Journal of Aerosol Science 73 (2014) 39–47

Contents lists available at ScienceDirect

Journal of Aerosol Science

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

Measurements of total aerosol deposition in intrathoracic conducting airway replicas of children

Azadeh A.T. Borojeni [a,*], Michelle L. Noga [b], Reinhard Vehring [a], Warren H. Finlay [a,**]

[a] Department of Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada T6G 2G8
[b] Department of Radiology and Diagnostic Imaging, University of Alberta, Edmonton, Alberta, Canada

ARTICLE INFO

Article history:
Received 6 January 2014
Received in revised form
18 March 2014
Accepted 19 March 2014
Available online 13 April 2014

Keywords:
Total intrabronchial deposition
Tracheobronchial tree
Children
Hollow replicate cast
In vitro

ABSTRACT

The objective of this research was to obtain a correlation that quantitatively predicts micrometer-sized aerosol particle deposition in the upper conducting airways (trachea to generation 3) of children. Experiments were conducted using steady inhalation air flow rates to measure the deposition of monodisperse particles with diameters of 3.5–5.5 μm in replicas of the upper tracheobronchial airways of 11 children aged 2–8 years. The total deposition of particles was measured in each replica using gravimetry. Validation was performed by also measuring deposition in five adult replicas and the Alberta Idealized Throat and comparing with existing published data. Although there is considerable inter-subject variability in our data, the empirical correlation of Chan & Lippmann (1980) was found to predict total deposition reasonably well in all of our adult and child replicas.

1. Introduction and background

Knowledge of aerosol deposition in human lung airways is essential to evaluate the efficacy of respiratory therapeutic drug delivery during inhalation aerosol therapy for different lung diseases and to investigate the health risks and impacts of inhaled air pollutants and toxicants (Kelly et al., 2004).

A large number of studies (see Cheng et al., 1999, 2001; Delvadia et al., 2012; Gurman et al., 1984b; Heenan et al., 2004; Kelly et al., 2004; Lambert et al., 2011; Lin et al., 2001; Liu et al., 2007; Luo & Liu, 2009; Martonen & Lowe, 1982; Oldham et al., 1997; Schlesinger & Lippmann, 1978; Smith et al., 2001; Su & Cheng, 2006; Verbanck et al., 2011; Xi et al., 2011; Yamada et al., 1994; Zhou & Cheng, 2005; also see Zhang & Finlay, 2005a for a review of this literature) have been conducted with engineering models to investigate particle deposition in various regions of the human lung. However, to date only a few quantitative studies have been reported on particle deposition in hollow tracheobronchial casts. Such polymer casts reproduce the real anatomical complexities of the human respiratory tract and mimic the essential parameters affecting aerosol deposition in the different anatomic regions of the human lung (Chan & Lippmann, 1980; Cheng et al., 1999; Grgic et al., 2004b; Gurman et al., 1984a; Schlesinger et al., 1974, 1977, 1982; Schlesinger & Lippmann, 1972, 1976; Storey-Bishoff et al., 2008). More recently, computed tomography (CT) and magnetic resonance imaging(MRI) have provided the capability

* Co-corresponding author. Tel.: +1 780 492 2161; fax: +1 780 492 2200.
** Corresponding author. Tel.: +1 780 492 4707; fax: +1 780 492 2200.
E-mail addresses: akhavant@ualberta.ca (A.A.T. Borojeni), mnoga@ualberta.ca (M.L. Noga), Reinhard.Vehring@ualberta.ca (R. Vehring), warren.finlay@ualberta.ca (W.H. Finlay).

http://dx.doi.org/10.1016/j.jaerosci.2014.03.005
0021-8502/

to generate realistic airway models of different parts of the human respiratory tract (see e.g. Golshahi et al., 2012; Kelly et al., 2004; Lambert et al., 2011; Luo & Liu, 2009; Storey-Bishoff et al., 2008).

While a large body of literature has explored deposition of aerosols in airway replicas in adults built using one of the above approaches, few such studies have been performed in child airway replicas. Extrathoracic deposition has been recently characterized in infant and child airway replicas (Golshahi et al., 2011, 2012; Storey-Bishoff et al., 2008; Zhou et al., 2013a,b) but studies in the tracheobronchial region that would allow general, quantitative, generation-by-generation predictions of pediatric conducting airway deposition are lacking (Oldham et al., 1997). In adults, such empirical correlations are well used in exposure assessment (ICRP, 1994) and respiratory drug delivery design (Finlay, 2001). While the extension of adult correlations to predict conducting airway deposition in children has been proposed (Hofmann et al., 1989; ICRP, 1994), validation of such extrapolation remains to be done.

In the present work, we measure aerosol deposition in airway replicas of the first few lung generations for 11 children and 5 adults and examine the ability of adult correlations to predict pediatric conducting airway deposition.

2. Materials and methods

2.1. Airway replicas

This study was approved by the Health Research Ethics Board (HREB) of the University of Alberta. CT scans of subjects who had been imaged for indications other than airway pathology were accessed from archives. A summary of both adult and child subject information is presented in Tables 1 and 2. Hollow airway replicas of 11 children aged 2–8 years old and 5 adults aged 50–80 years old were built using a rapid prototyping 3-D printer (Invision® SR 3D printer, 3D systems, Rock Hill, SC, USA) in Stereo-Lithography format. The replicas were based on CT scans imaged from each subject's chest in a single helix by a multi-slice CT scanner (Phillips, GEMINI TF TOF 16, The Netherlands). A 0.8 mm slice increment thickness (imaging mode was helix and the axial thickness of the reconstructed slices ranged from 0.8 mm to 1 mm) was used, as previously described by this research group (Golshahi et al., 2012; Grgic et al., 2004a,b; Storey-Bishoff et al., 2008). The resolution (row $\times$ column) of the raw CT images was 512×512 pixel. The pixel sizes are in the range of 0.379–0.633 mm, with an average of 0.504 ± 0.072 mm in children and 0.625–0.957 mm, with an average of 0.81 ± 0.088 mm in adults. The CT scan files were recorded in Digital Imaging and Communications in Medicine (DICOM) format. The details of importing CT scan files to the reconstruction software package (MIMICS 3D, Materialise, MI, USA) are explained in more detail elsewhere (Inthavong et al., 2010a,b; Mallepree & Bergers, 2009). Briefly, by selecting a threshold setting defined by a higher and lower bound (min: -1024 and max: -250 in the Hounsfield scale), the airway passage was extracted from the

Table 1
Summary of child subject information and airway diameters of child replicas. Sub. ID# is the subject's identity numbering. Generation 0 (Gen.0) is the trachea, Gen.1 are the main bronchi, Gen.2 are the bronchi and Gen.3 are the segmental bronchi. Stdev is the standard deviation of the range of diameters in each generation.

Age (year)	Subject ID #	Sex	Height (cm)	Weight (kg)	Diameter (stdev) (Gen.0) (mm)	Diameter (stdev) (Gen.1) (mm)	Diameter (stdev) (Gen.2) (mm)	Diameter (stdev) (Gen.3) (mm)
2	8c	F	82	11	5.15 (0.24)	4.03 (0.06)	3.89 (0.36)	2.89 (0.73)
4	10c	F	99	16	7.15 (0.04)	4.7 (1.19)	3.48 (0.27)	2.2 (0.23)
	14c	F	100	16	7.16 (0.15)	6.47 (2.77)	4.46 (0.69)	2.23 (0.76)
5	2c	M	117	22.9	7.05 (0.09)	6.03 (0.7)	6.00 (1.4)	4.35 (1.91)
	3c	M	112	20	7.99 (0.51)	5.39 (0.51)	4.93 (0.49)	2.33 (0.66)
	9c	M	113	20	7.56 (0.01)	6.44 (0.87)	5.26 (0.01)	3.38 (1.05)
6	5c	F	112	18	7.99 (0.42)	5.36 (1.14)	5.35 (1.41)	3.55 (1.00)
	6c	F	118	21.5	8.5 (0.3)	6.75 (1.32)	5.94 (1.32)	2.9 (1.47)
	12c	F	124	24	7.41 (0.46)	6.45 (2.72)	3.28 (0.26)	3.23 (0.9)
7	13c	F	121	20	9.78 (1.32)	7.64 (0.09)	6.48 (1.23)	3.58 (0.01)
8	11c	M	124.5	24.5	10.49 (0.95)	7.43 (2.26)	6.23 (1.42)	3.02 (0.35)

Table 2
Summary of adult subject information and airway diameters of adult replicas. Column headings are as given in the caption of Table 1.

Age (year)	Subject ID #	Sex	Height (cm)	Weight (kg)	Diameter (stdev) (Gen.0) (mm)	Diameter (stdev) (Gen.1) (mm)	Diameter (stdev) (Gen.2) (mm)	Diameter (stdev) (Gen.3) (mm)
50	7a	M	178	113	14.57 (2.04)	12.34 (1.08)	6.79 (1.62)	3.6 (0.15)
	8a	F	155	99	12.4 (0.01)	10.83 (2.68)	6.53 (2.27)	5.18 (0.23)
55	3a	F	159	68	14.94 (2.67)	14 (2.15)	9.45 (1.65)	7.46 (0.8)
62	4a	M	168	91	14.47 (2.09)	13.63 (2.5)	7.8 (1.04)	4.69 (1.04)
80	5a	M	173	76	16.13 (2.19)	14.27 (2.3)	6.89 (2.27)	4.47 (1.87)