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RISK ASSESSMENT OF INHALED PARTICLES INTEGRATING TIME-ACTIVITY PATTERNS WITH RESPIRATORY TRACT PARTICLE DEPOSITION MODELS*

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Abstract—Human daily activity patterns and age-scaled anatomical models are used to calculate expected daily particle deposition rates for adults and children. Daily doses in $\mu\text{g kg}^{-1}$ per day per $\mu\text{g m}^{-3}$ of air of particles in various sizes are calculated for the N-P, T-B and P regions of adults that work indoors at a low level of exertion or that work more heavily outdoors and for active children. Higher doses are seen for higher levels of activity, as expected. Whether or not children's doses are larger than those of adults depends on particle size and region of the respiratory tract considered.

INTRODUCTION

EVALUATING the risks associated with chronic exposure to aerosol particles requires a quantitative estimate of the actual mass depositing in the respiratory tract. Mathematical models available to predict particle deposition in the major regions of the respiratory tract generally predict deposition of particles of known size at specific ventilation rates. Risk assessments, however, generally involve making simplifying assumptions about 'typical' particle sizes and 'average' ventilation rates (e.g. breathing particles less than $10 \mu\text{m}$ at a $20 \text{ m}^3 \text{ day}^{-1}$ ventilation rate). However, particle deposition in the respiratory tract changes dramatically with particle size at different ventilation rates. Our research involves including realistic activity patterns and particle sizes in aerosol deposition predictions.

METHODS AND RESULTS

Recently-available studies of human daily activity patterns which provide estimates of the fraction of time U.S. subpopulations spend in activities with different ventilation rates were used to estimate daily time-activity distributions. Activity-specific ventilation rates throughout a typical day for persons aged 6 and 18 years were then used as input to aerosol deposition models (U.S. EPA, 1985). Ventilation rates are shown in Table 1.

The anatomical models were developed from the tracheobronchial data of PHALEN *et al.* (1985). The bronchial airways were scaled to a dead space volume based on height and the diameters were then increased by 20% to correspond to volumes at total lung capacity. The pulmonary airway models were created using the method presented in SCHUM and YEH (1980). The models are shown in Table 2.

Aerosol deposition in the respiratory tract was calculated using the YEH and SCHUM

*This paper was included in Poster Session 5 and the discussion included in the summary presented in Section 12.

TABLE 1. RESPIRATORY PATTERNS USED IN DEPOSITION CALCULATIONS

Activity	Tidal volume (cm ³)	Breathing frequency (breaths min ⁻¹)	Minute volume (l. min ⁻¹)	Inspiratory flow rate (cm ³ s ⁻¹)
Resting				
Adult	770	13	10.0	333.3
6 year old child	155	25	3.9	130.0
Light activity				
Adult	1300	15	20.0	666.7
6 year old child	270	29	7.8	260.0
Moderate activity				
Adult	2000	20	40.0	1333.3
6 year old child	445	35	15.4	520.0
Heavy activity				
Adult	2400	25	60.0	2000.0
6 year old child	500	45	23.2	780.0
Adult 20 m ³ day ⁻¹	1000	14	14.0	466.66
Adult 30 m ³ day ⁻¹	1300	15	20.8	666.66
Child 10 m ³ day ⁻¹	250	28	7.0	233.33

Adapted from PHALEN *et al.* (1985).

TABLE 2. ANATOMICAL LUNG MODELS USED FOR DEPOSITION CALCULATIONS. DIMENSIONS ARE THOSE AT TOTAL LUNG CAPACITY

N	Number of tubes	Airway length (cm)		Airway diameter (cm)		Branch angle (°)	Gravity angle (°)
		18 years	(6 years)	18 years	(6 years)		
1	1	8.900	(6.390)	2.298	(1.236)	0	0
2	2	3.830	(2.750)	1.688	(0.919)	36	20
3	4	1.470	(1.050)	1.181	(0.655)	35	31
4	8	1.050	(0.733)	0.870	(0.489)	28	43
5	16	0.800	(0.593)	0.519	(0.309)	35	39
6	32	0.700	(0.500)	0.402	(0.236)	39	39
7	64	0.490	(0.360)	0.351	(0.203)	34	40
8	128	0.360	(0.283)	0.286	(0.172)	48	36
9	256	0.330	(0.277)	0.234	(0.149)	53	39
10	512	0.300	(0.273)	0.195	(0.131)	54	45
11	1024	0.270	(0.251)	0.156	(0.114)	51	43
12	2048	0.250	(0.237)	0.130	(0.102)	46	45
13	4096	0.220	(0.217)	0.106	(0.085)	47	45
14	8192	0.200	(0.200)	0.088	(0.071)	48	45
15	16384	0.180	(0.180)	0.071	(0.057)	52	45
16*	32768	0.170	(0.170)	0.060	(0.048)	45	45
17	65536	0.150	(0.150)	0.058	(0.046)	45	45
18	131072	0.138	(0.135)	0.056	(0.044)	45	45
19	262144	0.127	(0.125)	0.054	(0.042)	45	45
20	524288	0.120	(0.118)	0.052	(0.039)	45	45
21	1048576	0.114	(0.113)	0.049	(0.037)	45	45
22	2097152	0.111	(0.091)	0.0475	(0.035)	45	45
23	4194304	0.077	(0.065)	0.0475	(0.0335)	45	45
24	8388608	0.056	(0.047)	0.046	(0.032)	45	45
25†	3 × 10 ⁸	0.024	(0.017)	0.029	(0.020)	45	45

*Terminal bronchioles; †alveoli.

N = generation number; gravity angle 90° corresponds to horizontal tube.

Based on PHALEN *et al.* (1985); SCHUM and YEH (1980).

TABLE 3. PREDICTED DEPOSITION EFFICIENCIES FOR MOUTH BREATHING FOR A YOUNG ADULT AND A 6-YEAR-OLD CHILD

Activity	Region*		Particle diameter, μm			
			0.1	0.5	2.5	6.5
Resting	TB	Adult	0.098	0.028	0.101	0.437
		(Child)	(0.159)	(0.046)	(0.167)	(0.611)
	P	Adult	0.251	0.094	0.335	0.382
		(Child)	(0.143)	(0.050)	(0.168)	(0.174)
Light activity	TB	Adult	0.070	0.023	0.128	0.561
		(Child)	(0.117)	(0.038)	(0.208)	(0.749)
	P	Adult	0.287	0.104	0.345	0.318
		(Child)	(0.200)	(0.068)	(0.200)	(0.137)
Moderate activity	TB	Adult	0.050	0.023	0.204	0.768
		(Child)	(0.082)	(0.037)	(0.314)	(0.909)
	P	Adult	0.275	0.092	0.286	0.163
		(Child)	(0.224)	(0.072)	(0.178)	(0.045)
Heavy activity	TB	Adult	0.039	0.021	0.274	0.875
		(Child)	(0.072)	(0.041)	(0.406)	(0.959)
	P	Adult	0.251	0.087	0.232	0.079
		(Child)	(0.213)	(0.065)	(0.136)	(0.013)

*TB = tracheobronchial; P = pulmonary.
 Calculated by the YEH and SCHUM (1980) predictive deposition model.

TABLE 4. PREDICTED NASAL DEPOSITION EFFICIENCIES. ADULT AND CHILD EFFICIENCIES ARE ASSUMED TO BE THE SAME AT EQUIVALENT LEVELS OF ACTIVITY

Activity	Particle diameter, μm			
	0.1*	0.5	2.5	6.5
Resting	—	0.023	0.322	0.741
Light activity	—	0.042	0.477	0.846
Moderate activity	—	0.078	0.636	0.913
Heavy activity	—	{mouth breathing only}		
Adult $20 \text{ m}^3 \text{ day}^{-1}$	—	0.031	0.395	0.797
Adult $30 \text{ m}^3 \text{ day}^{-1}$	—	0.042	0.477	0.846
Child $10 \text{ m}^3 \text{ day}^{-1}$	—	0.042	0.477	0.846

*Negligible.

(1980) predictive aerosol deposition model. Calculations were made for particle sizes of 0.1, 0.5, 2.5, and 6.5 μm MMAD in order to simulate realistic environmental aerosols. Predicted deposition fractions, uncorrected for deposition in the head, are reported for the tracheobronchial and pulmonary regions of the lung. Deposition efficiencies are shown in Table 3.

Nasal deposition efficiencies were estimated from YU *et al.* (1981), and are shown in Table 4. At the highest ventilation rate, it is assumed that people switch from nose to

TABLE 5. PREDICTED REGIONAL DEPOSITION RATES FOR NOSE BREATHING. RATES ARE PER $\mu\text{g m}^{-3}$ SIZE-SPECIFIC AEROSOL CONCENTRATION

Activity	Daily time fraction	Daily inhalation rate ($\text{m}^3 \text{day}^{-1}$)	N-P deposition rate ($\mu\text{g kg}^{-1}$ per $\mu\text{g m}^{-3}$)	T-B deposition rate ($\mu\text{g kg}^{-1}$ per $\mu\text{g m}^{-3}$)	Pulmonary deposition rate ($\mu\text{g kg}^{-1}$ per $\mu\text{g m}^{-3}$)	Total deposition rate ($\mu\text{g kg}^{-1}$ per $\mu\text{g m}^{-3}$)	
<u>Particle size 0.1 μm</u>							
Adult low							
Resting	0.65	9.36	0.000	0.012	0.031	0.043	
Light	0.33	9.50	0.000	0.009	0.038	0.047	
Moderate	0.02	1.15	0.000	0.001	0.004	0.005	
Heavy	0.00	0.00	0.000	0.000	0.000	0.000	
		Total	20.01	0.000	0.022	0.073	0.095
Adult high							
Resting	0.45	6.48	0.000	0.009	0.022	0.031	
Light	0.32	9.22	0.000	0.009	0.036	0.045	
Moderate	0.20	11.52	0.000	0.008	0.044	0.052	
Heavy	0.03	2.59	0.000	0.001	0.009	0.010	
		Total	29.81	0.000	0.027	0.111	0.138
Active child							
Resting	0.50	2.81	0.000	0.018	0.016	0.034	
Light	0.35	3.93	0.000	0.020	0.033	0.053	
Moderate	0.14	3.10	0.000	0.011	0.030	0.041	
Heavy	0.01	0.33	0.000	0.001	0.003	0.004	
		Total	10.17	0.000	0.050	0.082	0.132
<u>Particle size 0.5 μm</u>							
Adult low							
Resting	0.65	9.36	0.003	0.003	0.012	0.018	
Light	0.33	9.50	0.006	0.003	0.013	0.022	
Moderate	0.02	1.15	0.001	0.001	0.001	0.003	
Heavy	0.00	0.00	0.000	0.000	0.000	0.000	
		Total	20.01	0.010	0.007	0.026	0.043
Adult high							
Resting	0.45	6.48	0.002	0.002	0.008	0.012	
Light	0.32	9.22	0.005	0.003	0.013	0.021	
Moderate	0.20	11.52	0.013	0.003	0.014	0.030	
Heavy	0.03	2.59	0.000	0.001	0.003	0.004	
		Total	29.81	0.020	0.009	0.038	0.067
Active child							
Resting	0.50	2.81	0.003	0.005	0.006	0.014	
Light	0.35	3.93	0.007	0.006	0.011	0.024	
Moderate	0.14	3.10	0.010	0.005	0.009	0.024	
Heavy	0.01	0.33	0.000	0.001	0.001	0.002	
		Total	10.17	0.020	0.017	0.027	0.064
<u>Particle size 2.5 μm</u>							
Adult low							
Resting	0.65	9.36	0.040	0.009	0.028	0.077	
Light	0.33	9.50	0.062	0.009	0.024	0.095	
Moderate	0.02	1.15	0.010	0.001	0.002	0.013	
Heavy	0.00	0.00	0.000	0.000	0.000	0.000	
		Total	20.02	0.112	0.019	0.054	0.185

TABLE 5—continued

Activity	Daily time fraction	Daily inhalation rate (m ³ day ⁻¹)	N-P deposition rate (μg kg ⁻¹ per day per μg m ⁻³)	T-B deposition rate (μg kg ⁻¹ per day per μg m ⁻³)	Pulmonary deposition rate (μg kg ⁻¹ per day per μg m ⁻³)	Total deposition rate (μg kg ⁻¹ per day per μg m ⁻³)
<u>Particle size 2.5 μm</u>						
Adult high						
Resting	0.45	6.48	0.028	0.006	0.020	0.054
Light	0.32	9.22	0.060	0.009	0.023	0.092
Moderate	0.20	11.52	0.102	0.012	0.017	0.131
Heavy	0.03	2.59	0.000	0.010	0.008	0.018
		Total 29.81	0.190	0.037	0.068	0.295
Active child						
Resting	0.50	2.81	0.037	0.013	0.013	0.063
Light	0.35	3.93	0.080	0.018	0.018	0.116
Moderate	0.14	3.10	0.086	0.016	0.009	0.111
Heavy	0.01	0.33	0.000	0.006	0.002	0.008
		Total 10.17	0.203	0.053	0.042	0.298
<u>Particle size 6.5 μm</u>						
Adult low						
Resting	0.65	9.36	0.093	0.014	0.012	0.119
Light	0.33	9.50	0.111	0.011	0.006	0.128
Moderate	0.02	1.15	0.015	0.001	0.000	0.016
Heavy	0.00	0.00	0.000	0.000	0.000	0.000
		Total 20.01	0.219	0.026	0.018	0.263
Adult high						
Resting	0.45	6.48	0.064	0.010	0.009	0.083
Light	0.32	9.22	0.107	0.011	0.006	0.124
Moderate	0.20	11.52	0.147	0.011	0.002	0.160
Heavy	0.03	2.59	0.000	0.032	0.003	0.035
		Total 29.81	0.318	0.064	0.020	0.402
Active child						
Resting	0.50	2.81	0.084	0.018	0.005	0.107
Light	0.35	3.93	0.142	0.019	0.004	0.165
Moderate	0.14	3.10	0.124	0.011	0.000	0.135
Heavy	0.01	0.33	0.000	0.014	0.000	0.014
		Total 10.17	0.350	0.062	0.009	0.421

Daily time fractions estimated from U.S. EPA (1985).

mouth breathing. The estimated daily deposition rates, corrected for nasal deposition, are shown in Table 5.

DISCUSSION

The deposition patterns seen in Table 5 are similar to those reported by HOFMANN *et al.* (1989) and by KU and YU (1986). Total deposition rate increases as people spend a greater percentage of time at higher levels of exertion. Furthermore, at high levels of exertion children have a greater percentage of total deposition in the T-B region than

do adults for equivalent levels of activity. On a per kg basis, total deposition in the child is comparable to adults at equivalent activity levels.

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