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Detailed micro-particle deposition patterns in the human nasal cavity influenced by the breathing zone

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ABSTRACT

The breathing region connects the nasal cavity with the outside environmental air where flow is accelerated through the nostrils. Particles introduced into the nasal cavity without considering the breathing region neglect the influence of facial features and realistic boundary conditions at the nostrils. In this study, a new nasal cavity model is reconstructed combining facial features and an ambient environment focusing on the breathing region. The inhaled air from outside the nose is investigated and compared with a model that consists of the nasal cavity alone. An improved 2D surface mapping technique is applied to the 3D nasal cavity to visualize the particle deposition patterns onto a planar geometry. Using this technique, deposition of micron particles from 0.4 μm to 30 μm were investigated, and trajectories of 2.5 μm, 10 μm and 20 μm were compared with the 'nasal-only' case. Particle deposition efficiency curves and particle trajectories are plotted to show that the inclusion of the external nose and breathing region causes: (i) a change in the fluid flow within the anterior nasal cavity half but the flow patterns regulate in the posterior half; (ii) minimal difference for 2.5 μm particle deposition patterns; (iii) significant differences in 10 and 20 μm particle deposition patterns where more particles are deposited in the posterior nasal regions.

1. Introduction

The human nasal cavity plays an important role in respiration due to its three major physiological functions: air-conditioning, filtering and olfaction. The inhaled air flow behaviour in the nasal cavity can be investigated by reconstructing the airway from computed tomography (CT), magnetic resonance imaging (MRI), or ex vivo by plastination of cadavers. Experimental studies of airflow behaviour have been performed using particle image velocimetry (PIV) [1,2], or by dye injection into the flow stream [3,4]. However, due to the complex geometry, and perturbation introduced by experimental equipment, direct measurements inside cast models are difficult [5]. When considering particle inhalation, this problem becomes further compounded.

Computational Fluid Dynamics (CFD) analysis of nasal function have been investigated since the pioneering work by Keyhani et al. [6] in 1997. Since then computational studies have investigated its anatomical form, airflow patterns, and fluid-particle interactions to gain a better understanding of: respiration function [7–10]; air-conditioning [11,12]; and surgical implications [13–17]. When a secondary particle phase is introduced, inhaled particles coupled to the airflow field, allow studies of nasal drug delivery [18–22]; and inhalation toxicology [23–25] or general particle deposition studies [26,27]. The work by Wang et al. [28] indicated deposition efficiency for 22 μm particles in the nasal cavity reached 100% for light breathing and revealed deposition hot spots for micron-particles. Similarly Shi et al. [29] and Shanley et al. [30] produced high deposition for 20 μm particles at a flow rate of 7.5 L/min; all collecting in the anterior nasal cavity.

Within these studies a lacking feature is the omission of the external nose and facial features. This simplification influences the airflow patterns significantly in the breathing zone, outside the nasal cavity [31–33]. The exclusion of the outer environment means that an artificial and representative boundary condition the nostril inlet is applied. Recently Taylor et al. [34] investigated airflow in the nasal cavity by comparing different inflow boundary conditions (flat, parabolic and using an external face) and showed that regional wall shear stress and olfactory flux are sensitive to inflow boundary profiles by up to 100%. Later, studies by Zhu

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et al. [35] and Lu et al. [36] compared nasal airway flow patterns for three and ten computational models, respectively, that included the external nose and face. However these two studies did not consider particle inhalation.

Since airborne particles are transported by the fluid phase, the effects caused by facial features on particle deposition in the respiratory system should be considered. Studies by Se et al. [37] and Inthavong et al. [38] investigated the inhalability of particles via a realistic human head and indicated velocity vectors were directed slightly upwards towards the nostril opening, leading to a lower critical area for small particles and a higher critical area for heavy particles. Li et al. [39] included a nasal cavity model inside a simplified standing mannequin and placed in a large room. Their results showed the airflow field in the breathing zone exhibited high acceleration and particle track profiles at the nostril openings were not uniformly distributed, which is typically the case when the external environment is omitted.

In this study, we investigate the influence of the external nose and face on fluid and particle dynamics during inhalation. A new computational nasal model connected with realistic facial features was generated from CT scans and reconstructed carefully via image processing software. The airflow field was simulated by CFD from the external environment into the nasal cavity through to the nasopharynx. These results were compared with results obtained from the same nasal cavity model but without the external facial features and environment. Instead of an entire large room we focus on the breathing region reduce computational costs and increasing the resolution of the flow field in the breathing region. To identify and compare the precise particle deposition position, a mapping technique to convert the 3D nasal cavity onto a 2D-plane is presented. Particles with sizes from 0.4 μm to 30 μm were investigated and representative sizes (2.5 μm, 10 μm, and 20 μm representing PM2.5, PM10 and larger ambient particles respectively) were tracked and its deposition positions in the nasal cavity plotted for both models.

2. Method

2.1. Computational geometry

An integrated human respiratory model including a nasal cavity and head was reconstructed from computed tomography (CT) images of an Asian male and labelled as ‘NC03’. CT images (dimension: $512 \times 512 \times 512$ with pixel size 0.5 mm) were segmented semi-automatically using the medical image-processing software *Materialise-Mimics* to extract a 3D volume. This was refined manually, by excluding noise and repairing unrealistic regions. Further step-like surface regions were improved and smoothed using the 3D modelling software *Geomagic Studio*. For simplicity, openings to sinuses were omitted as their impact to air flow pattern and micron particle deposition were negligible [40]. The facial details were retained while the back of the head was omitted. An artificial straight pipe extension of 5 cm was attached to the nasopharynx to allow a more realistic boundary condition at the outlet. The surrounding ambient air was modelled with a simple cubic volume having dimensions of 15 cm-width, 12 cm-height and 20 cm-depth shown in the isometric view in Fig. 1.

Thirteen cross sections (from A–A′ to M–M′) were created along the main flow path of the nasal cavity geometry. The main passages are bounded by three bony folds (inferior/middle/superior turbinate), beneath which narrow airway passages called the meatuses are located. They expand from C–C′ located posterior to the nasal valve, and finally merge together in the choanae labelled as J–J′. The narrow main passage is represented by cross-section G–G′.

2.2. Mesh generation

The nasal cavity geometries were imported to *ICEM-CFD* to generate the mesh. Inside the nasal cavity domain, a mesh grid of 7.5 million unstructured tetrahedral cells was created with mesh size of 0.5 mm. For the ambient air in front of the face, 2.0 million

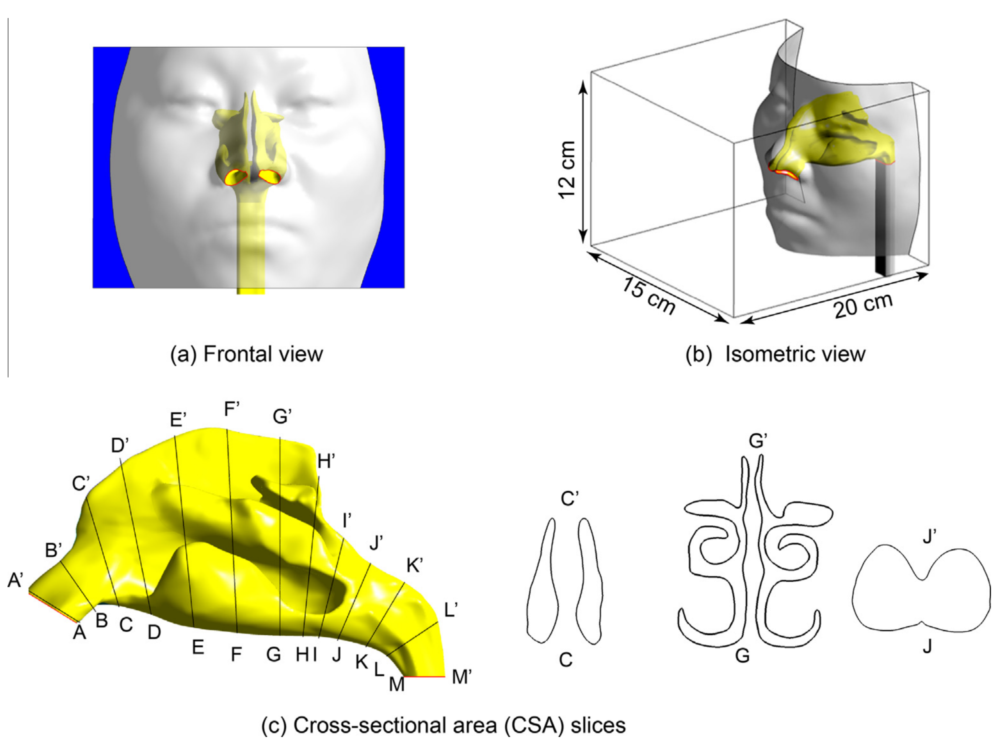

Fig. 1. Computational model of the nasal cavity, combined with detailed facial features and the external domain. (a) Frontal view of the whole model with an artificial extension attached at the nasopharynx for the outlet. (b) Isometric view of the computational domain. (c) Thirteen cross sections along the main flow path and shapes of posterior nasal valve, turbinate and choanae regions labelled as C–C′, G–G′ and J–J′.