DEPOSITION OF SUBMICRON PARTICLES FROM STEADY FLOWS IN A BRANCHED TUBE*

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SUMMARY

Local rates of deposition of submicron particles from steady flows were measured along the inner and outer walls of the daughter branches of a symmetrical Y-shaped glass model of junction with dimension based on the data of the secondary and tertiary bronchi of an average human respiratory tract. Monodisperse polystyrene latex microspheres were used to generate the aerosol by a Collison-type atomizer. The particles were 0.109μ in diameter and were electrically neutralized by bipolar ions. The aerosol passed through the daughter tubes at three constant inspiratory flow rates, 31.25, 62.5, and 125 ml/sec, which correspond to low, normal, and stressed breathing rates of average men. At all flow rates, the deposition rates along the inner walls were observed to have a maximum at the branch point and a second maximum at approximately two diameters distance from the branch point, while the deposition rates along the outer walls appeared to have a maximum at one diameter distance from the entrance to the daughter branch. Furthermore, the deposition rates were higher by one order of magnitude than the values calculated from the equation of convective diffusion with the assumption of a parabolic velocity profile. The data suggest that asymmetric flow profiles and secondary flows in daughter tubes have significant effects on the rates of particle deposition.

INTRODUCTION

The particles of an aerosol which flows in a conduit deposit on the walls at rates depending on the local flow characteristics and the properties of the particles. One important example of such transfer process is the deposition of inhaled particles in the human lung. The present study was motivated by the question of local deposition

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rates of submicron particles in the upper respiratory tract.

Much of the previous work on the general aspects of deposition from moving aerosols was reviewed by Davies (1), while Altshuler gave a detailed review on the behavior of airborne particles in the respiratory tract (2). The theory of particle deposition in the human lung was first developed by Findeisen (3) and subsequently modified by Landahl (4,5). For deposition in each straight branch of the airway tree, they considered the removal of particles from air by Brownian movements and gravitational settling but did not take into account the flow of the air carrying the particles. Steady state solutions to the equation of convective diffusion with a Poiseuille flow (6,7) have also been used for estimating deposition rates (8,9). While such calculations account to some extent for the effect of air flow on the deposition process, the flow profile used in the calculations differs significantly from the actual ones. The experimental results of Schroter and Sudlow (10) suggest that flow patterns in the human bronchial tree models are complex and parabolic flow cannot be assumed. For steady inspiratory flows with Reynolds numbers in the range 100 to 1500, the velocity profile in the plane of bifurcation in the daughter branches appears to be in the form of a skewed parabola, with the maximum shifted towards the inner edge (see Figure 2 for the terminology used), while the profile in the plane normal to bifurcation is M-shaped. Secondary motions were observed at all flow rates.

In this paper, we report the results of an experimental study of the local deposition rates of submicron particles in a branched tube for steady inspiratory flows with Reynolds numbers in the range 210 to 850.

EQUIPMENT AND METHODS

Figure 1 shows schematically the general arrangement of the apparatus. Suspensions containing 0.109μ polystyrene latex spheres were dispersed by a fluid atomization aerosol generator (Environmental Research Corporation Model 7300). Built in the generator was a Krypton 85 radioactive source which produced bipolar ions in the air. The charge distribution of the aerosol particles were brought to Boltzmann equilibrium by mixing with the bipolar ions. The relative humidity of the aerosol was about 35%.

Particle concentrations were measured by an electrostatic aerosol sampler (Thermo-Systems, Inc., Model 3100). The aerosol was drawn through the sampler by a vacuum pump and particles were collected on electron microscope grids placed in the sampler. The concentration was determined by counting particles on a known area of the grid after sampling a predetermined volume of aerosol. A sampling efficiency of 69%, reported by Liu, et al (11) for 0.109μ particles, was used in determining the concentration.

The bifurcating tube used as a model of the human bronchial airways was made out of glass tubings. The parent tube had an inner diameter of 0.8 cm and a length of 20 cm. The daughter tubes were 0.55 cm in diameter and 2 cm long. The values of these two diameters were based on the dimensions of the secondary and tertiary bronchi in the Lung Model A proposed by Weibel (12). The length of the parent tube, approximately ten times of that in Weibel's model, was chosen so that the velocity profile would become parabolic before reaching the bifurcation (13). The length of the daughter tubes were made about three times of those in Weibel's model. To eliminate effects of downstream disturbance, each daughter branch was connected to a detachable glass tubing of the same diameter. The model had a branching angle of 64° , which was based on the data of Horsfield and Cumming (14). Particle deposition on the walls of daughter tubes only was studied.

Electron microscope grids used in sampling and deposition studies were made of 400 mesh perforated copper grids, 3.05 mm in diameter, with thickness approximately 0.002 cm. A film prepared by evaporating silicon monoxide onto freshly cleaned NaCl crystal was transferred from the NaCl crystal to a grid by flotation. The grids were attached to the tube walls with double stick cellphane adhesive tapes. The thickness of the tapes was 0.008 cm.

Figure 2 shows the locations where the electron microscope grids were placed. Grids (1) through (5) were used to determine the deposition along the inner edge at distances 0.2, 0.5, 0.8, 1.1, and 1.4 cm from the bifurcation, while grids (6) through (8) were used to sample along the outer edge at distances 0.2, 0.5, and 0.8 cm from the entrance to the daughter tube. Grid (9) was placed in the other daughter branch at a position equivalent to that of grid (2) to check whether the deposition at grid (2) was affected by the protrusion of the grid placed upstream. The bifurcating tube was laid flat on the top of a horizontal plate so that both inner and outer edges of the daughter branches were approximately in the vertical direction.

The flows through the two daughter tubes, sustained by a higher pressure in the aerosol generator, were balanced with the rotameter valves. In this study, three flow rates in the daughter tubes were used: 31.25, 62.5, and 125 ml/sec, which corresponded, respectively, to low, normal, and stressed total breathing rates of average men. The duration of each run was 30 minutes.

A magnification of 15,000 was used to count the particles under an electron microscope (JEM-7A). The local deposition rates were determined by dividing the number of particles deposited per unit surface area by the duration of the run. To keep the relative error of counting within 6%, at least 275 particles were counted for the determination of each deposition rate, except in a few cases where the amount of deposition was too low to do so.

To check whether the re-entrainment and rebounding of particles were significant, a grid coated with adhesive was used in one of the runs. The result showed that there was no significant increase in deposition.

In order to obtain sufficiently high particle concentration, the suspensions containing 10% (by volume) latex spheres (Dow Chemical Co.) were diluted only 20 to 40 times. As a result, there were appreciable amounts of doublets and triplets present in the aerosols. Only singlets were counted in the determination of the deposition rates.

RESULT AND DISCUSSION

The rate of deposition per unit area of surface is commonly normalized by dividing by the concentration at some reference point. The ratio has the units of cm/sec and is called the velocity of deposition (1). Figure 3 shows the velocity of deposition, based on the main stream concentration, as a function of the distance from the bifurcation. For clarity, only the data from one typical run are shown for each flow rate. The data from different runs differ by factors from 2 to 5, but the shape of the curves is similar. The velocities of deposition computed from Levich's steady state solution to the equation of convective diffusion for laminar flow in a straight tube are also shown in the figure for comparison. In Levich's solution, the flow is assumed to be fully developed and the particle concentration profile at the entrance is flat. For aerosols moving into a daughter branch of a bifurcating tube, the particle concentration profile can be considered as flat in the inner half of the tube since the flow just splits into two streams at the carina. However, the velocity profile in the plane of bifurcation is, according to Schroter and Sudlow (10), considerably distorted, with a peak velocity, near the inner wall, being about twice the average velocity. Thus, the calculation of deposition rates based on Levich's straight tube solution cannot properly account for the effect of flow. It can be seen from Figure 3 that the rates of deposition along the inner edge are higher almost by one order of magnitude than those computed from the straight tube solution.

The deposition on the outer edge is quite different. The thin layer in the vicinity of the outer edge at the bifurcation is already depleted of particles because of the deposition taking place at the same edge in the parent tube. Thus, the particle concentration profile in this layer is not flat. Furthermore, the velocity gradient near the outer edge is less than that near the inner edge. In view of these differences, one would expect the rates of deposition along the outer edge to be lower than those at the inner edge. The experimental results show that this is

indeed the case. However, the observed velocities of deposition along the outer edge was still significantly higher than those calculated from the straight tube solution.

One interesting result of this experimental study is that for all flow rates tested, the local deposition rates along the inner edge have a maximum at approximately two diameters distance from the bifurcation, in addition to a maximum at the entrance, while the deposition rates along the outer wall appear to have a maximum at one diameter distance from the entrance. This suggests that secondary flows probably has an effect on deposition. The data suggest that secondary motions go outward at about 0.1 cm downstream from the bifurcation, reach the outer walls at about 0.5 cm and achieve a full cycle at about 1.1 cm. Grids (1), (3), and (5), being at the fringes of the main spiral flow, had deposition rates quite close to each other. Grid (2), being far from the main line of the spiral flow, had a lower deposition rate. Since grid (9) showed about the same deposition rate as grid (2), it could be concluded that the lesser deposition at 0.5 cm on the inner edge was not the effect of interference by the grid placed upstream. Although the relationship between the local deposition rates and the secondary flows discussed here are based on a small amount of experimental data and, therefore, may not be conclusive, it is interesting to note that the pattern of the secondary motions suggested by the deposition data is consistent with that visually observed by Schroter and Sudlow (10).

It should also be remarked that, although the protrusion of a grid appeared to have little effect on deposition at a downstream grid, it was observed that there was comparatively more deposition at sharp edges such as the edges of silicone monoxide film on the electron microscope grids.

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FIGURE 1 DIAGRAM OF APPARATUS

FIGURE 2 LOCATIONS OF GRIDS

FIGURE 3 LOCAL DEPOSITION RATES FOR FLOW RATES: V1=125, V2=62.5, AND V3 = 31.25 CC/SEC.