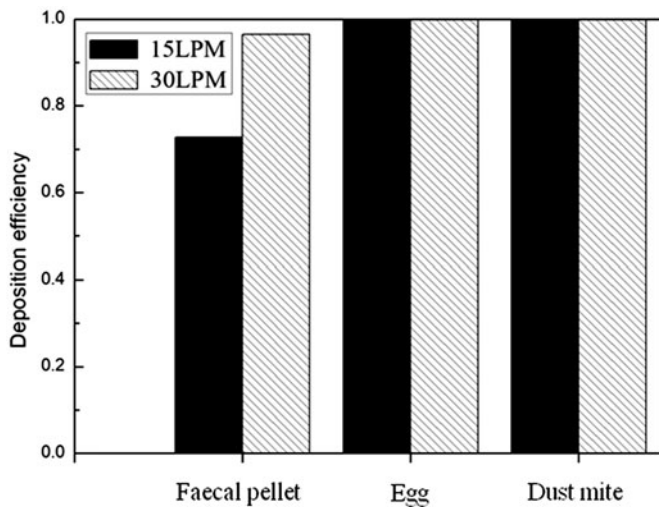


Figure 11. Simulated nasal passage total deposition efficiencies for different particles and different breathing rates.

rate increased in both the nasal vestibule and the anterior middle turbinate region, while it decreased in the nasopharynx (Figure 10). Figure 11 shows that as the particle size increased from $10\mu\text{m}$ (fecal pellet) to $102\mu\text{m}$ (egg), the deposition efficiencies raised from 0.73 to 1.0 for flow rate 15 L/min and from 0.96 to 1.0 for flow rate 30 L/min. With the increase of inspiratory flow, the total deposition efficiency of fecal pellet increased from 0.73 to 0.96. These were due to the increased inertial.

With the increase of inspiratory flow, the secondary flow, turbulence diffusion and the particle momentum all increased. Deposition was more affected by inertial impaction for allergen particles too large to follow the main flow

path. At 15 L/min, deposition was more posterior in the airway and dispersed which reflects the influence of gravity deposition and secondary flow.

Different body position

One-third of our life involves sleep and the bed has the highest incidences of high concentration of mites, which requires investigation of the effect of body position. The health effect analysis of different concentrations of allergens are very important but the major aim of this study was to compare allergens' deposition under lying and standing position. For simplicity, only deposition efficiencies (DE) were analyzed. The gravitational term was changed to the x -axis to simulate the condition of sleeping on the right ($-x$) or left ($+x$) lateral positions. The average deposition time of dust mite bodies and eggs is 0.0346 s. The vertical travel distance contributed by gravity can be estimated by $L = \frac{1}{2}gt^2 = 5.87\text{ mm}$, which is much larger than narrow nasal passages ($\sim 3\text{ mm}$). Therefore, considerable sedimentation can be observed even though the residence time is small. Figure 12 shows the PDF deposition of dust mite where the peak deposition shifted to the left. This suggests deposition rate of mite bodies and eggs increase on the side closer to the ground.

For fecal pellet, the PDF showed little change. Considering the low deposition rate in the sinus, a comparison in the number of fecal pellet in the right sinuses was performed (Figure 13). The number of the fecal pellet increased from 32 to 100, which showed that there was an 300% enhancement of entry into the sinus while sleeping. This highlights the importance of clearing allergenic particles in the bedroom, especially in beds.

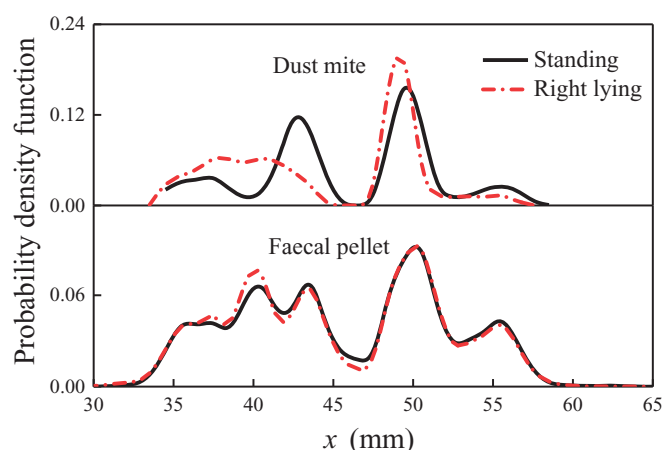


Figure 12. The probability density function (PDF) of dust mite and faecal pellet in x-axis under the standing and lying condition on the right-hand side.

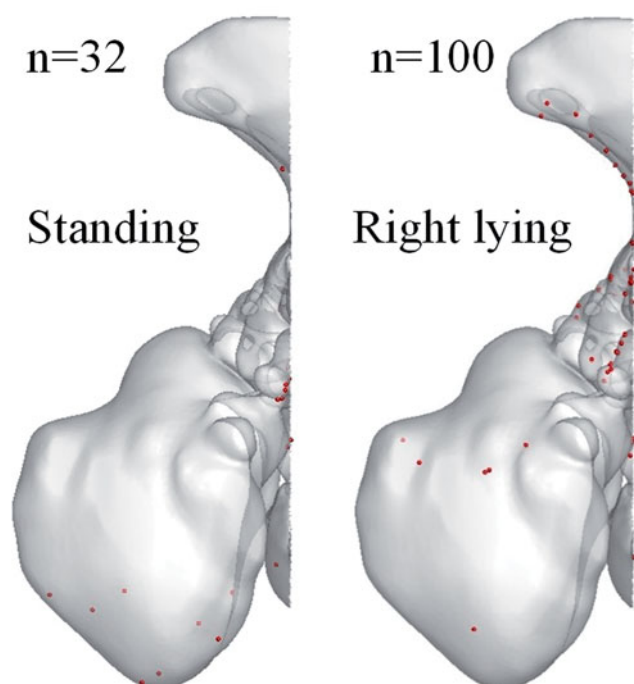


Figure 13. Surface deposition and the number of faecal pellet in the right sinuses under the standing inspiratory condition and right lying inspiratory condition.

Conclusions

Inhaled allergens derived from house dust mite play a major role in allergic rhinitis and asthma. In this paper, fluid-particle flow dynamics of allergen particles were studied using a CFD-DPM model, with special reference to role of the middle turbinate. The model was validated and confirmed by reasonably good agreement between the computational and rhinometry measurement of nasal resistance. The major findings from the study included: the importance of the anterior head of middle turbinates and the nasal swell body which functioned to filter dust mite allergens of different particle sizes, especially for higher flow rate of 30LPM. Furthermore, mite allergens like faecal pellets can enter maxillary sinuses with accessory ostium, especially when people

are lying down. It is expected that these results may assist in the design of new aerosols and guide practical clinical tests for allergens.

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