Cigarette Smoke Deposition in the Tracheobronchial Tree: Evidence for Colligative Effects

Robert F. Phalen,* Michael J. Oldham, and Richard C. Mannix
Air Pollution Health Effects Laboratory, Community and Environmental Medicine, University of California, Irvine, CA 92717-1825

G. Michael Schum
California Department of Toxic Substances Control, Sacramento, CA 94234

A series of cigarette smoke deposition studies was performed that used hollow models designed to represent the upper airways of adults and children. A major objective of the studies was to look for evidence of the influence of the colligative behavior of concentrated smoke on deposition in the hollow models. Another objective was to identify possible body-size–related factors in cigarette smoke deposition.

The concentrated sidestream smoke from 1R3 University of Kentucky unfiltered research cigarettes was drawn through three sizes of airway-like hollow models at flow rates representing resting levels of physical exertion. The models, made of silicone rubber, represented the pharynx, larynx, and first three or four generations of the tracheobronchial airways. The models were scaled in size to represent young adults, 7-year-olds, and 4-year-olds. After smoke deposition, the models were cut into smaller pieces which were ultrasonically agitated in isopropyl alcohol, and the recovered deposits were analyzed spectrophotometrically (at a wavelength of 350 nm). Through the additional analysis of exit filters behind the models, smoke deposition efficiency was quantified.

The study was unable to detect any significant effects of body size on the deposition efficiency of smoke. However, significant increases in deposition over those predicted (using accepted deposition models) for submicrometer particles were observed in all casts. The enhanced deposition could be attributed to the colligative behavior of smoke. In fact, the smoke aerosols, which had submicrometer diameter primary particles, deposited in the tracheobronchial trees as if they were between 6 and 7 μm in aerodynamic diameter.

INTRODUCTION

Estimates of the respiratory tract deposition efficiencies of inhaled cigarette smoke are complicated by the lack of agreement between computational predictions, as based on the known particle size distribution of cigarette smoke, and the results of actual measurements of the deposition of smoke when inhaled by humans or laboratory animals. Using accepted particle deposition models (e.g., Morrow et al., 1966; Stöber, 1984; Vincent et al., 1990; Yeh et al., 1991) and a typical cigarette smoke particle mass median aerodynamic diameter (MMAD) of 0.5 μm (Davies, 1988), one predicts a total respiratory tract deposition of about 10–20%. Measurements made that use human volunteers smoking cigarettes typically result in smoke depositions of 47–96% (Hinds et al., 1983). In fact, Black and Pritchard (1984) inferred

*To whom correspondence should be addressed.

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from clearance measurements that inhaled concentrated cigarette smoke deposited in human subjects as if it had an aerodynamic diameter of 6.5 μm. In contrast, Hiller et al. (1982) observed only 11% deposition in mouth-breathing subjects exposed to very dilute (0.05–0.1 mg/m^3) mixed and aged cigarette smoke. In that study the measured MMAD of both the inhaled and exhaled smoke was 0.4 μm; however, the authors state that hygroscopic particle size changes may not have been observable because of their measurement technique. Hygroscopic particle growth considerations are important, since Davies (1988) attributed much of the excess deposition reported by Black and Pritchard (1984) to that phenomenon. Stöber (1984) had previously concluded that hygroscopic growth was not a likely mechanism for the excess deposition, and he suggested electrostatic effects as a possible explanation. Also, Muller et al. (1990) was unable to fully account for the excess deposition by modeling a very substantial hygroscopic growth of 240–360%. Other investigators (Martonen, 1992; Ingebrethsen, 1989) stated that the excess deposition cannot be totally attributed to the hygroscopic growth or agglomeration of smoke particles in any event, because the increase in particle size would not be sufficient to significantly increase the deposition efficiency. Therefore, since experimental deposition measurements with monodisperse particles and other nonsmoke aerosols generally have agreed quite well with the mathematical predictions (Raabe, 1982; Vincent et al., 1990), mechanisms somewhat unique to highly concentrated smoke aerosols, such as hydrodynamic interactions among smoke particles, or the transfer of condensed vapor from particles to the moist airways, have been postulated to produce the observed high deposition values (Phalen, 1984; Ingebrethsen, 1989; Martonen, 1992).

Freshly generated cigarette smoke is a highly concentrated aerosol, both with respect to the number of particles per unit volume of air, and the aerosol mass concentration (Davies, 1988). Aerosols with large numbers of particles per unit volume of air can exhibit unusual properties. Highly concentrated aerosols have the potential for hydrodynamic interactions among nearby individual particles. Such interactions arise due to currents in the air that are produced by a particle moving in relation to the air (Fuchs, 1964). Manifestations of hydrodynamic interactions include enhanced settling in unbounded air volumes (also called cloud settling), preservation of the macroscopic size and shape of aerosol clouds, hindered settling in confined spaces (where wall effects are significant), and the establishing of flat upper boundaries in settling aerosols (Fuchs, 1964; Hesketh, 1979; Hinds, 1982). The temperature and vapor (including water vapor) and gas composition within a concentrated aerosol cloud may also differ from those of the surrounding air, giving it a different viscosity and density. Clouds eventually disperse by a variety of mechanisms that increase particle separation, including particle diffusion, differential sedimentation and agglomeration, and breakup due to air currents. Clouds may also exhibit fractal properties, and maintain a self-similar fine structure when they are examined under increasing magnification (Feder, 1988), making the assignment of a cloud size potentially difficult.

The unusual behavior of highly concentrated aerosols in relation to dilute counterparts has led to the use of several descriptive terms, but there is no accepted universal terminology. In unconfined spaces where the aerosol is surrounded by relatively particle-free air, Fuchs (1964) uses the term "cloud"; but when the entity is in a confined space, he refers to it merely as a "concentrated suspension," or "aerosol." Similarly, Hinds (1982) reserves the term "cloud" for concentrated aerosols that are completely surrounded in a much larger volume of relatively clean air, and he applies the concept of "bulk properties" that presumably will depend upon the degree of confinement. Hesketh (1979) permits "clouds" to interact with surfaces, which broadens the definition of cloud over that used by Fuchs and Hinds. Hidy and Brock (1970) briefly discuss "aerodynamic forces" that result from currents in the suspending fluid when particles travel near one another. These aerodynamic forces for spheres falling together in the Stokes regime serve to decrease the external fluid forces, suggesting that a group of particles will fall faster than will a single particle. In either free or confined spaces, highly concentrated aerosols can be expected to exhibit behavior that is influenced by aerodynamic (hydrodynamic) and other interactions among nearby particles. Because such interactions only occur in populations of airborne particles, we will refer to the unique behavior of concentrated aerosols as "colligative" behavior. Colligative behavior can then occur in either unbounded or bounded concentrated aerosols. We will also use Hesketh's concept of a cloud being a cloud even when it is in contact with a surface, although the cloud must not have a shape that is solely defined by surrounding surfaces. This allows us to consider a cloud entering a confined space, such as the human respiratory tract.

The conditions under which colligative effects become significant in aerosol behavior are not easy to define. Fuchs (1964) describes a "character of motion" parameter (M) for an unconfined aerosol as follows:

$$M = 0.27\pi N D_c^2 d \tag{1}$$

M depends on the number of particles (N) per cm^3 of gas, the effective cloud diameter (D_c) in cm raised to the second power, and the individual particle diameter (d), also in cm. If M greatly exceeds unity, then the ensemble moves in free air as a cloud, because in a wind the net force on the ensemble when treated as an entity is less than the sum of the forces on the individual particles. In this case, air will flow around, rather than through, the cloud, preventing its immediate breakup. An enhanced settling rate in still air over that expected for the individual particles is one manifestation of a large M, and the resultant cloud behavior. The enhanced settling rates of spherical clouds were treated by Hinds (1982) by considering the cloud as a single particle with a characteristic macroscopic diameter and bulk density greater than that of air. The expression that describes the cloud settling velocity (V_c) is:

$$V_c = (4\rho_c D_c g / 3C_d\, \rho_g)^{1/2} \tag{2}$$

where ρ_c is the cloud bulk density, g is the acceleration due to gravity, C_d the drag coefficient, and ρ_g the density of the surrounding gas. The equation does not take into account the small effect of nonrigidity of the cloud, which can produce internal circulation.

Both mainstream (smoke that has passed through the cigarette) and sidestream (smoke issuing between puffs) cigarette smoke appear to have properties that would produce significant colligative behavior, including enhanced settling rates and possibly enhanced deposition when inhaled. The particle size distributions of mainstream and sidestream cigarette smoke generated under controlled conditions are well known (Landahl and Tracewell, 1957; Keith and Derrick 1960; Phalen et al., 1976; Hiller et al., 1982, 1987; Davies, 1988). In brief, mainstream smoke aerosols have typical MMADs of 0.3–0.7 μm, and sidestream smoke aerosols have typical MMADs of about 0.4

μm; both aerosols have geometric standard deviations (GSDs) of about 1.4. Undiluted cigarette smoke typically has an initial concentration of about 3×10^9 particles/cm^3, which drops to about 8×10^8 particles/cm^3 after 2 s. Using a particle density of 1.06 g/cm^3 (Davies, 1988), fresh cigarette smoke clouds are estimated to have bulk densities of about 1.41 mg/cm^3, as compared to 1.21 mg/cm^3 for particle-free air. Thus, using Eqs. 1 and 2, a fresh 0.3-mm diameter (our measured mean wisp width; see Results) smoke cloud composed of 0.5-μm particles would have an expected M value of about 100. Such a cloud of fresh cigarette smoke could settle at a velocity, much larger than that of an individual 0.5-μm diameter smoke particle, which settles at about 0.001 cm/s in still air.

Cloud effects are possible mechanisms for producing the observed enhanced deposition of inhaled concentrated cigarette smoke. These effects were modeled by Martonen (1992) by postulating that airflow instabilities in the larynx and at bifurcations serve to create smoke clouds with dimensions of about 0.3 cm. Also, Ingebrethsen (1989) presented a theoretical treatment of cloud behavior of the inhaled cigarette smoke front as it meets relatively clean residual air, concluding that "cloud movement may be an important mechanism of mainstream smoke deposition." Because fresh (unmixed and undiluted) sidestream cigarette smoke is also initially a concentrated aerosol, it may be expected to exhibit behavior similar to that of mainstream smoke.

As part of continuing research on the deposition of inhaled cigarette smoke, our study was designed to evaluate the hypothesis that concentrated sidestream cigarette smoke deposits in surrogate hollow tracheobronchial models in an enhanced manner (i.e., above the value theoretically predicted for the individual smoke particles).

METHODS

Our protocol involved (a) generating concentrated sidestream smoke, (b) sizing the smoke aerosol with a multistage impactor so that particle size characteristics could be measured, (c) drawing the smoke through hollow tracheobronchial models, (d) determining the quantities of smoke deposited in the models and on back-up filters, (e) calculating the deposition efficiency in the entire casts, and in the different anatomical regions represented in the casts, and (f) comparing results experimentally obtained with the deposition efficiencies expected for the constituent smoke particles.

Simple idealized hollow tracheobronchial surrogate models of the first four generations of the human lung (trachea equaling generation 0) were constructed using a lost-wax technique described by Oldham (1977) and Martonen (1983). An adult cast, based upon a symmetric geometry (Phalen et al., 1985), and two smaller casts representing children, were constructed. The smaller casts represented 7- and 4-year-old children (only three generations for this case) based upon a relationship between tracheal diameter and body height (Phalen et al., 1985). Branch angles for all generations in all casts, except the trachea, were set at 45°. Hollow casts were made from either Silastic E (Dow Corning, Midland, MI) or RTV 664 (General Electric Co., Waterford, NY) silicone rubber. These hollow casts were connected using smooth transitions that facilitated connection with the smoke deposition system and flow controlling apparatus. The casts were attached to entry sections that had dimensions similar to those of human pharynges and larynges (Figure 1). Cast exit airways were connected through smoothly tapering connectors to exit filters. Thus, the anatomical models were designed to have realistic upstream airflow characteristics and downstream aerosol collectors that would

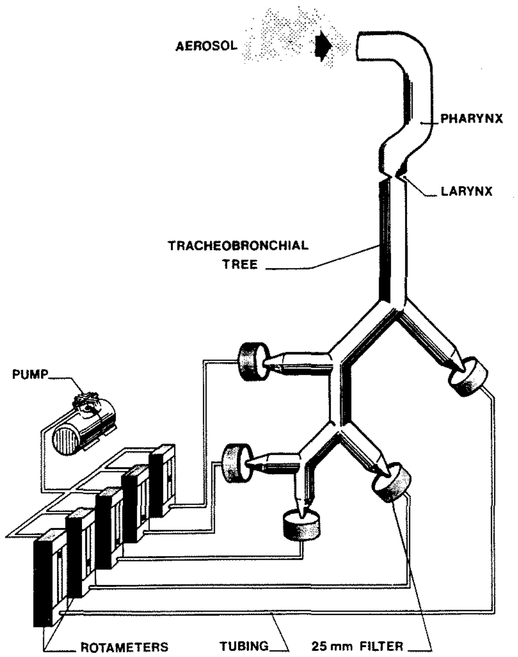


FIGURE 1. Schematic representation of hollow surrogate airway model and airflow control system used for the sidestream cigarette smoke deposition study. The model entrance was connected to the smoke delivery system shown in Figure 2.

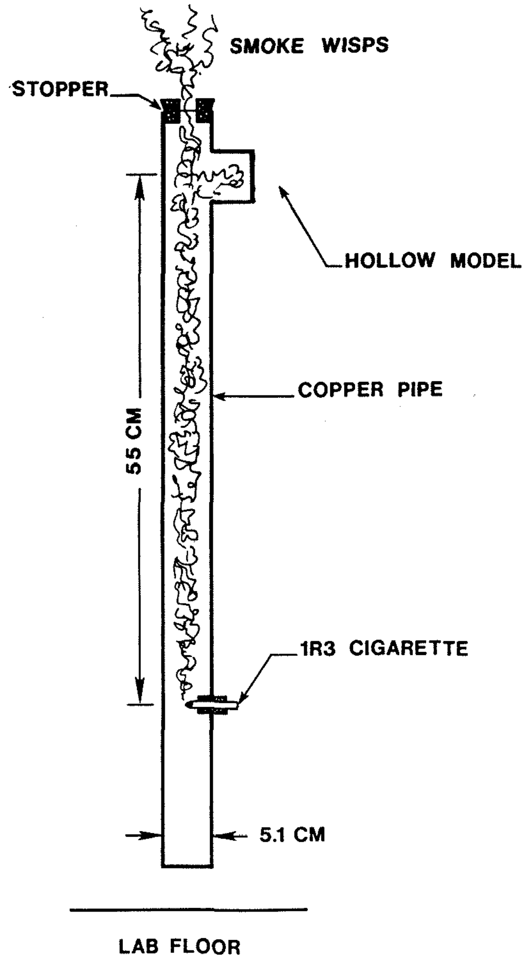


FIGURE 2. Apparatus used for delivery of sidestream cigarette smoke to hollow models, which are attached to the copper tee at the point shown.

not disrupt the airflow. Particle deposition experiments were conducted at steady inspiratory flows that represented a realistic resting ventilation for each age: 15.0 L/min was used for adult hollow casts, 3.2 L/min for the 7-year-old hollow casts, and 2.5 L/min for the 4-year-old hollow casts. Hollow casts were mounted in test stands with supports for cast airways in order to maintain desired branch angles and realistic inclinations to gravity (vertical tracheas) during experiments.

The experimental apparatus is shown in Figure 2. Sidestream smoke was supplied by smoldering 1R3 University of Kentucky (Tobacco and Health Research Institute, Lexington, KY) unfiltered research cigarettes. The cigarettes were stored prior to use in a sealed glass container on a rack over a saturated solution of sodium bisulfate in order to provide a constant $60 \pm 2\%$ relative humidity environment (at room temperature). After placing a lit cigarette in the smoke rise tube at the position indicated in Figure 2, the smoke passively rose 55 cm in the vertical 5.1-cm diameter copper pipe before being drawn by suction through the model for deposition studies or impactor sampling. This height was selected because it was greater than the distance required for the smoke stream to lose its rapid thermally driven vertical velocity. After approximately 25 cm of rise the smoke cloud was observed to break up into randomly oriented filament-like wisps. In order to size the wisps, a method utilizing slit illumination (from a 300 W carousel slide projector), and subsequent photography with a 35-mm camera fitted with a 50-mm close-up lens, was employed. An exposure time of 0.017 s using 400 ASA film provided photographs with good resolution of wisp detail. Wisp dimensions were measured by projecting the photographs on a screen and measuring the widths of wisps with a 0.01-mm scale constructed from a grid photographed using the same slit illumination setup and focal plane as were used to photograph the wisps.

Deposition studies were performed by situating the tracheobronchial casts under study in a vertical orientation such that sidestream smoke-containing air could be pulled through the cast from the rise tube at the position indicated in Figure 2. The smoke aerosol which remained in the airstream after it had been pulled through the cast by suction was collected on the backup filters situated at each exit of the cast. The backup filters were fluorocarbon-coated glass fiber filters (Pallflex Filters, Putnam, CT). Preliminary tests indicated that the filters collected 100% of the smoke particles. The sampling airflows at each cast exit were selected such that the appropriate total airflow (as previously noted) was maintained, and the airflow at each generation was the proper fraction of the total airflow (total airflow $\times 1/2^n$, where n = the generation number, with the trachea equaling generation 0). In some cases (children's casts with lower airflows than that used for the adult casts) it was necessary to burn several cigarettes in order to obtain enough smoke deposit in the cast to reliably quantitate. After the completion of the deposition phase of the study, the casts were removed and dissected into pieces representing the major anatomical areas (pharynx, larynx, trachea, bifurcations 1–3, or 1–2 for the 4-year-old, where bifurcation 3 was too small to manufacture). These pieces were subsequently ultrasonically agitated for 20 min in isopropyl alcohol using an ultrasonic bath. The extracts —filtered using 0.2-μm pore-size fluorocarbon syringe filters to remove filter fibers—were quantified using an absorption spectrophotometer (Spectronic 301; Milton Roy, Rochester, NY) operated at a wavelength of 350 nm (near-visible ultraviolet). This specific wavelength was selected for several reasons. Since cigarette smoke is a combustion-derived material, it contains a number of single and multiring aromatic compounds which absorb ultraviolet light (Guerin et al., 1992). Additionally, the results of an earlier study involving a comparison of impaction, centrifugal separation and electron microscopy for sizing cigarette smoke indicated that the size characteristics obtained using a Mercer impactor—with smoke deposits assayed spectrophotometrically at 350 nm—were in close agreement with those obtained using the other two methods (Phalen et al., 1976). Two samples of each extract were analyzed and prezeroed (pure alcohol-filled) cuvettes were used in order to provide an accurate measure of the smoke deposits. In addition, the zero of the spectrophotometer was checked between each sample reading. The backup filters and additional airway length sections—which were present to facilitate connections between the cast and filter cassettes—were similarly extracted and analyzed. The deposition efficiency of smoke in each cast was determined by dividing the total absorbance measured in the cast pieces by the total absorbance measured in the cast, the backup filters and the additional airway length sections that joined the casts to the filters. Fractional depositions for the various airway pieces were also determined. All deposition experiments were performed twice, and the results were expressed as the mean of the two experiments. In each case, the repetitions provided similar results. The observed deposition efficiencies were then compared to published values of measured and calculated monodisperse particle deposition in the tracheobronchial region. If our measured efficiencies were significantly higher than these accepted values, the result could possibly be an indication of the effect of colligative behavior (due to hydrodynamic mechanisms) on deposition of the smoke aerosol. In order to have a single point of comparison for an expected colligative behavior, we used 6.5-μm aerodynamic diameter, which is the aerosol equivalent size that Black and Pritchard (1984) matched to the total deposition of cigarette smoke in human subjects.

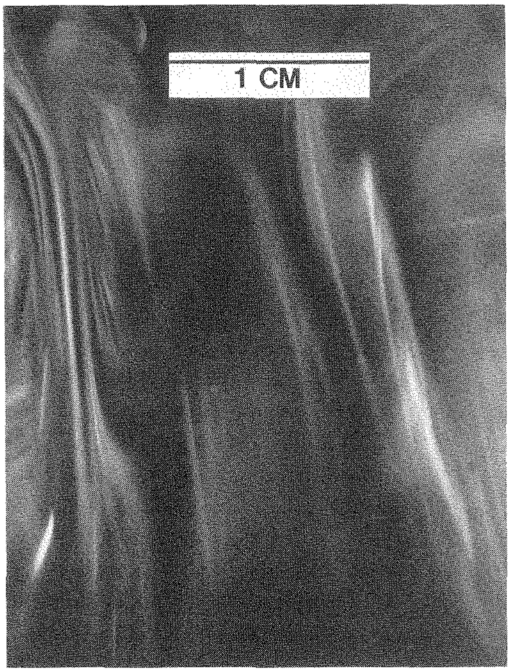
To obtain estimates of the MMAD and GSD of the smoke aerosol, a calibrated Mercer-type seven-stage cascade impactor (Model MCR 02-140; In-Tox Products, Albuquerque, NM) with a backup filter was used. When sampling, the impactor was placed in the apparatus at the position where the casts were attached. An airflow rate of 2 L/min was used. The stainless steel impactor stages (uncoated) and the exit filter were analyzed spectrophotometrically as described above. Several impactor samples were taken to provide a good degree of confidence in the results. The impactor data were fit to a log-probability function, and the MMAD and GSD were determined using a weighted (by percentage of the total deposit on each impactor stage) least squares fitting program.

RESULTS

Smoke Characteristics

The smoke characterizations included the measurement of the approximate smoke mass concentration, aerodynamic (impactor) sizing and the measurement of wisp dimensions (from photographs); see Figure 3. Employing a calibration factor relating the smoke particulate mass deposited on filters (which were allowed to dry overnight at low relative humidity) to the absorbance measured by the spectrophotometer for a given volume of alcohol, it was determined that the airborne smoke mass concentration was on the order of several hundred milligrams per cubic meter of air. This does not include the mass of the water associated with the smoke aerosol, or the mass of volatile organic compounds lost due to evaporation. The total mass concentration may well have been several times larger. The average MMAD of the cigarette smoke was 0.45 μm, and the estimated GSD was 1.3 (Figure 4), which are consistent with previously reported particle size measurements for cigarette smoke (Davies, 1988). Thus, the smoke behaved in the impactor as a standard, "classical" aerosol, with no evidence of colligative behavior observed in the measurement (negligible smoke deposits on the upper impactor stages). This presumably occurred due to the breakup of smoke wisps caused by the high jet velocities and shear forces within the impactor. Measurement of 33 smoke wisps from photographs gave a mean width of 0.32 mm, with a standard deviation of 0.26 mm. The wisps appeared to be ribbon-like strands, and they had widely variable lengths sometimes exceeding several centimeters. Because they were frequently longer than the photographic field of view, their lengths were not quantifiable. Our observations indicated that the widths of the wisps were relatively stable, while the

FIGURE 3. Photograph of sidestream cigarette smoke wisps inside the apparatus used for deposition measurements. Similar wisps were drawn through the hollow surrogate airway models.



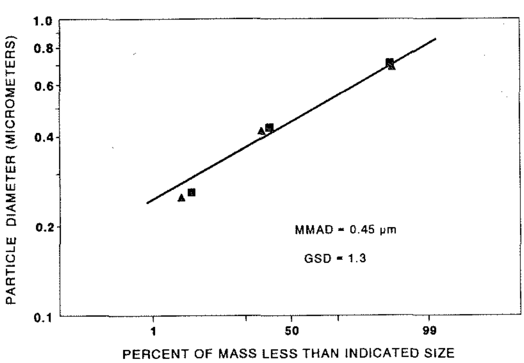


FIGURE 4. Cascade impactor data for sidestream cigarette smoke. Two identical seven-stage impactors were used, as indicated by the use of two data point symbols.

wisps were length-wise quite fragile (subject to easy disruption). For this reason, the critical cloud dimension (D_c) used in M parameter calculations was the observed mean width of the wisps. The number of particles or mass concentrations of the smoke wisps were not measurable, because the wisps could not be separated from the surrounding air.

Smoke Depositions in Surrogate Cast

The averages of recovered deposits, expressed as the percentage of the total smoke mass entering the casts, are presented in Table 1. The variation in deposition as a function of age was small. In general, the deposition efficiency per generation decreased as smoke penetrated deeper into the casts. As is shown in Fig-

TABLE 1. Deposition Efficiencies as Percentage of Total Entering the Cast for Each Segment of the Hollow Models

Cast	Deposition efficiencies					
	Pharynx	Larynx	Trachea	Bifurcation 1	Bifurcation 2	Bifurcation 3
Adult	3.3 (1.3)	2.2 (1.0)	2.5 (0.0)	1.8 (0.4)	0.9 (0.0)	0.5 (0.07)
7-Year	2.3 (0.5)	2.7 (0.1)	2.0 (0.1)	2.1 (0.8)	0.8 (0.2)	0.5 (0.07)
4-Year	2.3 (0.1)	1.6 (0.4)	1.3 (0.6)	1.3 (0.1)	0.8 (0.1)	Not applicable

Mean (SD).

ure 5, stirring the smoke with a fan placed in the rise tube, or passing the smoke through a 10-mCi Kr-85 deionizer placed just in front of the cast, had little effect on smoke deposition. Some variability in deposition was observed in the laryngeal region, but this effect is believed to have been due to slight geometrical differences in the joint connecting the pharyngeal segments to the rise tube.

Comparison to Predicted Deposition

Figures 6–8 show our measured smoke depositions in comparison to those predicted for two sizes of monodisperse particles using the Yeh and Schum (1980) equations, and published measurements of the deposition of 7.1-μm MMAD particles in a replica cast of human airways (Schlesinger et al., 1977). As can be seen, the smoke deposited similarly to what would be expected for particles about 6.5–7.1 μm MMAD. The deposition predicted for 0.45-μm MMAD aerosols is substantially less than the observed values, even though our impactor sizing gave that median size for the smoke aerosol. The correspondence of our observed smoke depositions with what one expects for much larger particles is consistent with the observation of Black and Pritchard (1984) that inhaled cigarette smoke deposited as if it were composed of particles approximately 6.5-μm in diameter.

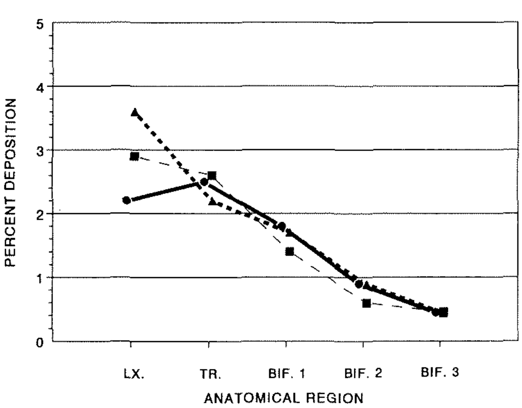


FIGURE 5. The effects of stirring (▲) or electrically discharging (■) the smoke prior to its entering the cast. Circles represent unstirred, undischarged smoke deposition data.

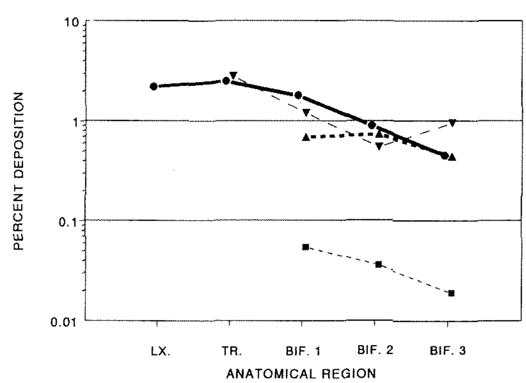


FIGURE 6. Measured smoke deposition efficiencies in the adult-sized model segments (●) in comparison to predicted values for 0.45-μm aerodynamic diameter particles (■) and 6.5-μm particles (▲), and deposition of 7.1-μm particles (▼) as reported by Schlesinger et al. (1977).

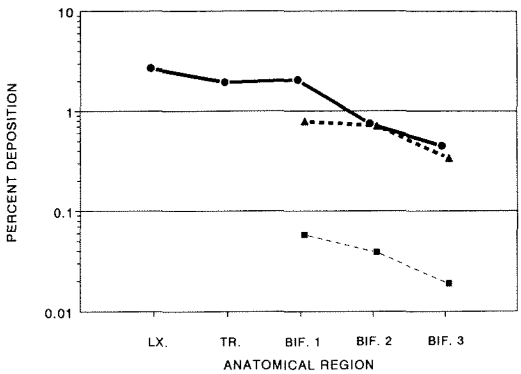


FIGURE 7. Measured smoke deposition efficiencies in the 7-year-old sized model segments (●) in comparison to predicted values for 0.45-μm aerodynamic diameter particles (■) and 6.5-μm particles (▲).

DISCUSSION

The data from our study clearly indicate that the concentrated sidestream smoke had an unusually high deposition efficiency in our hollow surrogate airway models. The 0.45-μm MMAD sidestream smoke aerosols behaved as if they were composed of particles 6 μm or larger in aerodynamic diameter. As previously mentioned, Black and Pritchard (1984) inferred from clearance measurements that concentrated mainstream smoke inhaled by human volunteers deposited in the respiratory tract in a manner equivalent to that of 6.5-μm aerodynamic diameter particles. The agreement between their result and the hollow surrogate model result is striking, and it supports the possibility that similar mechanisms occurred in the two studies. Phenomena that could produce our observed enhanced deposition in casts include (1) aerosol colligative behavior, (2) electrostatic charge effects, and (3) vapor deposition on airway walls.

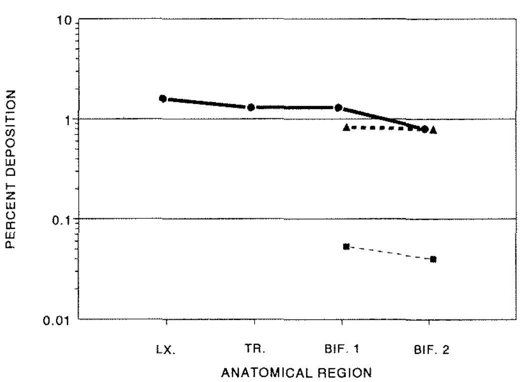


FIGURE 8. Measured smoke deposition efficiencies in the 4-year-old sized model segments (●) in comparison to predicted values for 0.45-μm aerodynamic diameter particles (■) and 6.5-μm particles (▲).

Aerosol colligative behavior could include both hydrodynamic interactions among neighboring particles and changes in aerosol density due to the trapping of heavy gases by the densely packed particles. If Fuchs' *M* parameter is used as an index for the influence of hydrodynamic interactions on aerosol behavior, our sidestream smoke wisps are likely to exhibit colligative behavior (*M* parameter of over 30, which is clearly in the regime of hydrodynamic interaction dominance over individual particle behavior). Therefore, colligative behavior would be expected to occur in free space, and possibly within the airway passages.

Another colligative mechanism that could have produced enhanced deposition is the trapping of heavy gases in the smoke aerosol. Such trapping might occur in dense aerosols, at least for a short time. Carbon monoxide makes up about 80% of the gas phase of sidestream smoke (Guerin et al., 1992). This gas is about 50% more dense than air, which is certainly sufficient to produce rapid settling and even enhanced impaction of smoke clouds. However, the rapid diffusion rates of gases led Martonen (1992) to assign the effect of gas density on smoke deposition as only a complement to the hydrodynamic interaction mechanism discussed above. Because it takes about 3 s for smoke from the cigarette to rise to the level of the cast, we do not believe that trapped gas is a major mechanism producing our result.

A noncolligative mechanism that could produce enhanced deposition of inhaled cigarette smoke is the transport and deposition of vapor from particles to airway walls. Such deposited vapor could be detected via spectrophotometry together with the deposited particles. Ingebrethsen (1989) reported experiments with humans which indicated that volatility of smoke components was positively correlated with deposition efficiency. On the other hand, the vapor phase of cigarette smoke is dominated by carbon monoxide and carbon dioxide, so the mass of vapor that could be detected along with deposited particles is probably insufficient to produce the high measured deposition values. Also, our casts were dry, so uptake of water-soluble gases or vapors could not have produced the heavy deposition that was observed. Another factor, electrostatic attraction of charged smoke particles to airway walls, is not likely to have produced our enhanced deposition because discharged smoke had nearly identical depositions to nondischarged smoke (Figure 5). Thus, we are left with the conclusion that colligative effects were likely to have been the major factor producing our deposition values. It is curious that stirring the smoke with a small fan, which appeared to break up the larger cloud structure, if not the wisps themselves, did not alter deposition (Figure 5).

The effect of cast size ("age") on the deposition of smoke was not striking in our study (Figures 6–8). In fact, a weak trend toward greater deposition in the larger models was seen only in the pharynx region (Figure 9). This region had the most variable deposition from run to run, presumably due to entrance effects, so we cannot draw any firm conclusions from these data.

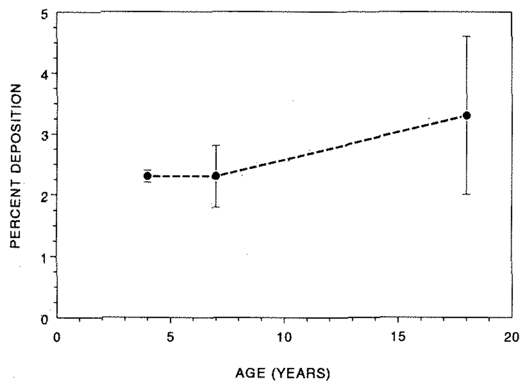


FIGURE 9. The effect of cast size, as represented by the approximate equivalent age of a human, on smoke deposition efficiency in the pharynx. Error bars represent ± 1 SD.

The implications of our study to risk estimates from inhaled sidestream smoke are clear. Upon inhalation of fresh concentrated smoke, the deposition in bronchial airways is likely to be severalfold greater than one would predict on the basis of the size distribution of the smoke aerosol. At this time, we cannot project the deposition efficiencies of inhaled aged sidestream smoke. Presumably, at some time after generation the dilution by air and the breakup of smoke clouds would increase the distances between smoke particles to the point where colligative effects would no longer occur. In this circumstance, the particles would be expected to deposit as individual submicrometer particles upon inhalation.

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