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The Deposition of Concentrated Cigarette Smoke in Airway Models

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Previous studies have indicated that inhaled concentrated cigarette smoke deposited as if the particles were 6–7 μm in aerodynamic diameter. Here, we examine cigarette smoke deposits in hollow airway replica casts and perform an elementary smoke modeling exercise. The results imply that cloud effects should be considered in dose models for concentrated cigarette smoke.

Keywords: cloud effects; deposition; cigarette smoke

INTRODUCTION

Concentrated aerosols, including fresh cigarette smoke, can exhibit anomalous aerodynamic behavior when separations between particles are small and hydrodynamic forces between nearby particles are significant. Such behavior includes rapid settling when concentrated aerosols are unconfined, and hindered settling in confined spaces. When inhaled, concentrated cigarette smoke exhibits deposition efficiencies in the respiratory tract that are often much greater than expected for the small particle sizes of the smoke aerosol (Hinds *et al.*, 1983; Ingebrethsen, 1989). Among theoretical treatments of the aerodynamics of concentrated aerosols are those of: Fuchs (1964), who treated 'clouds' (unconfined) and 'concentrated suspensions' (confined or unconfined) using a character of motion parameter (M); Hinds (1999), who treated 'bulk motion aerosols' by considering the increased density of the entire aerosol relative to the surrounding gas; and Martonen (1992), who modeled cigarette smoke deposition in human airways using a characteristic upper limit cloud dimension of 0.3 cm, based on the laryngeal opening.

Cigarette smoke is sufficiently concentrated when fresh to exhibit cloud behavior. Cigarette cloud dimensions are difficult to characterize. Experimental values from measurements on photographs of sidestream cigarette smoke wisps (Phalen *et al.*, 1994) led to a characteristic wisp diameter estimate of 0.32 mm, which is similar to the dimensions of 'parcels'

observed by Chung and Dunn-Rankin (1996) using a laser scanning technique. Using idealized symmetric branching airway models, Martonen (1992) found that cigarette smoke deposition patterns were similar to that for 6.7 μm aerodynamic diameter monodisperse particles, and Phalen *et al.* (1994) reported cigarette smoke aerosol deposition efficiencies in symmetric airway models that were characteristic of 6.5–7.1 μm aerodynamic diameter particles. These observations of smoke deposition are consistent with Black and Pritchard's (1984) conclusion that radio-labeled inhaled cigarette smoke deposited in human volunteers as if the particle aerodynamic diameters were 6.5 μm . The large effective diameters of cigarette smoke exceed those that would be produced by coagulation or hygroscopic growth (Ingebrethsen, 1989). Because fresh cigarette smoke particles are $\sim 0.5 \mu\text{m}$ in diameter, and particle counts are of the order of $10^9/\text{cm}^3$, the high deposition efficiency in airways is evidence that cloud-related phenomena are important in relation to deposition in the respiratory tract.

MATERIALS AND METHODS

The primary objective of this study was to measure the deposition of fresh, concentrated sidestream and mainstream cigarette smoke in realistic replica hollow airway casts. The hollow models were derived from large, intermediate and small human organ donors' airways (Fig. 1). For smoke exposure, pulsatile airflow was used. Smoke was generated using 1R3 research cigarettes supplied by the University of Kentucky. Cigarettes were puffed in accordance with

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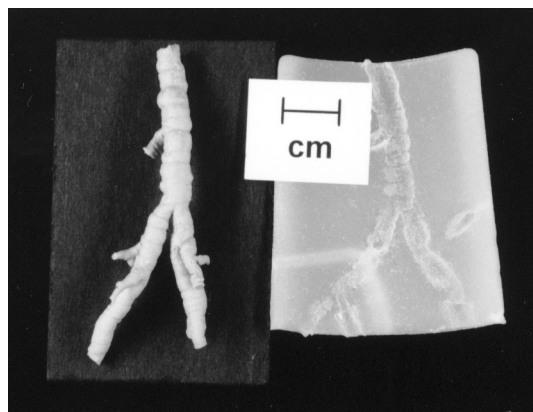


Fig. 1. Scanned images of a solid silicone rubber cast of human intermediate airways and the top half of a hollow transparent silicone rubber mold of the solid cast. The exits on the hollow cast were mated to plastic tubing.

the US Federal Trade Commission's protocol. Hollow models were oriented such that the force of gravity was approximately perpendicular to the main airflow. The 'inspired' aerosol was warmed (37°C) and humidified with an annular entry (to near saturation) to mimic respiratory tract conditions. The undiluted aerosol primary particle size (as ultraviolet particulate material, UVPM) was measured using a seven-stage cascade impactor with a backup filter (RJR model, In-Tox Products, Albuquerque, NM).

A secondary objective was to modify a mechanistic theoretical inhaled aerosol deposition model (Yeh and Schum, 1980) to account for free-cloud and wall-interaction effects. The smoke aerosol was portioned into two categories in the model: the fraction exhibiting cloud behavior, and the fraction exhibiting single-particle behavior. Free-cloud effects were modeled by decreasing the viscosity of the inhaled air in inverse proportion to Fuchs' M parameter. This new effective viscosity was then applied to that portion of the aerosol particles that were undergoing cloud motion. Wall effects were accounted for, at each airway generation, by adjusting the proportion of aerosol that exhibited single-particle aerodynamics in proportion to the ratio of cloud cross-sectional area to the airway cross-sectional area. When the wisp and airway cross-sectional areas were equal (0.1 mm^2), no cloud effects occurred. The model also included hygroscopic growth of the smoke particles by superimposing an empirical growth rate curve for cigarette smoke onto the inhalation–exhalation cycle (Schum and Phalen, 1997).

RESULTS

The experimental deposition efficiencies of mainstream and fresh sidestream cigarette smoke in the hollow models were combined, as they were indistin-

Table 1. Combined mainstream and sidestream cigarette smoke deposition in hollow replica human airways (averages of three to five runs)

Airways	MMAD (μm)	Observed deposition (%)	Calculated deposition (%)
Larynx	0.3	0.13	<0.70
Upper airway	0.3	0.20	0.20
Intermediate airway	0.5	6.60	0.37
Distal airway model 3	0.5	5.20	<0.01
Distal airway model 4	0.5	4.50	<0.01

MMAD, aerosol mass median aerodynamic diameter. Calculated deposition is for $0.4\text{ }\mu\text{m}$ particles using the model of Yeh and Schum (1980), and the NCRP (1997) report.

guishable (Table 1). Visual inspection of the smoke deposits indicated that they were frequently focal; deposition was heavy on the bifurcations and on the bottom surfaces (with respect to gravity) of all airways. However, there was no strong focal deposition on bifurcations just distal to the larynx. The deposition efficiencies were close to those expected without cloud effects for the larynx and large bronchial airways. However, deposition was elevated, and similar to that expected if cloud effects were significant, for intermediate and small airways.

The mathematical model results for representative generations of an idealized model are shown in Table 2. Hygroscopic effects on deposition were minimal, but cloud effects were often significant. Deposition of cigarette smoke in the bronchial airways was increased 10-fold over that expected for single particles due to cloud effects. This increased local dose correlates with the location of bronchial cancers in cigarette smokers (Martonen *et al.*, 1987). In the deep lung regions, modeled smoke deposition was minimally affected by cloud behavior, due to the offsetting effects of nearby airway walls. The larynx was not included in the theoretical model.

DISCUSSION

Strong evidence of cloud effects was observed in the hollow model cast deposition studies for intermediate and small branching airways, but not for the larynx or large bronchial airways. It is possible that high air velocities in the larynx (150 cm/s , $Re = 1250$) prevented wisps that touched the wall from depositing as clouds and that downstream turbulent flow affected the large airways. The high deposition efficiencies in the intermediate and small bronchial airways imply that, at lower air velocities, cloud structure is not completely destroyed on contact with airway walls.

With respect to the theoretical model, the results were consistent with the hollow model studies. Quantitative comparisons between the hollow model and

Table 2. Results of the mathematical model for smoke deposition in terms of percent of the aerosol that exhibits cloud behavior

Airway	Generation	Cross-section (cm ²)	Cloud portion (%)	Deposition with clouds (%)	Deposition without clouds (%)
Main bronchus	2	1.3	99.9	0.68	0.0065
Segmental bronchus	6	0.2	99.5	0.72	0.0070
Bronchiole	10	0.036	98.0	0.14	0.0140
Terminal bronchiole	16	0.002	60.0	3.50	0.0600
Respiratory bronchiole	24	0.001	10.0	1.96	1.9600

The cloud cross-section used was 0.008 cm². The percent deposition values include two mechanisms: impaction and sedimentation.

theoretical model results could not be made because the hollow models used in bench-top deposition studies were complex, realistic replicas. Of necessity, the theoretical model assumed all airways were smooth, right circular cylinders with bends in the tubes representing bifurcations. Furthermore, the theoretical model did not include several potentially important phenomena. Such omitted phenomena included the effects of gases and vapors in cigarette smoke, particle electrical charge, thermal gradients, Raleigh–Taylor instabilities, non-ideal airway shapes, reversing air flows, the string-like shapes of wisps, and the complex spatial variation of particle counts within wisps.

The hollow model studies and theoretical modeling both implied that cloud effects should be considered in dose assessments for fresh concentrated mainstream and sidestream cigarette smoke. Dilute environmental cigarette smoke is not expected to exhibit cloud behavior.

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