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Total Aerosol Deposition in Realistic and Idealized Pediatric Central Conducting Airway Geometries

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Introduction

Knowledge of regional aerosol deposition in the lungs is important in evaluating the efficacy of inhaled drugs and in investigating the health risks of inhaled particulate matter.

For adults, quantitative studies measuring aerosol deposition in airway casts, or replicas based on medical images, have resulted in empirical correlations that are used in engineering models to predict deposition in upper and tracheo-bronchial airways.

For children, similar studies that would allow general, quantitative, generation-by-generation prediction of pediatric airway deposition are lacking in the tracheo-bronchial region.

The present work was conducted to explore the extension of an adult correlation[1] to predict deposition measured in central conducting airway replicas of children.

Additionally, an idealized geometry was designed to mimic average total aerosol deposition in the airways of 4-8 year old children by scaling a previously described adult idealized geometry[2].

Materials & Methods

Airway Replicas:

This study was approved by the Health Research Ethics Board (HREB) of the University of Alberta.

Five adult and eleven child airway replicas were built based on segmentation of CT scans of subjects with healthy airways[3].

Generational airway diameters are summarized in Tables 1 and 2 as the average of equivalent circular cross-section diameters evaluated at 2 mm increments along the length of each airway segment.

Table 1. Summary of subject information and airway diameters of adult replicas. Generation 0 (Gen.0) is the trachea, Gen.1 are the main bronchi, Gen.2 are the lobar bronchi, and Gen.3 are the segmental bronchi. Diameters are presented as average (standard deviation) for 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)
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)

Table 2. Summary of subject information and airway diameters of child replicas. Table headings are the same as described above for 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)
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)

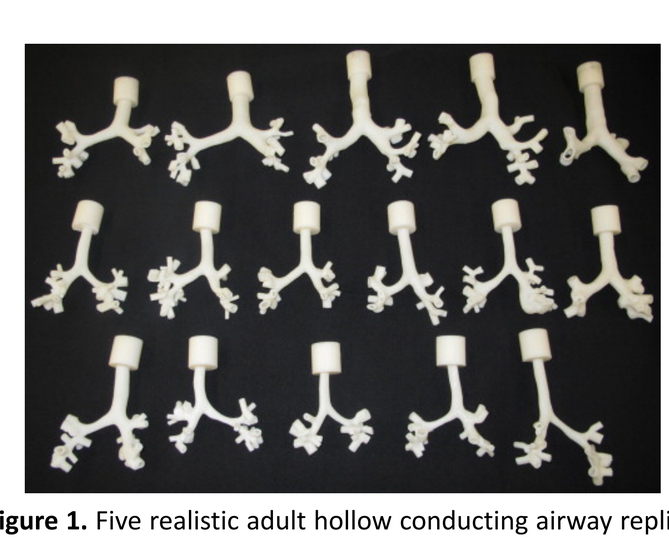

Figure 1. Five realistic adult hollow conducting airway replicas (top row) and 11 child hollow conducting airway replicas (second and third rows). Outer wall thickness is 2mm.

Deposition Experiments:

Monodisperse (GSD < 1.22) DEHS aerosols ranging in diameter between 3.5 to 5.5 µm were produced by a condensation aerosol generator (Model 3475, Topas, Dresden, Germany). Aerosol size was monitored using an aerodynamic particle sizer (Model 3321, TSI Inc., MN, USA).

Aerosol and make-up air were drawn by vacuum through airway replicas positioned in an exposure chamber. For adult replicas, steady flow rates of 60 l/min and 90 l/min were used. For child replicas, flow rate was adjusted between 4.8 and 9.3 l/min to match expected mean inspiratory flow rate during tidal breathing at rest for each subject.

Aerosol deposition was determined by gravimetry using a calibrated analytical balance to weigh replicas and all downstream filters before and after each experimental run.

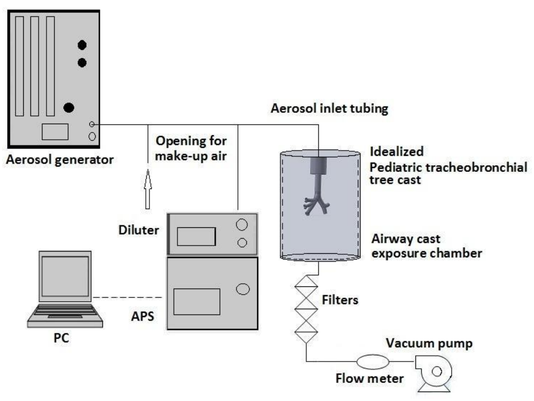

Figure 2. Experimental set-up used to measure total particle deposition in realistic and idealized airway replicas. Dashed line indicates paper filters which surrounded the internal surfaces of the artificial thorax

Empirical Correlation:

Generational deposition in adult and child replicas was predicted using the Chan and Lippmann correlation[1]: $\boldsymbol{\eta_i = 1.606}\mathrm{Stk} + \boldsymbol{0.0023}$, where Stk is the particle Stokes number based on mean generational diameter.

Total deposition in each replica was then determined as:

$$\eta_{\mathrm{total}} = 1 - \prod_{i=0}^{3} (1 - \eta_i)$$

Idealized Geometry:

An idealized 4-8 year old child central conducting airway geometry was designed by scaling the idealized adult geometry proposed by Zhang and Finlay (2005)[2].

An isotropic scale factor was determined using the Chan and Lippmann correlation to match the average total deposition in the 4-8 year old child replicas.

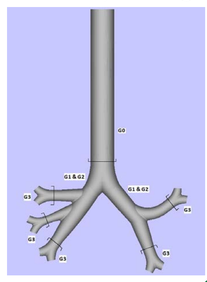

Figure 3. The idealized geometry. Dimensions are reported in Borojeni et al. (2015)[4].

Results

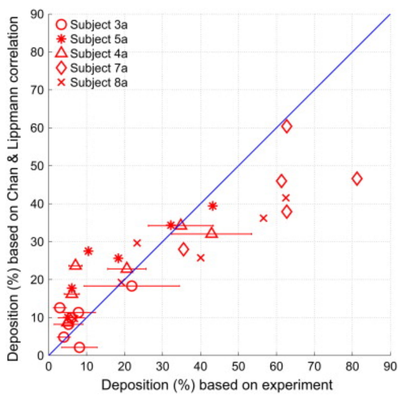

Figure 4. Comparison of predicted vs. measured conducting airway (generation 0–3) deposition in adult replicas. Each data point is the average of three runs. Error bars, where visible, indicate standard deviation between runs.

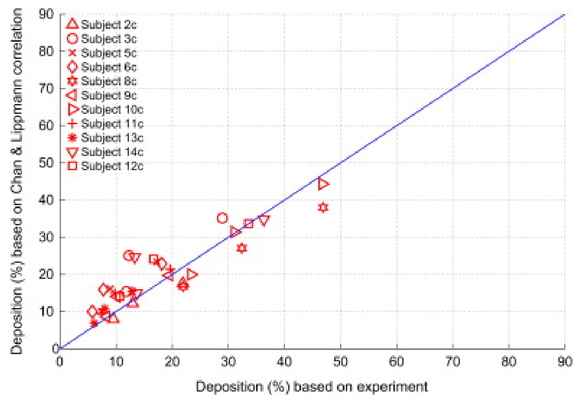

Figure 5. Comparison of predicted vs. measured conducting airway (generation 0–3) deposition in child replicas. Each data point is the average of three runs.

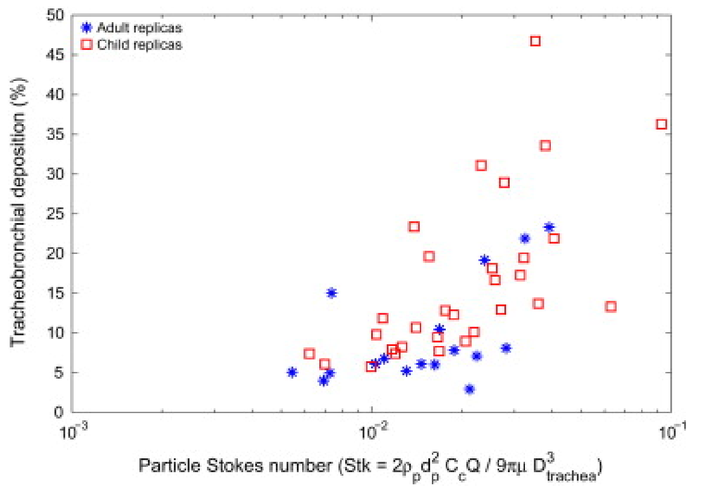

Figure 6. Comparison of central conducting airway deposition measured in the adult and child replicas plotted vs. the Stokes number in the trachea. Each experimental data point is the average of three runs.

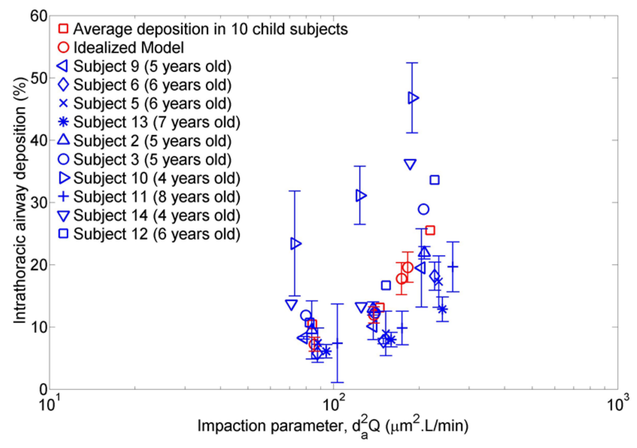

Figure 7. Central conducting airway deposition in the idealized and realistic child geometries plotted against the impaction parameter. Error bars indicate the standard deviation of three replicates. Where error bars are not visible for a data point, they are smaller than the data point in question.

Conclusions

Aerosol deposition in pediatric central conducting airways, at least for generations 0-3, may be predicted using an existing Stokes number-based correlation developed for adult airway deposition.

The validity of a Stokes number-based correlation across age groups permitted design of a child idealized central conducting airway geometry as a scaled version of an existing adult idealized geometry.

Experiments confirmed that aerosol deposition in the idealized child central conducting airway geometry was consistent with the average deposition measured in 10 realistic replicas for children 4–8 years old.

References

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