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DEPOSITION OF INHALED CHARGED ULTRAFINE PARTICLES IN A SIMPLE TRACHEAL MODEL

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Abstract—The deposition of ultrafine ($d \leqslant 200$ nm) particles on airway surfaces is an important determinant of the radiation dose that results from inhalation of radon progeny. Diffusion is the dominant deposition mechanism for radon progeny since most of the alpha particle activity is on ultrafine particles. Freshly formed ^{218}Po is rapidly neutralized but, there remains some charged fraction of each short-lived decay product. Theoretical predictions suggest that a measurable increase in airway deposition may result from particle charge. We have measured and compared the deposition (η) of monodisperse singly charged, and charge neutralized, particles with diameters from 15 to 95 nm in simple tracheal models. Differences in deposition were detectable for particles < 30 nm in diameter in 10, 23 and 30 cm long tubes, and for particles up to 95 nm for the longest (30 cm) tube tested. Variations in the magnitude of electrostatic deposition with particle and flow parameters is consistent with theoretical predictions.

INTRODUCTION

Radon, a naturally-occurring radioactive gas, decays to a series of short-lived progeny that remain airborne. The median diameter of particles to which the radon progeny attach is small ($d < 500$ nm). Although bronchial deposition efficiency is low for these small particles it is this fraction that delivers the significant radiation dose from ambient radon progeny to the cells that are critical in the genesis of cancer. In the absence of any charge on the particles, deposition in the upper airways of the respiratory system occurs by impaction for large particles and diffusion for small particles. Sedimentation is negligible due to the high flow rates in these airways. For the randon progeny, impaction is not important. It was shown in a previous study (Cohen and Asgharian, 1990) that for charge neutralized particles of 40–200 nm diameter in a flow field of 300–600 cm^3 s^{-1} through a hollow cast of human airways, particle deposition takes place mainly by diffusion.

Airborne particles are charged by free ions in the air that are produced by cosmic rays and by natural radioactivity. The particle charge distribution can be estimated for equilibrium conditions from Boltzmann's law. The predicted charge as a function of particle size is shown in Table 1. For particles with $d = 20$ nm more than 10% are expected to be charged and the number rises to over 50% for $d > 80$ nm, with equal numbers of particles of either sign. Equilibrium conditions are not normally met and when charge distributions are measured, a larger fraction of charged particles and an excess of charge of one sign is common. The first decay product of ^{222}Rn is ^{218}Po. It is estimated that after formation, about 90% of the airborne ^{218}Po atoms have a single positive charge at the end of the recoil path, the rest being neutral (Hopke, 1990; NCRP, 1988). Although the ^{218}Po is rapidly neutralized, there remains some charged fraction. NCRP (1988) reports that a positive charge is regained during growth or attachment to ambient aerosol. One set of measurements of charge has been reported for radon progeny. Those measurements in a ^{222}Rn test chamber suggested that 32% of the ^{218}Po and 91% of its offspring, ^{214}Pb, were charged (Maiello and Harley, 1989).

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Table 1. Percent of particles carrying n_p units of charge at Boltzmann equilibrium*

Particle diameter (nm)	Percent of particles with indicated charge						
	$n_p = -3$	-2	-1	0	1	2	3
10			0.34	99.32	0.34		
20			5.23	89.53	5.23		
40		0.23	16.22	67.10	16.22	0.23	
60	0.01	1.25	21.30	54.88	21.30	1.25	0.01
80	0.08	2.78	23.37	47.53	23.37	2.78	0.08
100	0.26	4.39	24.09	42.52	24.09	4.39	0.26

* Adapted from D. Y. H. Pui and B. Y. H. Liu: Electrical Aerosol Analyzer: Calibration and Performance. Presented at Aerosol Measurement Workshop, University of Florida, Gainesville, Florida, 24–26 March 1976. Particle Technology Laboratory Publication No. 304.

There is a fraction of the ^{218}Po that is not attached to ambient aerosol particles. NRC (1991) has reviewed the published data on particles in the indoor environment and concludes that the unattached activity typically represents about 8% of airborne alpha activity but can be much higher, and has a diameter of about 1.1 nm (range $\sim$ 0.5–5 nm). This unattached fraction is highly mobile, and the portion that is inhaled deposits efficiently. Most short-lived radon progeny, however, are attached to submicrometer-sized ambient particles. For particles in this size range, diffusion is the dominant mechanism for deposition, but electrostatic deposition may be significant.

Experiments conducted *in vivo* in humans (Melandri *et al.*, 1977; Tarroni *et al.*, 1980; Melandri *et al.*, 1983) have all shown an increase in respiratory tract deposition due to the particle charge. For these experiments there was a threshold value of charge on the particle (q_c) above which the electrostatic charge enhances deposition. The value of q_c depends on the particle size as well as the airway size (Yu, 1985) but is normally greater than $30e$, where e is the elementary unit of charge. These experiments were performed for particles for which deposition by diffusion is small ($d \geqslant 300$ nm) thus enhanced deposition on the upper airways was not significant. Particle deposition took place mainly in the alveolar region by gravitational settling and electrostatic charge effects. In most practical situations it appeared that enhanced deposition was only important in the alveolar region (John and Vincent, 1985). This view is valid when the total mass deposited in the respiratory tract is the important consideration. However, when the number of particles that deposit on bronchial epithelium is the critical factor as it is for alpha particle radiation from radon progeny, enhanced deposition of singly charged ultrafine particles may be significant.

This paper first examines whether current theoretical models predict a detectable increase in particle deposition on the airways from a single charge on an ultrafine particle, and then compares the deposition efficiency (η) measured for charged and charge-neutralized ultrafine particles in simple tracheal models.

THEORETICAL

In the major airways deposition of particles may occur by a combined mechanism of diffusion and electrostatic charge. To estimate the relative importance of each by simple analysis, we assume that each mechanism acts independently and then proceed to determine the efficiency due to each.

Deposition of ultrafine particles in a developing flow through a circular duct has been shown by Ingham (1984) to depend on the entrance length and Schmidt number. For a fully developed (laminar) flow, these two quantities may be grouped to form a new nondimensional quantity called Δ on which deposition solely depends (Cohen and Asgharian, 1990). Δ is the ratio of particle residence time in the duct to the particle mean diffusion time. Knowing that deposition fraction, η, depends only on Δ, the measured data of Cohen (1987) are fitted to

$$\eta = a\Delta^b, \tag{1}$$

where a and b are found to be 2.97 and 0.568, respectively, for $10^{-9} > \Delta > 10^{-4}$.

$$\Delta = \frac{\pi L D}{4Q} \tag{2}$$

in which L is the airway length, Q is the flow rate through the airway, and D is the diffusion coefficient given by

$$D = \frac{kTC}{F}, \tag{3}$$

where k is the Boltzmann constant, T is the absolute temperature, F is the drag per unit velocity, and C is the Cunningham correction factor, given by

$$C = 1 + \mathrm{Kn}(1.257 + 0.4\,e^{-1.1/\mathrm{Kn}}), \tag{4}$$

where Kn is the Knudsen number given as:

$$\mathrm{Kn} = \frac{2\lambda}{d} \tag{5}$$

in which d and λ are the particle diameter and the mean free path in air, respectively. Equation (1) gives higher values than the expression obtained by Ingham (1975) for fully developed laminar flow by a factor of 2 in the uppermost airways. However, it approached Ingham's as the airway generation number increased.

There are two electrical forces which cause particles to deposit on the airway surfaces. One is due to interaction between the particle and the wall (image force) and the other is due to the mutual repulsion between particles with like charge (space charge force). The image force is a single particle effect and increases as the particle nears the wall. The space charge force on the other hand depends on the particle concentration and is found to be much smaller than the image force in the lung due to low particle concentration (Yu, 1977).

For the deposition efficiency due to image force alone (η_i), we employ the expression by Yu (1977) for deposition of particles uniformly distributed in a cylindrical tube:

$$\eta_i = 1 - \chi^2, \tag{6}$$

where χ is a parameter related to τ_e, such that

$$\tau_e = 4(\chi^{-1} - 2\ln\chi - \chi) \tag{7}$$

and

$$\tau_e = \frac{q^2 t C}{4\pi\varepsilon_0 F R^3} \tag{8}$$

in which q is the charge on the particle, t is the elapsed time in the airway, ε_0 is the permittivity of air and R is the radius of airways. For $\tau_e \ll 1$, Pich (1978) obtained the following simple results for the case where deposition by image forces is very small:

$$\eta_i = (6\tau_e)^{1/3}. \tag{9}$$

Since the flow in the upper airways is not parabolic, the result obtained by Thiagarajan and Yu (1979) for fully developed laminar parabolic flow is not used here. Their results can only be applied to the deep lung where the flow has slowed down and a parabolic profile prevails. In this analysis, we employed equations (8) and (9).

To determine the importance of diffusion and charge, we find the ratio of equation (1) and equation (9):

$$\alpha = \frac{\eta_d}{\eta_i} = 1.63\,\frac{\Delta^{0.568}}{\tau_e^{1/3}} \tag{10}$$

and calculate the value of α for different particle sizes and flow situations. Results calculated for unit charge (unipolar) particles of diameters between 10 nm and 100 nm for flow rates from 300 $cm^3\,s^{-1}$ to 600 $cm^3\,s^{-1}$ show that α increases from 1.4 for $d = 100$ nm to about 4.4

for $d = 10$ nm. This implies that for this range of particle size deposition by diffusion and electrostatic charge effects are of the same order of magnitude. Although the effect of charge decreases with increasing diameter, its importance increases relative to deposition by diffusion.

Prediction of deposition by diffusion plus electrostatic forces in human airways is hampered by the lack of detailed knowledge of the flow pattern in each airway. In the upper airways flow is neither laminar, nor turbulent and lengths are insufficient for full development of the boundary layer. In addition deposition by diffusion and electrical forces are not independent processes and thus are not additive. Simple addition of the two deposition efficiencies is only an approximation. Several approaches to calculation of deposition efficiency by combined mechanisms have recently been presented (Chen and Yu, 1993; Gentry *et al.*, 1994; and Asgharian and Anjilval, 1994). The models of Gentry *et al.* (1994) and Asgharian and Anjilval (1994) address the combined deposition mechanisms of sedimentation and diffusion in lung airways. The former model is based on vector addition; the latter is empirical. Lung airway orientation is an important consideration for deposition by sedimentation but is unimportant for diffusion and electrostatic deposition. Chen and Yu (1993) propose an equation of the form $\eta_{12} = [\eta_1^2 + \eta_2^2 - (\eta_1 \eta_2)^2]^{1/2}$, where η_1 and η_2 are respectively individual deposition efficiencies by mechanisms 1 and 2 and η_{12} is the efficiency for the combined mechanisms. The theoretical solutions they derived for combined electrostatic and diffusive deposition for highly charged particles and uniform flow compare well with numerical results previously derived by Yu and Chandra (1977). They predict that any additional deposition resulting from a single charge will be virtually indistinguishable from deposition by diffusion.

EXPERIMENTAL

We have measured and compared the deposition of charged and neutral ultrafine particles in simple tracheal models. Nebulized NaCl particles were size classified with an Electrostatic Classifier to produce monodisperse, singly charged, particles with diameters from 15.5 to 95 nm. Deposition in cylindrical copper tubes was compared for charged and "neutralized" aerosols.

Experimental methods

Particles nebulized from a 0.1 N NaCl solution were passed through a 2 stage cascade impactor, thoroughly dried, and size classified with an electrical mobility analyzer (TSI Model 3071 Electrostatic Classifier (ESC)). The ESC initially charges the incoming aerosol particles to produce a bipolar charge distribution. The aerosol passes between concentric cylinders across which a high electric field is imposed. Only particles with a given electrical mobility can exit through a slit at the end of the charged central cylinder. The impactor stages remove the largest droplets thereby reducing the number of doubly charged particles that can accompany singly charged particles with the same mobility. The resulting aerosol is a very monodisperse stream of singly charged particles (Asgharian *et al.*, 1992). To "neutralize" the charges the particle stream was passed through a deionizer (DEI) consisting of a 3″ diameter copper tube containing a radioactive alpha particle emitter ^{210}Po. Particles are neutralized to approximately Boltzmann equilibrium.

The monodisperse singly charged, or "neutralized", particles were passed through a 1.9 cm (3/4″) diameter conducting copper pipe 10, 23, or 30 cm long to simulate the conducting inner surface of the trachea, or an equivalent path without the pipe. Test sections compare with tracheal dimensions measured in lungs obtained at autopsy of 10 cm length, 1.9 cm diameter for a human, and 23 cm length, 2.0 cm diameter for a mongrel dog. A limited number of measurements were also made with a 60 cm tube using fluorescein particles. Particles were directed to either a condensation particle counter (CPC) (TSI Model 3025) or a Faraday Cup (FC). The CPC was linked to a chart recorder to permit averaging of counts over time. Fluctuations in the measured concentration for any given configuration were about 6%, thus small deposition differences were not detectable for any individual reading. Subsequently the CPC was linked to a computer to permit accumulation of counts over a 30 second time period. This was long enough to accumulate 10^5–10^6 particles, but short enough to minimize concentration changes due to the generator. For this system, the average variability is about 0.6%, reducing the lower limit of detection for an individual measurement of the deposition efficiency in the tube to about 2.8%.* Based on the results of Liu *et al.* (1985), all tubing was Tygon (PVC) which does not sustain an electric field. Glass valves were used to avoid any Teflon® which does sustain charges. The entire line was frequently scanned with a ^{210}Po source to prevent buildup of stray electrostatic fields. The experimental arrangement is shown schematically in Fig. 1.

Aerosol flow rates were monitored throughout each experiment by a mass flow meter incorporated into the ESC. Flow rate was recorded for each measurement ($n > 300$) and ranged from 4.1 to 5.5 $\mathrm{l\,min^{-1}}$ with a mean $\pm$ sd of 4.64 ± 0.35. Individual flow rates were used to calculate deposition efficiency as a function of the diffusion parameter (Δ) for each data point.

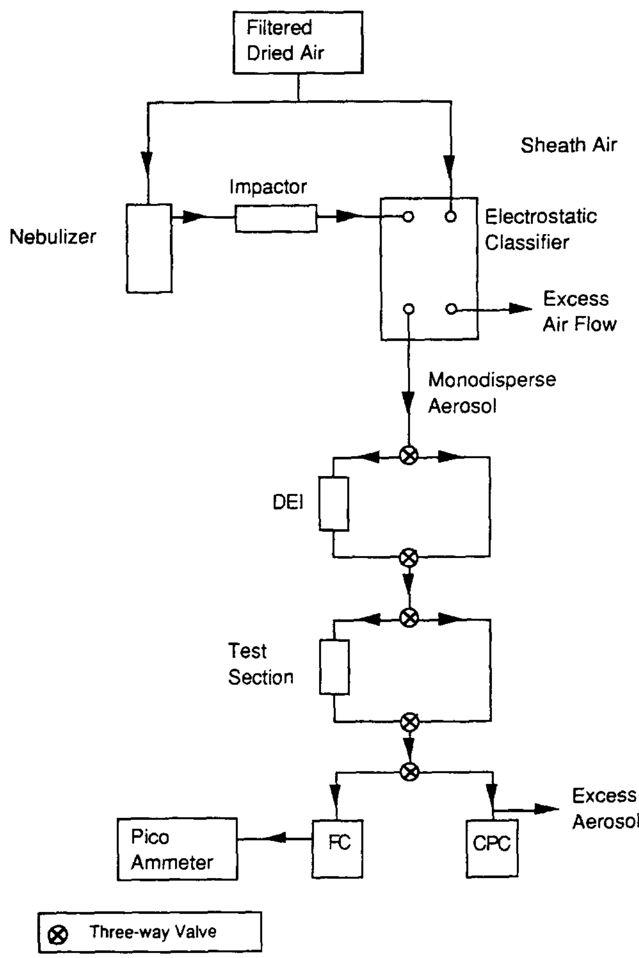

Fig. 1. Schematic diagram of experimental setup. DEI: deionizer, FC: Faraday Cup, CPC: condensation particle counter.

*The lower limit of detection is defined here as 4.66 sd (standard deviation) which applies for $\alpha = 0.05$ and $1 - \beta = 0.95$ (Pasternack and Harley, 1971).

Analytical

Percent deposition in the test section was calculated as follows:

$$\eta(\%) = 100\frac{C_x - C_t}{C_x}, \tag{11}$$

where C_t = concentration at outlet of path with the tracheal tube; C_x = concentration at outlet of the alternate path (without tracheal tube).

Equation (11) neglects the very small fractional deposition in the connecting tubing. We confirmed that this introduced negligible error by comparing the results obtained using equation (11) with the results for deposition determined from a set of measurements in which the total input was measured. In that case the number of particles entering either branch of the experimental system was measured at the exit of the ESC for the charged aerosol and at the exit of the charge neutralizer for the "neutralized" aerosols. For Faraday Cup measurements, C is replaced by N, as the measured current determined the total number of singly charged particles collected per unit time. These were normalized for any change in flow rate when necessary.

For each particle size from 15.5 to 95 nm, tests were done for the singly charged particles then immediately repeated with charge neutralized particles. The fraction deposited by diffusion (η_d) was estimated from equation (1). This empirically derived expression gives higher values than the analytical expression for fully developed laminar flow, but lower values than for uniform flow (Cohen and Asgharian, 1990). It is expected to better approximate the deposition under these experimental conditions where flow in the tracheal section is not well defined. The deposition efficiency due to image force alone, η_i, was then calculated from the total measured η as follows:

$$\eta_i = \frac{(\eta - \eta_d)}{(1 - \eta_d)}. \tag{12}$$

Deposition by image forces for the charged particle fraction of the neutralized aerosol was accounted for by applying equation (12) to the fraction shown in Table 1 for each particle size.

RESULTS

Percent deposition was calculated for measurements with the CPC for both charged and "neutralized" particles. For measurements made with the FC deposition could only be measured for charged particles, charge "neutralized" are not detectable. There is always some fraction of particles that are charged when an aerosol is neutralized to Boltzmann equilibrium. Approximately equal numbers are positive and negative so no net signal is detectable with the FC.

Deposition as measured for different particle sizes are shown in Table 2. Each data point represents a minimum of five replicate measurements. Deposition was higher for charged particles < 30 nm in each of the tracheal tubes, and for all particle sizes in the longest (30 cm) tube. Differences in the number of particles detected were near the limit of detection of the system. This substantially impacted the precision of the measurements for individual cases. But when the data are grouped as noted, differences in both cases are statistically significant at $p = 0.03$ by a nonparametric sign test.

The deposition data were examined in terms of the diffusion parameter Δ since this is the dominant deposition mechanism for neutral particles in this size range. Results are shown in Figs 2–4 where the deposition efficiency (in percent) is plotted as a function of Δ. Figures 2 and 3 are for measurements made with the CPC for singly charged and charge neutralized particles respectively. Figure 4 shows the results of Faraday Cup measurements for the charged particles. The lines shown are the best fit to the deposition efficiency using a weighted mean where weighting is by the inverse of the standard error. A reasonably good linear fit can be obtained indicating that diffusion is dominant; however, deviations result

Table 2. Percent deposition efficiency, $\eta(\%)$ *, measured by condensation particle counter (CPC) and Faraday Cup (FC) in 10, 23 and 30 cm copper surrogate tracheas. (mean flow rate = $4.6 \pm 0.4\ \mathrm{l\,min^{-1}}$)

d_p †	$\eta(\%) \pm$ se‡(CPC)			$\eta(\%) \pm$ se(DEI§, CPC)			$\eta(\%) \pm$ se(FC)		
(nm)	10 cm	23 cm	30 cm	10 cm	23 cm	30 cm	10 cm	23 cm	30 cm
15.5	4.84 ± 1.94	3.36 ± 1.95	2.59 ± 2.06	3.68 ± 0.83	1.45 ± 1.40	2.28 ± 0.82	7.48 ± 3.30	7.68 ± 2.43	9.46 ± 1.25
24.0	4.71 ± 1.04	2.02 ± 0.61	1.56 ± 1.32	1.91 ± 0.52	0.90 ± 0.61	0.90 ± 0.49	5.86 ± 1.21	3.71 ± 1.17	5.05 ± 1.29
35.7	0.88 ± 0.60	0.80 ± 0.64	1.58 ± 0.46	1.37 ± 0.73	1.34 ± 0.50	0.74 ± 0.36	1.72 ± 0.55	2.47 ± 0.52	4.30 ± 1.09
51.7	1.04 ± 0.65	0.97 ± 0.41	1.60 ± 0.79	1.31 ± 0.44	1.27 ± 0.32	1.30 ± 0.73	2.41 ± 0.62	3.43 ± 0.67	4.01 ± 0.88
64.5	0.67 ± 0.40	1.13 ± 0.69	1.04 ± 0.36	0.07 ± 0.75	0.64 ± 0.32	0.19 ± 0.19	0.80 ± 0.38	2.90 ± 0.95	3.19 ± 0.91
75.7	0.62 ± 0.53	0.35 ± 0.66	1.43 ± 0.58	0.32 ± 0.28	0.61 ± 0.30	0.29 ± 0.29	2.43 ± 0.11	2.32 ± 0.28	3.54 ± 0.73
95.3	0.32 ± 0.32	0.45 ± 0.45	0.00 ± 0.00	0.43 ± 0.48	− 0.54 ± 0.78	0.00 ± 0.00	1.21 ± 0.53	1.57 ± 0.72	1.46 ± 0.32

* Calculated from equation (11) (see text).
† Particle size.
‡ Standard error.
§ Charge-neutralized with deionizer.

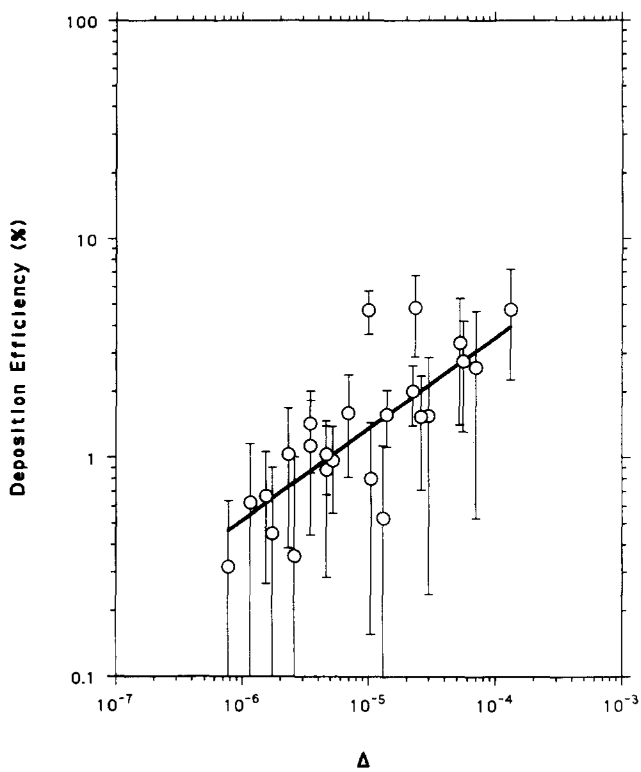

Fig. 2. Deposition efficiency (η) of singly charged particles in tracheal tubes as measured with a CPC (mean $\pm$ se). Deposition parameter Δ as defined in equation (2).

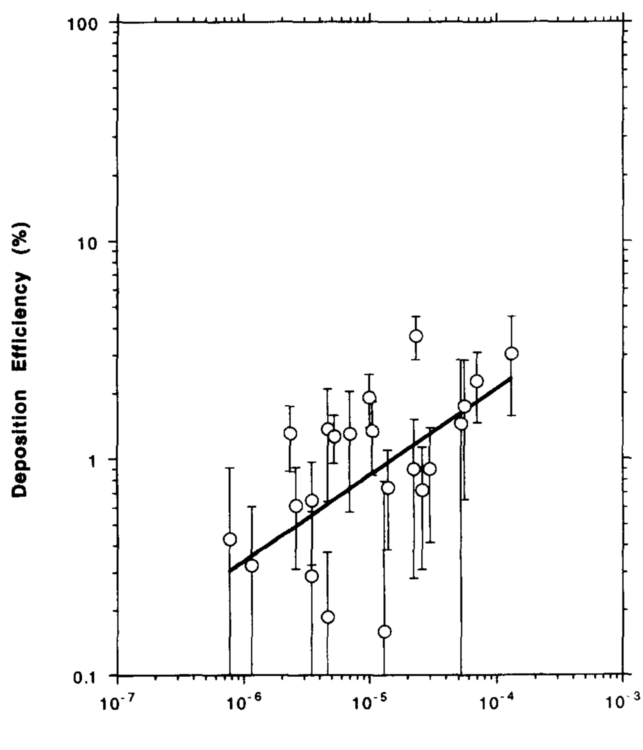

Fig. 3. Deposition efficiency (η) of charged neutralized particles in tracheal tubes as measured with a CPC (mean $\pm$ se). Deposition parameter Δ as defined in equation (2).

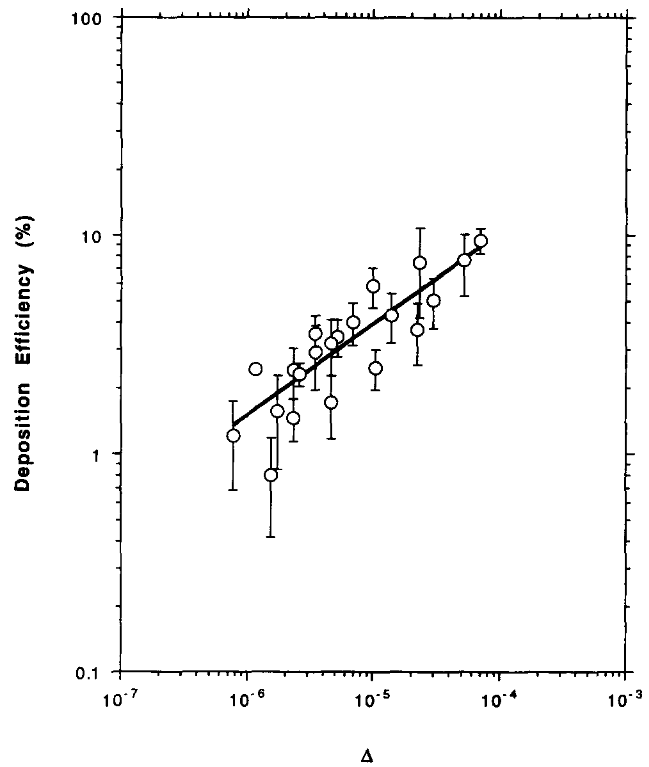

Fig. 4. Deposition efficiency (η) of singly charged particles in tracheal tubes as measured with a Faraday Cup (mean $\pm$ se). Deposition parameter Δ as defined in equation (2).

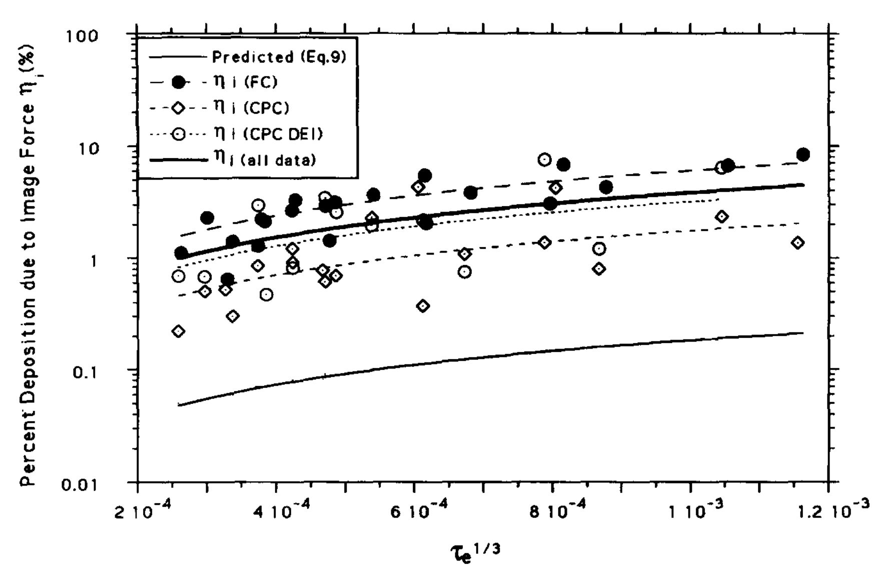

Fig. 5. Deposition efficiency of singly charged particles in tracheal tubes due to image forces [$\eta_i(\%) = 100(\eta - \eta_d)/(1 - \eta_d)$] equation (12). Data points are mean values for singly charged particles as measured with the CPC (open diamonds), Faraday Cup (closed circles) and the charged fraction of the "neutralized" particles (open circles). The latter were calculated from the measured CPC–DEI deposition data. The lines are a linear least squares fit to the data, weighted by standard error. The upper solid line is a single fit to all of the data points similarly weighted. The lower solid line represents values predicted from $\eta_i(\%) = 100\,(6\tau_e)^{1/3}$ equation (9).

from deposition by electrostatic forces. Stray triboelectric fields, existing in spite of our effort to maintain all tubing and valves without charge, may contribute to the large variability seen for some points.

Deposition by image forces (equation (12)) is shown in Fig. 5 as a function of $\tau_e^{1/3}$. Curves individually fitted to the FC, CPC and charged fraction of the CPC–DEI data are shown. The last set of points were calculated by estimating the fraction of particles that were charged from the Boltzman distribution (Table 1). A single curve fit through all the data is also displayed. Values are significantly greater than predicted, but the form of the response is clearly similar to that predicted by equation (9) which is shown for comparison.

DISCUSSION

From the CPC data we conclude that there is more deposition for charged particles than for charge neutralized particles. The Faraday Cup results indicate higher deposition than that measured with the CPC. We attribute this to the greater sensitivity of the Faraday Cup. There are two reasons for the higher sensitivity: (1) the FC collects the total aerosol for an integrated sample while the CPC samples a small part of the airstream, and (2) the sensitivity of the CPC decreases for very small particles.

In agreement with previously reported measurements deposition efficiencies are nearly an order of magnitude greater than predicted by the Ingham equation for deposition by diffusion from laminar flow (Cohen, 1987). Similarly the magnitude of the deposition by image forces, η_i is much greater than that predicted by the equation of Pich. For the latter, some of the higher deposition may result from an underestimate of η_d by equation (2), so that although it is clear that charge will increase tracheal deposition, the absolute magnitude of the increase is uncertain. The value of η_d predicted by equation (2) that was used in these analyses is greater than that for parabolic flow but less than that predicated for uniform flow (Cohen and Asgharian 1990). If η_i is evaluated from the experimental data using η_d predicted for uniform flow, the excess deposition by image forces would be reduced, but a large excess would still be seen. For both diffusive and electrostatic forces much of the increased deposition must result from convective flow patterns that carry particles near to the surface. Flow in normal human airways is disturbed by the presence of the larynx and surface irregularities, resulting in substantially enhanced deposition when compared with predictions based on simplified flow fields.

Mechanisms by which airborne particles may become charged have been summarized by Liu *et al.* (1985). They measured penetration of aerosols with diameters from 30 to 500 nm, singly charged, diffusion charged, and charge neutralized, through conducting and nonconducting tubing of Tygon (polyvinyl chloride), polyethylene, and Teflon. The three aerosols with different levels of charge gave comparable penetration values at $1\ \mathrm{l\,min^{-1}}$ when detected with an electrical aerosol detector. The curves they presented for deposition of singly charged and diffusion charged aerosols in a 300 cm long copper tube with 0.432 cm inside diameter, appear to diverge from the curve for the charge neutralized particles for $d_p < 200$ nm. Penetration was significantly less than that predicted for deposition by diffusion alone. They concluded that the increased deposition they detected was due to other mechanisms than charge, but image forces must have contributed to the discrepancy.

When particles in the size range we tested are neutralized by a ^{210}Po source to Boltzmann equilibrium many of the particles will carry single positive or negative charges as shown in Table 1. Therefore any enhanced deposition that results from charge will also occur when testing a "neutralized" aerosol. Detection of any differences can only be accomplished for the neutral fraction. Thus, it is reasonable that little difference is seen for our larger test particles ($\Delta < 10^{-5}$) since for 95 nm "neutralized" particles less than 45% carry zero charge. Differences become more detectable for the smaller particles where a smaller fraction is normally charged, e.g., at 40 nm 67% of the "neutralized" particles are uncharged.

For detailed analysis of the deposition of ultrafine particles separate terms are required for diffusion and electrostatic deposition (e.g., Ingham, 1981, 1981a). These analysis indicate that there must be increased airway deposition in people of inhaled ultrafine particles due to electrostatic charge. Investigation in hollow human airway casts is in progress to quantify the deposition efficiency.

CONCLUSIONS

Differences in deposition between singly charged and charge neutralized particles were detectable in surrogate tracheas for ultrafine particles. The increase in deposition for charged compared with neutral particles should be considered in lung airway dosimetry. As expected, deposition efficiency increased with decreased particle size and substantially exceeded that predicted for deposition from parabolic flow. Deposition of ultrafine particles is very low in the upper airways compared with total respiratory tract deposition, but because most lung cancers are bronchogenic, this small fraction is clearly important for toxicants that act before they are removed by normal clearance. It is particularly important for radon progeny in homes and mines, but also affects dose predictions for other agents that evoke responses based primarily on airway deposition (e.g., acid aerosols). Diffusion is the dominant mechanism for deposition of very small particles. Only a few percent of inhaled particles are deposited in the airways for particles with diameters from 50 to 200 nm. The additional deposition in airways that results from image forces will be most important where deposition is ordinarily low, because in such cases even a small enhancement can cause a significant increase in the calculated dose.

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