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CFD simulation of total and regional fiber deposition in human nasal cavities

Alireza Dastan [a], Omid Abouali [b,*], Goodarz Ahmadi [c]

[a] Mechanical Engineering Department, Fasa Branch, Islamic Azad University, Fasa, Iran
[b] School of Mechanical Engineering, Shiraz University, Mollasadra Street, Shiraz, Iran
[c] Department of Mechanical and Aeronautical Engineering, Clarkson University, Potsdam, NY, USA

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ABSTRACT

In this study, CFD simulations of fibrous particle deposition in different realistic human nasal cavities were performed. The airflow field in the cavity was evaluated by solving the Navier–Stokes and continuity equations using commercial software, while a Lagrangian trajectory analysis approach for solving the coupled translational and rotational equations of motion of ellipsoids was developed and used to investigate fiber transport and deposition in the nasal passages. Different breathing rates in the laminar flow regime in the nose and a range of fiber lengths and diameters were used in these simulations. It was shown that the aerodynamic diameter based on the Stokes equivalent diameter is an appropriate parameter for correlating the fiber deposition rate. Presenting the deposition fraction results versus the Stokes-based and pressure-based impaction parameters collapsed the results of different cases for various nose models roughly to a single curve. The simulated regional fiber deposition results were also presented for different nasal cavities. A simple approach developed earlier for modeling non-spherical particles using the shape factor in the drag force was also studied, and the resulting deposition fraction was compared with the present coupled translational–rotational trajectory analysis approach.

1. Introduction

The study of fiber deposition in the human respiratory tract is of great importance because of the potential for serious adverse health effects. The nasal airway is the main point of entry for the human respiratory system, and the first line of defense against penetration of particulate pollutants into the lung. The deposition fraction defined as the ratio of the number of deposited particles to the number of particles entering the nostril indicates the fraction of the inhaled fibers that enters the lower respiratory system. Although the use of asbestos fibers has been banned, there are still many old buildings that have asbestos-based insulation. In addition, new fibrous materials such as man-made vitreous fibers (MMVFs) are currently being manufactured for new applications. It has been shown that some particular MMVFs may have adverse carcinogenic effects similar to those of asbestos (Cavallo et al., 2004). Therefore, the potential risk of lung diseases related to fiber inhalation is still a serious health issue. The adverse effects of particulates depend on the region of the airway in which the particles or fibers deposit. Thus, knowledge of regional deposition of fibers in the respiratory tract is of considerable importance. Regional deposition is not likely to be studied in *in-vivo* or *in-vitro* experimental investigations. Computational modeling approaches do have the capability to conveniently estimate the regional deposition pattern of aerosols including fibrous particles. In particular, the location of peak deposition in different parts of the respiratory tract can be identified.

* Corresponding author. Tel.: +98 711 613 3034; fax: +98 711 628 7508.
E-mail addresses: ardastan@yahoo.com (A. Dastan), abouali@shirazu.ac.ir (O. Abouali), gahmadi@clarkson.edu (G. Ahmadi).

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Experimental and numerical studies of the flow dynamic and spherical particle deposition in the nasal cavity have been the subject of many investigations (Edgar et al., 2010; Hsu & Chuang, 2012; Kelly et al., 2004; Moghadas et al., 2011; Shanley et al., 2008; Shi, 2006; Xi & Longest, 2008). Recently, Tu et al. (2013) have provided a summary of the literature in their book. The filtering behavior of nasal airways for particles released by spray devices increases the deposition of medications at particular regions along nasal cavities, and this issue has been studied (Inthavong et al., 2011; Inthavong et al., 2006; Longest & Holbrook, 2012). All earlier studies suggest that in an inertial regime ($d^p \geq 1$ μm), particle deposition increases as particle diameter and air flow rate increase, although there are some differences in the estimated values of deposition fraction between different studies, even those based on models constructed from a single set of medical images. This is in part due to the small relative dimension of the nasal airway, so that slight differences in the model geometry significantly affect the deposition fraction of particles. In addition, the variability of the nasal cavity of different subjects results in variation of the aerosol deposition under seemingly identical conditions (Garcia et al., 2009; Wang et al., 2008). The differences between the evaluated deposition fractions for cavities of the same human subject may arise from the resolution of the MRI or CT scan images, the number of coronal images used to produce the 3-D geometry of the cavity, and the different techniques of replica cast fabrication. The reasons for the differences in the estimated deposition fraction can be categorized into "wall roughness" and "surface smoothness" (Schroeter et al., 2011). Accordingly, the term "wall roughness" is used to denote the surface resolution of the rapid prototyping machine used to fabricate the nasal replica casts, while the term "surface smoothness" is used to describe surface irregularities due to coarse imaging data and poor interpolation between consecutive cross-sections in sectional anatomic data.

Figure 1 shows a summary of spherical particle deposition from previous experimental and numerical studies in which the nasal model was constructed based on the same set of MRI images initially developed by Swift (1991). In this figure, the term "IP" stands for impaction parameter defined as

$$\mathrm{IP} = d_{eq}^2 Q \tag{1}$$

where d_{eq} is the equivalent aerodynamic diameter, which is the diameter of a spherical particle with a unit density having the same fall velocity, and Q is the airflow rate. It should be noted here that, for consistency in this paper, Q is the flow rate that enters one nostril. Clearly, the total breathing flow rate is the double of this value. In Fig. 1, results for two experimental replicas of Kelly et al. (2004) were reproduced. These results correspond to two different manufacturing approaches noted as the Viper and the SLA models. The Viper model was produced by a finer cutting device which resulted in introducing less roughness in the model. As Fig. 1 shows, the model fabricated with a higher resolution method (Viper) has a lower deposition fraction compared to that of the SLA model which is produced using a different method. Additional experimental investigations performed on the same nasal cavity were described in the study of Garcia et al. (2009). The results, however, are the same as those for the Viper model of Kelly et al. and therefore were not included in the figure for the sake of brevity. Numerical studies of Shi et al.(2007) and Schroeter et al. (2011) investigated, respectively, the effects of wall roughness and surface smoothness. In Model C of Schroeter et al. (2011), the sinusoidal shape of walls from the older work of Swift (1991), which were produced with less accurate image processing compared to today's standards, were smoothed artificially. In contrast, Model A is exactly the same as it was in the original experimental work of Swift (1991), and Model B is less smooth than Model C. Figure 1 shows that wall roughness and surface smoothness of the fabricated replica or computational domain markedly affect the particle deposition results. For an IP of about 500 μm^2 L/min, for example, the measured and/or computed deposition fraction for the same nasal cavity estimated by different studies differ by a factor of five.

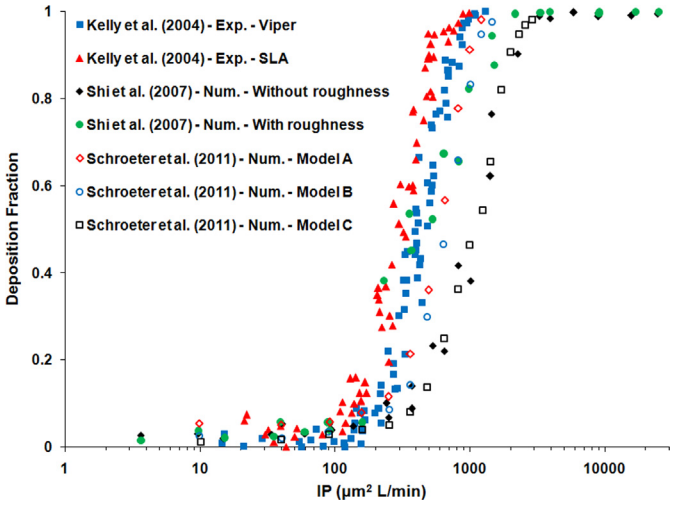

Fig. 1. Comparison of spherical particle deposition fraction of different experimental (Exp.) and numerical (Num.) studies performed on nasal cavities constructed from the same set of MRI images.