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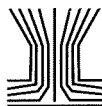
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Comparisons of Calculated Respiratory Tract Deposition of Particles Based on the Proposed NCRP Model and the New ICRP66 Model

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ABSTRACT. Task Groups of the National Council on Radiation Protection and Measurements (NCRP) and the International Commission on Radiological Protection (ICRP) have independently revised respiratory tract dosimetry models of inhaled radioactive aerosols. Both models contain modules for calculating inhaled particle deposition. In this report, the deposition of particles in the respiratory tract was calculated based on both the NCRP and the ICRP66 models, under the same particle size distribution, lung volume, and breathing conditions. The results indicate that the largest discrepancy between the two models is for ultrafine particles, where the ICRP66 model predicts a lower tracheobronchial deposition and a higher pulmonary deposition than the NCRP model. This difference is attributed to the fact that the ICRP66 model does not take into account the enhanced diffusional deposition due to the effect of the entrance configuration of a bifurcation. This may have significant implications on dose estimates of inhaled ultrafine particles, including radon and radon progeny. *AEROSOL SCIENCE AND TECHNOLOGY* 25:134-140 (1996)

INTRODUCTION

Task Groups of the National Council on Radiation Protection and Measurements (NCRP) and the International Commission on Radiological Protection (ICRP) have been independently reviewing and revising respiratory tract dosimetry models for inhaled radioactive aerosols. The newly proposed NCRP respiratory tract dosimetry model (Phalen et al. 1991) represents a

significant change in philosophy from the old ICRP Task Group model (Task Group on Lung Dynamics 1966; ICRP 1979). The proposed model describes respiratory tract deposition, clearance, and dosimetry for radioactive substances inhaled by radiation workers and the general public. The model is expected to be published in 1996 (NCRP, in press). In support of the NCRP proposed model, computer software (NCRP/ITRI model) is being developed at our Institute (Chang et al. 1991; Phalen et al. 1991; Yeh 1991). Although this software is still incom-

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plete, the deposition module of the software is complete and can be used to calculate inhaled particle deposition within the respiratory tract. Recently, the ICRP published their new dosimetric model for the respiratory tract, ICRP66 (ICRP 1994). Based on ICRP66, the National Radiological Protection Board of the UK developed a PC-based software, LUDEP (version 1.1), for calculating particle deposition and internal doses (Jarvis et al. 1994). The purpose of this report is to compare the calculated respiratory tract deposition of particles based on these two models, under the same particle size distribution, lung volume, and breathing conditions.

METHODS

The NCRP/ITRI deposition model is based on the model of Yeh and Schum (1980). In this model, the respiratory tract is divided into three main regions: the naso-oro-pharyngolaryngeal (NOPL), tracheobronchial (TB), and pulmonary (P) regions. The major modifications to the Yeh and Schum model (1980) are briefly described as follows:

1) Nasal and oral deposition: Data for ultrafine particles became available during the last ten years. Because the structures in the nasopharyngeal region are extremely complex, empirical equations are often used to calculate nasopharyngeal deposition. For particle diameters $> 0.2 \mu\text{m}$, measurements of nasal and oral deposition have been reported. These data, summarized by Yu et al. (1981), were fit by log-logistic functions and can be written as:

$$N_i = 1 / \left[1 + (\rho d^2 Q / 4600)^{-0.94} \right] \quad (1)$$

$$N_e = 1 / \left[1 + (\rho d^2 Q / 2300)^{-1.01} \right] \quad (2)$$

$$O_i = 1 / \left[1 + (\rho d^2 Q / 30000)^{-1.37} \right] \quad (3)$$

$$O_e = 0$$

$$\text{(assumed if no other information),} \quad (4)$$

where N_i and N_e are the nasal deposition efficiencies during inspiration and expiration, respectively; O_i and O_e are the oral deposition efficiencies during inspiration and expiration, respectively; ρ is the particle density (g/cm^3); d is the particle diameter (μm); and Q is the average flow rate (cm^3/sec). For particle diameters $< 0.2 \mu\text{m}$, data from Cheng et al. (1988, 1990, 1991) and Yamada et al. (1988) were used. These can be written as (Cheng et al. 1990, 1991):

$$N_i = 1 - \exp(-12.8Q^{-1/8}D^{1/2}) \quad (5)$$

$$N_e = 1 - \exp(-15.0Q^{-1/8}D^{1/2}) \quad (6)$$

$$O_i = 1 - \exp(-57.1Q^{-1/8}D^{2/3}) \quad (7)$$

$$O_e = 1 - \exp(-48.8Q^{-1/8}D^{2/3}), \quad (8)$$

where D is the diffusion coefficient (cm^2/s) of the particles.

2) Inhalability: Before particles can deposit in the respiratory tract, they must be inhaled from the ambient air. It follows that particles that do not enter the nose or mouth are unavailable for deposition. Inhalability is defined as the fraction of the suspended material in ambient air that actually enters the nose or mouth with the volume of air inhaled. For the NCRP/ITRI model, the inhalable fractions defined by the American Conference of Governmental Industrial Hygienists (ACGIH, 1985) were adopted:

$$E = 50(1 + e^{-0.06d_{ae}}), \quad \text{for } 0 < d_{ae} \leq 100 \mu\text{m} \quad (9)$$

where E is the fraction of ambient airborne particles that are inhalable and d_{ae} is the particle aerodynamic diameter.

3) Correction for diffusional deposition in the TB region: Because of the nature of the airway branching in the TB region, the air flow enters a daughter airway segment (or vice versa) at an angle (branching angle). The effect of this entrance configuration is the enhancement of

diffusional deposition. In their experimental study of ultrafine particle deposition in a human tracheobronchial cast, Cohen et al. (1990) reported that the measured deposition is about twice that predicted based on the Ingham equation (1975) for a straight tube. Because this effect can be attributed to the presence of turbulence, secondary flow, developing flow, and the branching angle at the entrance of the daughter airway segment in the branching airways (Boelta et al. 1948; Yu and Cohen 1994), Yeh (1974) suggested the following equations to correct for the entrance configuration effect:

$$P_D^E = 1 - (1 - P_D)^{f_e} \quad (10)$$

$$f_e = 1 + C_1(2R/L) \quad \text{for } L/R > 10 \quad (11)$$

where P_D^E = diffusion deposition probability, taking into account the effect of the entrance configuration; P_D = predicted diffusion deposition (Ingham, 1975); $C_1 = (2\theta/\pi)(13 - 12\theta/\pi)$; and θ = bend angle or branching angle (in radians). The empirical enhancement factor in equation (11) was given by Boelta et al. (1948) based on their study on the effect of entrance configuration on heat transfer coefficients in circular tubes. Equation (10) was derived by Yeh (1974) based on heat and mass transfer analogy. Table 1 shows the ratio of P_D^E/P_D for $\theta = 20^\circ$, 45° , and 90° . P_D usually is < 0.1 for any airway segment, and θ ranges from 18° to 51° (Yeh and Schum

1980). This ratio of P_D^E/P_D ranging from 1.48 to 2.4 is compatible with the values reported by Cohen et al. (1990).

- 4) Use of the model for infants and children: The Yeh and Schum model was adapted for use in infants and children by scaling the airway dimensions and using an appropriate ventilation rate according to Phalen et al. (1985).
- 5) Application to polydisperse aerosols: In the home or workplace, the aerosols are usually polydisperse. To predict the initial regional respiratory tract deposition pattern after polydisperse aerosols are inhaled, the program was modified to integrate the deposition over the size distribution (Yeh et al. 1993). The user needs only to specify the aerosol size distribution (e.g., mass median diameter and geometric standard deviation) in addition to the other usual parameters (such as breathing frequency, tidal volume, functional residual capacity, pause between breaths, etc.).

In the NCRP/ITRI model, the respiratory tract is divided into NOPL, TB, and P regions, whereas in the ICRP66 model, the respiratory tract is divided into five regions: extrathoracic 1 (ET₁), extrathoracic 2 (ET₂), bronchial (BB), bronchiolar (bb), and alveolar-interstitial (AI) regions. The corresponding regions between the two models are as follows: NOPL vs. (ET₁ + ET₂), TB vs. (BB + bb), and P vs. AI. Therefore, the depositions within ET₁ and ET₂ were summed to compare with NOPL, and BB and bb were summed to compare with TB. The deposition calculations were based on

TABLE 1. Calculated Ratio of P_D^E/P_D

P_D (given)	$\theta = 90^\circ$		$\theta = 45^\circ$		$\theta = 20^\circ$	
	P_D^E	P_D^E/P_D	P_D^E	P_D^E/P_D	P_D^E	P_D^E/P_D
0.00001	0.000024	2.40	0.00002	2.00	0.0000152	1.52
0.0001	0.00024	2.40	0.0002	2.00	0.000152	1.52
0.001	0.0024	2.40	0.002	2.00	0.00152	1.52
0.01	0.0238	2.38	0.0199	1.99	0.0151	1.51
0.05	0.116	2.32	0.0975	1.95	0.0749	1.50
0.1	0.223	2.23	0.19	1.90	0.148	1.48

the following conditions corresponding to normal breathing at rest for both models: nose breathing with tidal volume = 770 mL, breathing frequency = 13 breaths/min, functional residual capacity = 3000 mL, particle density = 1.0 g/cm³, and particle size range 0.001–10 μm with two particle size distributions (monodisperse with geometric standard deviation, $\sigma_g = 1.0$; and polydisperse with $\sigma_g = 2.5$). The latest version of the NCRP/ITRI software (Yeh et al. 1993) and the LUDEP version 1.1 were used for the calculations.

RESULTS AND DISCUSSION

Both the ICRP66 and NCRP/ITRI deposition models are based on a semi-empirical modeling approach. In the extrathoracic region, empirical deposition equations derived from fitting experimental deposition data were used by both models. The major differences between the ICRP66 and the NCRP/ITRI models are evident in modeling the tracheobronchial and pulmonary re-

gions: (1) different anatomical lung models were used; (2) the ICRP66 model grouped the first nine generations of the conducting airways as BB and the last seven generations of the conducting airways as bb, whereas the NCRP/ITRI model preserved all sixteen generations in the conducting airways; and (3) empirical deposition equations from fitting data obtained from the partial lung cast or data from a theoretical calculation for the regions of concern were used in the ICRP66 model, whereas the NCRP/ITRI model used an analytical approach based upon a generation-by-generation calculation.

Results are shown in Figures 1 and 2. Figure 1 shows the comparison between the two models for monodisperse aerosols. For particles > 2.5 μm, the ICRP66 model predicted higher NOPL deposition than the NCRP/ITRI model did. Particles deposited in the NOPL will not be available for deposition in the TB; consequently, the ICRP66 model has lower TB and P deposition. This can be explained by the fact that

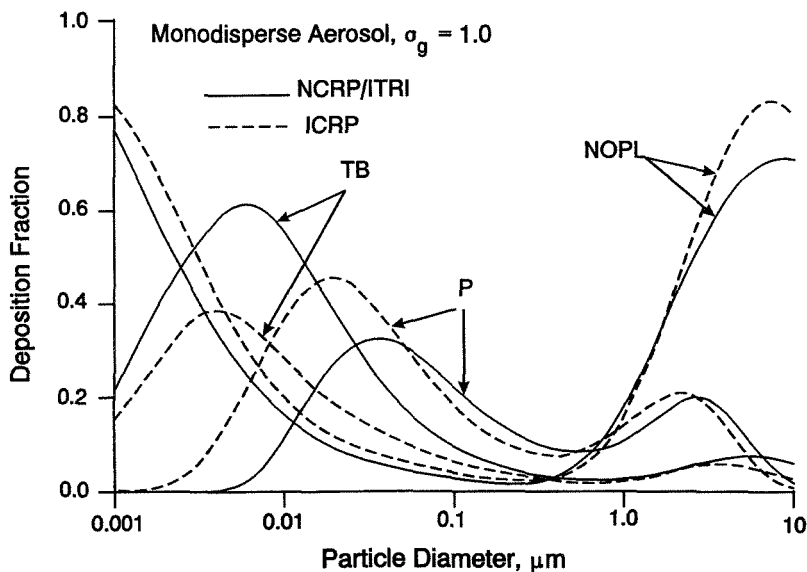


FIGURE 1. Comparison of inhaled particle depositions between NCRP/ITRI and ICRP66 models for monodisperse aerosols with a geometric standard deviation = 1.0 (particle density = 1.0 g/cm³, tidal volume = 770 mL, breathing frequency = 13/min, and functional residual capacity = 3000 mL).

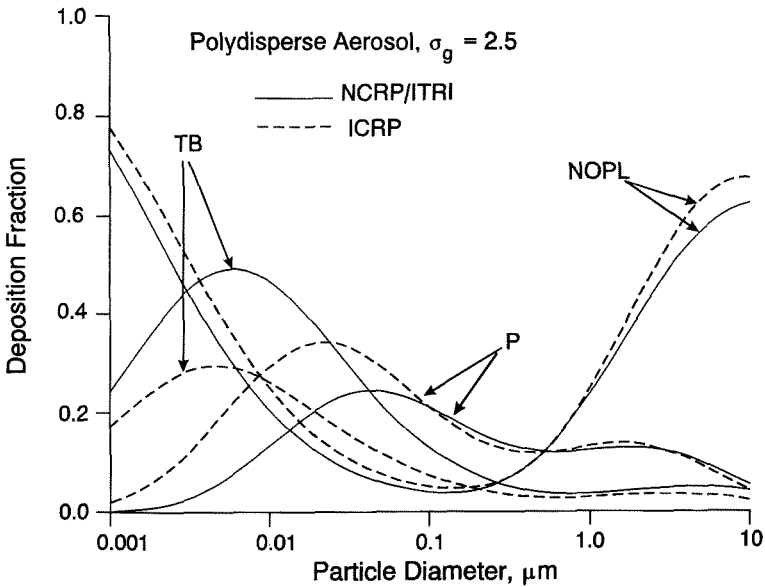


FIGURE 2. Comparison of inhaled particle depositions between NCRP/ITRI and ICRP66 models for polydisperse aerosols with a geometric standard deviation = 2.5 (particle density = 1.0 g/cm³, tidal volume = 770 mL, breathing frequency = 13/min, and functional residual capacity = 3000 mL).

the two models use different inhalability equations. The NCRP/ITRI model uses the inhalability equation recommended by the American Conference of Governmental Industrial Hygienists (ACGIH, 1985), whereas the ICRP66 model uses an alternative equation that includes wind speeds (ICRP 1994). For particles less than about 0.2 μm , the ICRP66 model predicted a slightly higher NOPL deposition; however, the NCRP/ITRI model predicted a higher TB deposition, resulting in a lower P deposition for particles < 0.05 μm . The basis of the discrepancy between the two models for NOPL deposition for ultrafine particles is unclear, because the same data sets (Cheng et al. 1988, 1990, 1991, 1993; Swift et al. 1992) were used in both models. The difference may be due to the fact that different equations were used to fit the data. The NCRP/ITRI model predicts higher TB deposition for ultrafine particles where deposition is dominated by a diffusion mechanism. This is because the NCRP/ITRI model takes into account the

effects of branching (or entrance configuration) on diffusional deposition at a bifurcation (Yeh 1974; Cohen 1990). Consequently, the ICRP66 model predicts a higher P deposition for ultrafine particles. As shown in Figures 1 and 2, these differences are substantial for particles < 0.03 μm .

Polydisperse aerosols are most commonly encountered in the environment. Figure 2 shows the comparison between the two models for polydisperse aerosols with $\sigma_g = 2.5$. The relative trends were similar to the results for the monodisperse aerosols, showing two peaks in deposition curves for both the TB and P depositions: around 0.003–0.008 μm and 3–6 μm for the TB deposition and 0.02–0.05 μm and 2–4 μm for the P deposition. However, these two peaks were somewhat flattened and were lower for the polydisperse aerosols than for the monodisperse aerosols.

In summary, the general trends of the deposition curves for the two models are

similar. For particles $> 0.2 \mu\text{m}$, the difference between the two models is small; the ICRP66 model predicts a slightly higher NOPL (or ET) deposition when particles are less than about $1\text{--}2 \mu\text{m}$. However, because the ICRP66 model does not consider the enhanced diffusion deposition due to branching bifurcation, it predicts a much lower TB deposition and thus a much higher P deposition than the NCRP/ITRI model for particles $< 0.2 \mu\text{m}$. This will significantly affect the dose estimate of inhaled ultrafine particles, including radon and radon progeny.

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