Computers in Biology and Medicine 52 (2014) 73–81

Contents lists available at ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/cbm

Numerical investigation of regional particle deposition in the upper airway of a standing male mannequin in calm air surroundings

Arash Naseri [a], Omid Abouali [a,*], Pejman Farhadi Ghalati [a], Goodarz Ahmadi [b]

[a] School of Mechanical Engineering, Shiraz University, Shiraz, Iran
[b] Department of Mechanical and Aeronautical Engineering, Clarkson University, Potsdam, NY, USA

ARTICLE INFO

Article history:
Received 25 January 2014
Accepted 12 June 2014

Keywords:
Calm air
Regional deposition
CFD
Mannequin
Aerosol
Outdoor and indoor condition
Human upper airway
Particle

ABSTRACT

A 3-D realistic computational model of the airway system integrated into a standing male mannequin was developed. The computational domain includes the regions around the mannequin and the inside of the airway passages. The simulation was performed for low activity breathing rates with calm air around the mannequin. The flowfield of the inhaled air was first obtained from solving the Navier–Stokes and continuity equations. Then the particles were released in the domain around the mannequin and their trajectories were evaluated by using the Lagrangian approach for solving the particle equation of motion. The regional aerosols deposition was evaluated for different parts of the human airway system and the results were compared with those obtained from the separate modeling of the airway system without the interaction of the airflow with the mannequin external face. The results showed when the upper airway is integrated into the mannequin, the regional deposition of inhaled particles mainly changes in the airway system.

1. Introduction

Understanding the process of inhalation of aerosols has attracted considerable attention because of its significance to human exposure to particulate pollutants, and transmission of infectious diseases. In this connection, the nasal airway plays an important role in the human respiratory system. It heats and humidifies the inhaled air, and protects the lungs by capturing suspended particulate matters. The effective filtering of the nose becomes more critical in atmospheres with carcinogenic particles which could lead to serious health effects [1,2].

In the past few years, inhalation drug delivery via pharmaceutical aerosols through breathing has been developed. In order to maximize the absorption of pharmaceutical aerosols in the upper airways (nasopharynx and larynx), particles larger than 20 μm have been used to ensure their deposition and to prevent particles from entering the lungs [3]. In other cases, it is desirable to have the drug delivered deep into the lungs. Therefore, submicrometer aerosols are used to decrease the undesirable deposition in upper airways [4].

Estimating the regional deposition fraction of pharmaceutical aerosols is of interest for treating localized respiratory tract infection. For an acceptable average drug dose, it is still important to be aware of the regional deposition rates. Since, a high local drug dose may cause tissue injuries or initiate a new disease. Thus, understanding the regional particle deposition in human upper airway and the fraction of particles entering the lungs are very important for controlled pulmonary drug delivery.

Experimental and numerical study of the flow dynamic and particle deposition in the nasal cavity has been the subject of many researches. The investigations of Zachow et al. [5] and Wen et al. [6] are examples of some recent numerical studies for the airflow in the nasal cavity. Earlier Zamankhan et al. [7], Xi and Longest [8], Wang et al. [9], Inthavong et al. [10] and Moghadas et al. [11] presented the numerical results for the micro/nanoparticle deposition in the nasal cavity. Hahn et al. [12], Kelly et al. [13] and Doorly et al. [14] performed a series of experimental investigations of airflows in the nasal cavity. Kelly et al. [15,16] measured the particle deposition in a nasal cavity replica model with different surface qualities. These included a Stereo-lithography (SLA) nasal replica model with greater surface roughness and a Viper nasal replica model (manufactured with a Viper Si2 machine) with a smooth surface.

More recently considerable attention was given to the regional deposition of particles in the respiratory system (Abouali et al. [17], Farhadi Ghalati et al.[18], Tavakoli et al.[19] and Jayaraju et al. [20], Wang et al. [21], Mylavarapu et al. [22], Xi et al. [23], Ghahremani et al. [24], Dastan et al. [25]). In these earlier

* Corresponding author. Tel.: +98 711613304.
E-mail address: abouali@shirazu.ac.ir (O. Abouali).

http://dx.doi.org/10.1016/j.compbiomed.2014.06.007
0010-4825/

investigations, a separate airway system with either a uniform pressure or uniform inlet airflow velocity was considered and the external body was not included in the computational model. It is, however, generally known that many parameters such as particle size, air ventilation conditions, ambient airflow speed and temperature, as well as even people positions significantly affect the particle inhalation and particle deposition in the respiratory track. Recently, understanding the effect of external body feature on human exposure to particulate matter has attracted some attention. Kennedy and Hinds [26] used a full-sized and torso mannequin and studied particle inhalation through nose or mouth during breathing. Se et al. [27] studied the effect of human facial feature on particle inhalation and the total deposition in human airways using computational fluid dynamic (CFD) for a crude mannequin model.

In their experimental studies, Berry and Froude [28] and Baldwin and Maynard [29] paid more attention to the calm air environment. They defined the calm air as a condition where the wind speed rarely exceeds 0.3 m/s. Using a mannequin, Der-Jen Hsu et al. [30] measured the inhalablility of ultra large aerosol in a calm air environment under different breathing conditions. They showed that the breathing condition and age do not significantly affect the aspiration ratio and suggested an empirical correlation for inhalability for nasal breathing. i.e.,

$$E = 3.01 + 0.64(\text{Log } d_{ae})^2 - 2.78 \text{ Log } d_{ae}$$

Here d_{ae} is the particle aerodynamic diameter. In their work, torso mannequins of an adult and a child were exposed to non-spherical airborne particles. Several volume flow rates corresponding to human activity condition (rest, moderate and heavy exercise) were studied. Yu-Tung Daia et al. [31] measured the nasal inhalability of aerosol particles under a calm air condition for ten subjects exposed to different inspiratory flow rates. Comparison of in vivo and mannequin measurements suggested that the natural convection from the human body could affect the particle motions in calm air and cause slightly higher inhalability for particles smaller than 50 μm. Li et al. [32] simulated simplified model of humanoid and then investigated effect of facial features on nostril velocity profile and then conducted resulted velocity profile as an inlet boundary condition of nasal cavity. They stated facial features effect only on a small region in front of the face (10–20 mm) and lead into non-uniform velocity profiles at the inlet of the nostril that it may affect particle inhalation. Inthavong et al. [33] integrated the human upper airway into a mannequin and placed inside a room, facing different airflow speeds. This study revealed better understanding about the air and particle flow patterns near mannequin exposed to different indoor conditions. In a detail study, Taylor et al. [34] investigated the effect of the inflow geometry on flow predictions for the numerical simulation of steady nasal inspiration. They compared the cases of: blunt velocity profile applied to the nares, a tapered pipe inflow and a model that fully replicate the internal and external nasal airways. Investigating the airflow inside the nasal airway, they found that a tapered pipe inflow provides a better approximation for the natural inflow than a blunt velocity profile applied to the nares. Recently, Inthavong et al. [35] investigated the source and trajectories of deposited particles in the upper respiratory system using a computational model that combined the mannequin and respiratory airway in an indoor environment for free stream airflow velocities of 0.05, 0.2 and 0.35 m/s, which is common in an indoor environment.

The presented brief literature review shows that the study of regional deposition in the upper human airway was reported only for a detached model of the airway. In this paper the regional particle deposition in the upper airway in a realistic mannequin situated in a calm air environment was studied. The computational model included the surrounding of the mannequin, as well as the upper airways, so that effects of the external body on regional particle deposition could be assessed.

2. Model description

2.1. Geometry

The mannequin used in the study is shown in Fig. 1. The mannequin resembles a typical American male [36,37].

The external computational domain is a 4 m side cube with the mannequin standing at its center as shown in Fig. 2. This computational domain is expected to be sufficiently large to eliminate the boundary effect. The grid sensitivity study was performed and the grid independency was achieved for a mesh of about 5.5 million cells.

In order to investigate the importance of including the mannequin external body in computational study of deposition of particles in the human airway, a 3-D model of the airway is constructed and is connected to the external computational domain. Fig. 3 shows some samples of the coronal and sagittal cross sections of the upper airways of a healthy adult male. These CT scans were used for construction of the nasal and the rest of upper airway passages. The CT scans were provided by TABA imaging center (Shiraz, Iran). A CTI whole body scanner was obtained using a GE medical imaging system with the following parameters: 0.625 mm slices increment, 24.2 cm field of view, 120 kV peak and 99 MA. The boundary between the airway

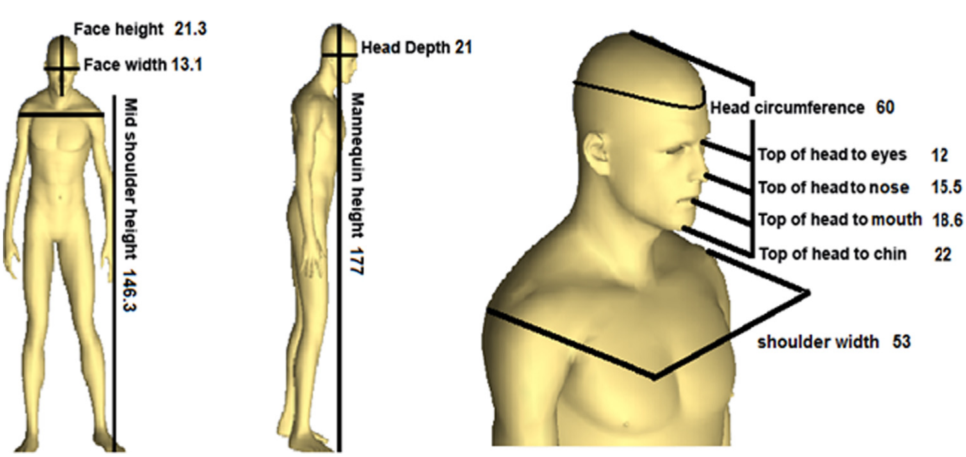

Fig. 1. Views of the mannequin and details of facial features used in the study. All lengths are in centimeters.