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ABSTRACT

The Task Group has developed a new model of the deposition of inhaled aerosols in each anatomical region of the respiratory tract. The model is used to evaluate the fraction of airborne activity that is deposited in respiratory regions having distinct retention characteristics and clearance pathways: the anterior nares, the extrathoracic airways of the naso- and oropharynx and larynx, the bronchi, the bronchioles, and the alveolated airways of the lung. Drawn from experimental data on total and regional deposition in human subjects, the model is based on extrapolation of these data by means of a detailed theoretical model of aerosol transport and deposition within the lung. The Task Group model applies to all practical conditions, and for aerosol particles and vapors from atomic size up to very coarse aerosols with an activity median aerodynamic diameter of 100 μm. The model is designed to predict regional deposition in different subjects, including adults of either sex, children of various ages, and infants, and also to account for anatomical differences among Caucasian and non-Caucasian subjects.

The Task Group model represents aerosol inhalability and regional deposition in different subjects by algebraic expressions of aerosol size, breathing rates, standard lung volumes, and scaling factors for airway dimensions.

INTRODUCTION

The ICRP Task Group on Human Respiratory Tract Models for Radiological Protection will recommend a new model to evaluate the deposition of inhaled aerosols. The Task Group has designed the model to give defensible estimates of deposition in each region of the respiratory tract for which radionuclide retention and dose need to be assessed (see articles by W. J. Bair, Bailey et al., and James et al. in this volume). This new deposition model is designed to be used in conjunction with the clearance and dosimetry models to provide defensible estimates of doses to radiosensitive tissues in the respiratory tract (and also of radionuclide activity transferred to the blood) for radiological protection of both workers and the general public. The new model is required to be practical and yet far broader in application than the current ICRP Lung Model[1]: to include adults of either sex, children of various ages, infants, and also subjects of different ethnic origins, wherever such differences affect respiratory tract anatomy and physiology. The available experimental data, although extensive, apply essentially to the adult Caucasian male and they relate in the main to a limited range of particle size (from about 1-μm to 10-μm aerodynamic diameter). The Task Group has adopted both empirical and theoretical modeling methods to simulate the experimental data, and to make predictions of regional deposition beyond the observations, for various conditions of exposure, including levels of physical exertion, and a particle size range extending from atomic dimensions to large environmental aerosols characterized by an activity median aerodynamic diameter (AMAD) on the order of 100 μm. This paper outlines the methods used by the Task Group to model respiratory tract deposition, and their validation by experimental data. The application of the Task Group's proposed model to various subjects is emphasized.

MODELING APPROACH

The approach adopted by the Task Group is to represent each region of the respiratory tract as an equivalent particle filter that acts in series, as shown in Figure 1. The deposition in each region is expressed as a function of the efficiency of the equivalent filter, η_f, with additional terms to allow

for the volume of the preceeding filters in the series[2,3]. The efficiencies themselves are expressed as semi-empirical functions of particle size and certain respiratory parameters. The volumetric terms express the effects on regional deposition of tidal volume and variation of anatomical airway volumes between different subjects.

The deposition efficiency of each region of the respiratory tract is evaluated by considering two components: η_{ae}, which represents particle deposition by the "aerodynamic" processes of impaction and gravitational settling, and η_{th}, which represents deposition by the "thermodynamic" process of particle diffusion by Brownian motion. Since aerodynamic and thermodynamic processes act competitively to remove particles, it can be shown[4] that the combined deposition efficiency of region R is given by Equation (1):

$$\eta(R) = (\eta_{ae}^2 + \eta_{th}^2)^{1/2} \qquad (1)$$

The Task Group has modeled the fractional deposition of aerosols in the various regions of the respiratory tract for discrete values of particle size, where the component of deposition due to gravitational settling and impaction is represented in terms of the particle aerodynamic diameter, d_{ae} (in $g^{1/2}\ cm^{-3/2}\ \mu m$), and the component due to thermodynamic motion is represented in terms of the particle diffusion coefficient, D (in $cm^2\ s^{-1}$). In practice, it is necessary to consider that radioactive aerosols are generally polydisperse, i.e., they consist of particles distributed lognormally in size[5]. Thus, the deposition of *activity* in the respiratory tract is characterized by the *activity median aerodynamic diameter* (AMAD) and the analogous parameter *activity median thermodynamic diameter* (AMTD).

To derive reference values of regional deposition as functions of aerosol AMAD and AMTD, the task group assumes that the geometric standard deviation (σ_g) in particle size varies from unity for vapors in the atomic size range to approximately 2.5 for aerosols with median sizes on the order of 1 μm and larger. The task group proposes to represent this variation of σ_g with median aerosol size by Equation (2):

$$\sigma_g = 1 + 1.5\ [1 - (100\ AMD^{1.5} + 1)^{-1}] \qquad (2)$$

where AMD (in μm) is the activity median aerodynamic or thermodynamic diameter of the aerosol considered. This assumed variation of σ_g is shown in Figure 2.

AEROSOL PARTICLE INHALABILITY

The experimental data that were reviewed by Vincent et al.[6] on the efficiency of the human head as a particle sampler in moving air, are shown in Figure 3. These values are averaged over all radial orientations of the head with respect to the air movement. The task group assumes that the inhalability (η_I), or efficiency with which particles in ambient air enter the nose or mouth, is represented by Equation (3). This equation includes a term to allow for increased inhalability of large particles at high wind speeds:

$$\eta_I = 1 - 0.5\ [1 - (7.6 \times 10^{-4}\ d_{ae}^{2.8} + 1)^{-1}] + [1.0 \times 10^{-5}\ U^{2.75}\ \exp(0.055\ d_{ae})] \qquad (3)$$

where d_{ae} is the aerodynamic diameter of the particle and U is the windspeed in m s^{-1}.

Particle inhalability does not appear to be influenced markedly by breathing rate or dimensions of the nose or mouth. Therefore, it is assumed that Equation (3) defines inhalability of particles by subjects of any age, and under all conditions. This assumption is conservative for large particles in still air, where Breysse and Swift[7] found for 30-μm aerodynamic diameter particles that inhalability is only about 30%. To evaluate intakes of large particles in indoor environments, the task group proposes to use Equation (3) with wind speed U = 0. This yields a constant value of 50% for the inhalability of particles larger than about 30 μm.

DEPOSITION IN THE EXTRATHORACIC AIRWAYS

The Task Group has adopted an empirical approach to model the deposition efficiency of the extrathoracic airways during nose or mouth breathing.

Nasal Deposition

The experimental data on nasal deposition of particles in the size range from about 1-μm to 10-μm aerodynamic diameter (for adult male Caucasian subjects) are represented[8] in terms of an "aerodynamic" deposition efficiency, η_{ae}, by Equation (4):

$$\eta_{ae}(ET_{nasal}) = 1 - (2.1 \times 10^{-4}\, d_{ae}^{\,2}\, Q_{nasal} + 1)^{-1} \qquad (4)$$

where Q_{nasal} is the component of the total volumetric airflow rate that is inspired through the nose (in $cm^3\ s^{-1}$).

For the thermodynamic size range, insufficient data are available from human subjects to establish a model of nasal deposition efficiency. Studies of particle deposition in hollow casts of the nasal and oral passages, made from cadavers or from *in vivo* magnetic resonance images (MRI), have shown that the "thermodynamic" deposition efficiency of the nose (or oral passageway) can be represented in terms of the particle diffusion coefficient, D, and the flow rate, Q, by Equation (5)[9]:

$$\eta_{th}(ET) = 1 - \exp(-k\, D^{1/2}\, Q^{-1/8}) \qquad (5)$$

The value of the coefficient, k, in Equation (5) is not yet well established. Measurements of the deposition of very small particles (unattached ^{218}Po and ^{212}Pb) in several nasal casts have yielded significantly different estimates. For D expressed in $cm^2\ s^{-1}$ and Q in $cm^3\ s^{-1}$, Cheng et al.[9] obtained k = 19, whereas Strong and Swift[10] obtained k = 11. The lower value of k appears at present to be more consistent with the approximately 60% nasal deposition of unattached ^{218}Po obtained in an early study by George and Breslin[11] of human subjects *in vivo*. In this case, k = 11 implies that the diffusion coefficient of unattached ^{218}Po under the particular conditions of the *in vivo* study was 0.035 $cm^2\ s^{-1}$. This value is considered typical of unattached ^{218}Po in indoor air[12]. However, the conditions of George and Breslin's experiment (which are not known) could possibly have yielded ^{218}Po with a lower diffusion coefficient, which in turn would imply a higher value of k, approaching that obtained by Cheng et al.[9].

In the absence of more definitive results from studies with nasal casts, or of well-characterized *in vivo* measurements in human subjects, the Task Group assumes that the "thermodynamic" deposition efficiency for the nasal passages of an adult Caucasian male is given by Equation (6):

$$\eta_{th}(ET_{nasal}) = 1 - \exp(-11\ D^{1/2}\ Q^{-1/8}) \qquad (6)$$

Oral/Laryngeal Deposition

The deposition efficiency of the oral cavity and oropharynx is less than that of the nose. The bulk of deposition in the oral passageway during mouth breathing is considered to occur in the larynx[2]. The experimental data from adult male Caucasian subjects who inhaled particles in the aerodynamic size range indicate that the oral (laryngeal) deposition efficiency is represented in terms of particle aerodynamic diameter, d_{ae}, by Equation (7)[8]:

$$\eta_{ae}(ET_{oral}) = 1 - [1.1 \times 10^{-4}\ (d_{ae}^{2}\ Q_{oral}^{0.6}\ V_t^{-0.2})^{1.4} + 1]^{-1} \qquad (7)$$

where Q_{oral} is the component of the total volumetric airflow rate that is inspired through the mouth (in $cm^3\ s^{-1}$) and V_t is the tidal volume (in cm^3).

There are no human data on oral deposition of particles in the thermodynamic size range. However, studies with hollow casts of the oral passageway down to the larynx have shown that the deposition efficiency of this pathway may be as high as 75% of that of the nose for the same flow rate and particle size[10]. However, in the absence of confirmatory data *in vivo*, the Task Group assumes a more conservative oral deposition efficiency that is 50% of the nasal value, as given by Equation (8):

$$\eta_{th}(ET_{oral}) = 1 - \exp(-5.5\ D^{1/2}\ Q^{-1/8}) \qquad (8)$$

Oronasal Breathing

It has been shown that even so-called "mouth breathers" normally inhale partly through the nose[13,14]. Therefore, for the purpose of deriving exposure standards, it is unrealistic to consider the example of a pure mouth breather[15]. On the other hand, at a sufficiently high rate of ventilation

in response to exercise, a normal "nose breather" will augment nasal flow by breathing partly through the mouth. The task group assumes that the typical pattern of change between nasal and oral breathing is that found in adult subjects by Niinimaa et al.[13,14]. Thus, the proportion of the total airflow inhaled nasally by mouth breathers is assumed to decrease from 70% at rest to 30% under heavy work. Normal nose breathers are assumed to switch from 100% nasal breathing to partial (50%) mouth breathing at a total respiratory rate of about 2.1 $m^3\ h^{-1}$ for the adult Caucasian male.

Scaling for Body Size

Yu and Xu[16] and Swift[17] used the dimensional factor $1/L^3$ to scale inertial deposition effects in the nose for airway dimensions. In the absence of direct measurements of the critical linear dimension of the nasal passageway in different subjects, these authors assumed that this parameter is scaled in proportion to the diameter of the subject's trachea. The Task Group proposes to adopt the same procedure to evaluate nasal deposition in adult and child subjects by reference to that in the adult Caucasian male. Thus, Equation (4) is generalized to apply for all subjects as follows:

$$\eta_{ae}(ET_{nasal}) = 1 - (2.1 \times 10^{-4}\ d_{ae}^{\ 2}\ Q_{nasal}\ SF_t^{\ 3} + 1)^{-1} \qquad (9)$$

where SF_t, the scaling factor, is the ratio of tracheal diameter in the adult Caucasian male to that in the subject.

Equation (7) for the "aerodynamic" deposition efficiency of the oral passageway is modified in an analogous manner.

To scale the "thermodynamic" deposition efficiencies of the nasal and oral passageways for body size, the flow rate Q in Equations (6) and (8) can be replaced by the dimensionless Reynolds number, Re[18]:

$$Re = L\ V/\nu \qquad (10)$$

where L = hydraulic diameter (in cm)
V = fluid velocity (in cm s^{-1})
ν = kinematic fluid viscosity.

Substituting the volumetric flow rate Q for V in Equation (10) gives:

$$Re = k' L Q/L^2$$
$$= k' Q/L \quad (11)$$

where k′ is a constant term.

Therefore, the scaling factor to be applied to Q in Equations (6) and (8) is L_{ref}/L_s, where L_{ref} is a characteristic airway dimension for the adult Caucasian male, and L_s is the corresponding dimension for the subject considered. The diameter of thc trachea provides an adequate index dimension. Thus, for any subject:

$$\eta_{th}(ET_{nasal}) = 1 - \exp(-11\ D^{1/2}\ \{Q\ SF_t\}^{-1/8}) \quad (12)$$

$$\eta_{th}(ET_{oral}) = 1 - \exp(-5.5\ D^{1/2}\ \{Q\ SF_t\}^{-1/8}) \quad (13)$$

Partition of Deposition Between Extrathoracic Airways

In the absence of a mechanistic model to predict the distribution of deposited particles within the nasal passages, it is assumed for dosimetry that the activity deposited in the extrathoracic airways during nasal breathing is partitioned equally between the anterior nares (region ET_1) and the posterior nasal passages, which are part of the main extrathoracic region, ET_2. (See articles by Bailey et al. and James et al. in this volume for descriptions of the task group's regional clearance and dosimetry models). Thus, it is assumed that

$$\eta_{nasal}(ET_1) = 0.5\ \eta(ET_{nasal})\ F_{nasal}$$
$$= \eta_{nasal}(ET_2) \quad (14)$$

where F_{nasal} is the fraction of the inspired air that is taken in through a subject's nose.

For the complementary fraction of the inspired air that is inhaled through a subject's mouth, extrathoracic deposition occurs only in region ET_2. Thus,

$$\eta_{oral}(ET_2) = \eta(ET_{oral})\ V_E(oral)/V_E(total) \quad (15)$$

and the overall deposition efficiencies of regions ET_1 and ET_2 are given by:

$$\eta(ET_1) = 0.5\ \eta(ET_{nasal})\ F_{nasal} \tag{16}$$

$$\eta(ET_2) = 0.5\ \eta(ET_{nasal})\ F_{nasal} + \eta(ET_{oral})\ (1 - F_{nasal}) \tag{17}$$

The fractions of airborne particles to which a subject is exposed that deposit in each part of the extrathoracic region are then given by:

$$DE(ET_1) = \eta_I\ \eta(ET_1) \tag{18}$$

$$DE(ET_2) = \eta_I\ \eta(ET_2) \tag{19}$$

where η_I is the particle inhalability (see Equation [3]).

SUMMARY OF MODELED EXTRATHORACIC DEPOSITION

To illustrate the application of the task model, fractional deposition in each extrathoracic region (DE[ET_1] and DE[ET_2]) is shown in Figure 4 for various Caucasian subjects engaged in light exercise and breathing through the nose. Figure 5 shows the fractional deposition in region ET_2 for subjects who are nominal "mouth breathers." In these figures, deposition is expressed as a fraction of the activity present in the volume of ambient air that is inspired, and the activity is assumed to be lognormally distributed as a function of particle size.

DEPOSITION IN THORACIC REGIONS

To evaluate regional deposition in the thorax, the Task Group has applied a theoretical model of aerosol deposition and gas transport based on the work of Taulbee and Yu[19] and Pack et al.[20]. The model was further improved and compared with experimental data by M. J. Egan and W. Nixon[21-25]. The theoretical model evaluates the combined effects of convective and diffusive

gas transport, and aerosol loss processes within the airways of the lung. The structure of the lung is represented explicitly by a morphometric model, which was developed jointly by Egan, Nixon and the Task Group to take into account airway dimensions in various body sizes and, in the case of infants, immaturity of the alveolated airways.

Empirical observations of particle impaction in hollow casts of the human bronchi[26] provide a basis for the theoretical modeling of inertial deposition in the larger bronchial airways. Inertial deposition is insignificant in other parts of the lung. Gravitational settling of particles, which occurs throughout the airways, is modeled explicitly in relation to physical airway dimensions[24]. Particle diffusion in parts of the lung where the airflow is viscous (the conducting and respiratory bronchioles, and the alveoli) is also treated explicitly in relation to airway dimensions. However, for the bronchial airways where the airflow is more complex, this theoretical treatment of particle diffusion needs to be corrected empirically to account for the observations of Cohen et al.[27] of enhanced particle deposition in hollow airway casts.

Egan and Nixon's model has been validated by comparing the predicted fractional deposition in the thorax with experimental data from human subjects. The calculated deposition fractions relate to the number of inspired particles predicted to deposit in the thorax, excluding extrathoracic deposition; therefore, in each experimental example shown for comparison here, the measured values have been corrected to remove the effect of extrathoracic deposition.

Figure 6 compares the calculated fractional deposition in the tracheobronchiolar airways (the trachea + bronchi + bronchioles) with measurements of the fraction of inhaled particles deposited in the thorax and then cleared in a distinct "fast" phase of tracheobronchiolar clearance[28-30]. The comparison is drawn for four different breathing patterns (denoted in the figure by a combination of flow rate, Q, and tidal volume, V_T). In general, the measured "fast-cleared" fractions are well predicted by the calculated tracheobronchiolar deposition fraction (shown in Figure 6 by the

solid curves). The overall value of the coefficient of determination r^2 is 0.85.

The dashed curves in Figure 6 show the effects of the Task Group's assumption that 20% of the tracheobronchiolar deposit is cleared slowly (see article by Bailey et al. in this volume). As expected, for large particles, the assumption is shown to underestimate the observed fraction of thoracic deposition that is cleared rapidly. In contrast, for small particles ($\leq$ 4 μm diameter), the experimental data in conjunction with the modeled deposition indicate that rather more than 20% of the tracheobronchiolar deposit may be cleared slowly, and is therefore not detected in the "fast" phase of thoracic clearance. Although the Task Group recognizes this coarseness in the model of bronchial and bronchiolar clearance, the additional complexity introduced by making delayed clearance particle-size dependent is, at present, unwarranted in view of the uncertainties associated with the extent of delayed clearance.

Figure 7 shows the complementary patterns of predicted deposition in the alveolar-interstitial region, together with the "slow-cleared" deposition fraction that was measured by Stahlhofen et al.[28-30]. In general, it is again shown that the observations are well predicted by the calculated alveolar-interstitial deposition, and also that the task group's assumption of 20% slow tracheobronchiolar clearance is conservative for large particles.

For very small particles, there are no human data to test predicted values of regional thoracic deposition. However, it is shown in Figure 8 that the measured total deposition of ultrafine particles in the thorax[31] is well predicted by Egan and Nixon's theoretical model.

FORMULAE FOR REGIONAL THORACIC DEPOSITION

For practical representation of regional aerosol deposition in different subjects, and under various breathing conditions, the task group proposes to adopt formulae developed by G. Rudolf[8] (at the Gesellschaft für Strahlen- und Umweltforschung m.b.H., Frankfurt/Main, Federal Republic of Germany). These formulae were developed to fit regional thoracic deposition for

monodisperse aerosols predicted by Egan and Nixon's theoretical model for the adult Caucasian male and female, 10-year-old and 5-year-old children, and 1-year-old and 1-month-old infants. The proposed formulae are given in Table 1, and the values of anatomical and physiological parameters that are substituted for each subject are summarized in Table 2.

In Figure 9, fractional deposition predicted by the Task Group's formulae for the tracheobronchiolar region as a whole is compared with the observations made by Lippmann[32] and Chan and Lippmann[33] from a large group of adult male subjects at New York University (NYU). In common with earlier theoretical models[34,35] and with the data of Stahlhofen et al.[28-30], Figure 9 shows that Egan and Nixon's calculated values (denoted by the solid curve) underpredict the NYU data on tracheobronchiolar deposition for particles larger than 0.5-μm diameter. The predicted and observed values of fractional deposition in the alveolar-interstitial region are compared in Figure 10. In this case, the figure shows that the NYU observations are, on the average, underpredicted for particles of diameter around 1-μm, but overpredicted for large particles.

In view of the current divergence between results from the principal experimental studies of regional lung deposition, the Task Group proposes to take the conservative approach of adjusting the model to yield deposition values consistent with the higher tracheobronchiolar and alveolar-interstitial deposition observed in the NYU studies. This adjustment of the model's predictions is achieved by applying a normalization factor, ψ_{ae}, developed by J. K. Briant at the Pacific Northwest Laboratory. The effects of this empirical adjustment on the deposition values predicted by the Task Group's model are shown in Figures 9 and 10 (by the hatched curves).

SUMMARY OF MODELED THORACIC DEPOSITION

To illustrate the application of the Task Group's model in evaluating fractional deposition in the thoracic regions of the respiratory tract, Figures 11 through 13 show the values given for bronchial (BB), bronchiolar

(bb), and alveolar-interstitial deposition (AI) for various subjects. These values relate to Caucasian subjects who are engaged in light exercise, and are breathing normally through the nose. In these figures, deposition is again expressed as a fraction of the activity present in ambient air, for polydisperse aerosols.

CONCLUSION

The Task Group has attempted to compile a practical model of regional aerosol deposition in the respiratory tracts of adults, children, and infants that is soundly based on experimental human data and on the reasonable extrapolation of these data using empirical and theoretical modeling techniques. Further development of the deposition model will address variability of regional deposition under given conditions of exposure (as far as this can be determined from the variability in experimental data), and also respiratory tract deposition of reactive or soluble gases and vapors.

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REFERENCES

1. International Commission on Radiological Protection (ICRP). *Limits for Intakes of Radionuclides by Workers.* ICRP Publication 30 (Oxford: Pergamon Press) (1979).

2. Rudolf, G., Gebhart, J., Heyder, J., Scheuch, G., and Stahlhofen, W. *Modelling the Deposition of Aerosol Particles in the Human Respiratory Tract.* J. Aerosol Sci. 14: 188-192 (1983).

3. Stahlhofen, W., Rudolf, G., and James, A. C. *Intercomparison of Experimental Regional Aerosol Deposition Data.* J. Aerosol Med. 2:285-308 (1989).

4. Rudolf, G. *Note on Exact Superimposition of Stochastic and Deterministic Particle Transport.* J. Aerosol Sci. (in press).

5. Task Group on Lung Dynamics. *Deposition and Retention Models for Internal Dosimetry of the Human Respiratory Tract.* Health Phys. 12:173-207 (1966).

6. Vincent, J. H., Mark, D., Miller, B. G., Armbruster, L., and Ogden, T. L. *Aerosol Inhalability at Higher Wind Speeds.* J. Aerosol Sci. 21:577-586 (1990).

7. Breysse, P. N., and Swift, D. L. *Inhalability of Large Particles into the Human Nasal Passage: In Vivo Studies in Still Air.* Aerosol Sci. Technol. 13:459-464 (1990).

8. Rudolf, G., Köbrich, R., and Stahlhofen, W. *Modelling and Algebraic Formulation of Regional Aerosol deposition in Man.* J. Aerosol Sci. (in press).

9. Cheng, Y. S., Swift, D. L., Su, Y. F., and Yeh, H. C. *Deposition of Radon Progeny in Human Head Airways.* In: Inhalation Toxicology Research Institute Annual Report 1988-89. LMF-126 (Albuquerque, New Mexico: Lovelace Biomedical and Environmental Research Institute) pp. 29-30 (1989).

10. Strong, J. C., and Swift, D. L. *Deposition of "Unattached" Radon Daughters in Models of Human Nasal Airways.* Presented at the 29th Hanford Symposium on Health and the Environment, "Indoor Radon and Lung Cancer: Reality or Myth?" October 15-19, 1990, Richland, Washington.

11. George, A. C., and Breslin, A. L. *Deposition of Radon Daughters in Humans Exposed to Uranium Mine Atmospheres.* Health Phys. 17:115-124 (1969).

12. Hopke, P. K. *The Initial Behavior of ^{218}Po in Indoor Air.* Environ. Int. 15:299-308.

13. Niinimaa, W., Cole, P., Mintz, S., and Shephard, R. J. *The Switching Point from Nasal to Oronasal Breathing.* Respir. Physiol. 42:61-71 (1980).

14. Niinimaa, W., Cole, P., Mintz, S., and Shephard, R. J. *Oronasal Distribution of Respiratory Airflow.* Respir. Physiol. 43:69-75 (1981).

15. Miller, F. J., Martonen, T. B., Ménache, M. G., Graham, R. C., Spektor, D. M., and Lippmann, M. *Influence of Breathing Mode and Activity Level on Regional Deposition of Inhaled Particles and Implications for Regulatory Standards.* Ann. occup. Hyg. 32(Suppl. 1):3-10 (1988).

16. Yu, C. P., and Xu, G. B. *Predicted Particle Deposition of Diesel Particles in Young Humans.* J. Aerosol Sci. 18:419-429 (1987).

17. Swift, D. L. *Age-related Scaling for Aerosol and Vapor Deposition in the Upper Airways of Humans.* Health Phys. 57(Suppl. 1):293-297 (1989).

18. Cheng, Y. S., Yamada, Y., Yeh, H. C., and Swift, D. L. *Diffusional Deposition of Ultrafine Aerosols in a Human Nasal Cast.* J. Aerosol Sci. 19:744-751 (1988).

19. Taulbee, D. B., and Yu, C. P. *A Theory of Aerosol Deposition in the Human Respiratory Tract.* J. Appl. Physiol. 38:77-85 (1975).

20. Pack, A., Hooper, M. B., Nixon, W., and Taylor, J. C. *A Computational Model of Pulmonary Gas Transport Incorporating Effective Diffusion.* Respir. Physiol. 29:101-124 (1977).

21. Egan, M. J., and Nixon, W. *A Model of Aerosol Deposition in the Lung for Use in Inhalation Dose Assessments.* Radiat. Prot. Dosim. 11:5-17 (1985).

22. Egan, M. J., and Nixon, W. *Mathematical Modeling of Fine Particle Deposition in the Respiratory System.* In: Deposition and Clearance of Aerosols in the Human Respiratory Tract, Ed. W. Hofmann (Vienna: Facultas Universitätsverlag) pp. 34-40 (1987).

23. Nixon, W., and Egan, M. J. *Modelling Study of Regional Deposition of Inhaled Aerosols with Special Reference to Effects of Ventilation Asymmetry.* J. Aerosol Sci. 18:563-579 (1987).

24. Egan, M. J., Nixon, W., Robinson, N. I., James, A. C., and Phalen, R. F. *Inhaled Aerosol Transport and Deposition Calculations for the ICRP Task Group.* J. Aerosol Sci. 20:1305-1308 (1989).

25. Egan, M. J., and Nixon, W. *On the Relationship between Experimental Data for Total Deposition and Model Calculations - Part II: Application to Fine Particle Deposition in the Respiratory Tract.* J. Aerosol Sci. 20:149-156 (1989).

26. Gurman, J., Lippmann, M., and Schlesinger, R. B. *Particle Deposition in Replicate Casts of the Human Upper Tracheobronchial Tree Under Constant and Cyclic Inspiratory Flow. I. Experimental.* Aerosol Sci. Technol. 3:245-252 (1984).

27. Cohen, B. S., Sussman, R. G., and Lippmann, M. *Ultrafine Particle Deposition in a Human Tracheobronchial Cast.* Aerosol Sci. Technol. 12:1082-1091 (1990).

28. Stahlhofen, W., Gebhart, J., and Heyder, J. *Experimental Determination of the Regional Deposition of Aerosol Particles in the Human Respiratory Tract.* Am. Ind. Hyg. Assoc. J. 41:385-398 (1980).

29. Stahlhofen, W., Gebhart, J., and Heyder, J. *Biological Variability of Regional Deposition of Aerosol Particles in the Human Respiratory Tract.* Am. Ind. Hyg. Assoc. J. 42:348-352 (1981).

30. Stahlhofen, W., Gebhart, J., Heyder, J., and Scheuch, G. *New Regional Deposition Data of the Human Respiratory Tract.* J. Aerosol Sci. 14:186-188 (1983).

31. Schiller, C. F., Gebhart, J., Heyder, J., Rudolf, G., and Stahlhofen, W. *Deposition of Monodisperse Insoluble Aerosol Particles in the 0.005 to 0.2 μm Size Range within the Human Respiratory Tract.* Ann. occup. Hyg. 32(Suppl. 1):41-49 (1989).

32. Lippmann, M. *Regional Deposition of Particles in the Human Respiratory Tract.* In: Handbook of Physiology - Reaction to Environmental Agents, Ed. D. H. K. Lee (Bethesda: American Physiology Society) pp. 213-232 (1977).

33. Chan, T. L., and Lippmann, M. *Experimental Measurements and Empirical Modeling of the Regional Deposition of Inhaled Particles in Humans.* Am. Ind. Hyg. Assoc. J. 41:399-409 (1980).

34. Yeh, H. C., and Schum, G. M. *Models of Human Lung Airways and their Application to Inhaled Particle Deposition.* Bull. Math. Biol. 42:461-480 (1980).

35. Yu, C. P., and Diu, C. K. *A Comparative Study of Aerosol Deposition in Different Lung Models.* Am. Ind. Hyg. Assoc. J. 43:54-65 (1987).

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Figure 12. Fractional Deposition in the Bronchiolar (bb) Region Given by the Task Group's Model for Nose-breathing Subjects Engaged in Light Exercise.

Figure 13. Fractional Deposition in the Alveolar-interstitial (AI) Region Given by the Task Group's Model for Nose-breathing Subjects Engaged in Light Exercise.

Table 1. Summary of Formulae Recommended by the Task Group to Evaluate the Fractions of Activity Deposited in the Thoracic Regions of the Respiratory Tract[a].

Bronchial Deposition:

$$\eta_{ae}(BB) = 1 - \exp\{-4 \times 10^{-6}\ SF_t^{2.8}\ [Q\ \Psi_{ae}\ d_{ae}^{(2\ +\ 0.17\ (1\ -\ \Psi ae))}]^{1.15}\} \quad (1.1)$$

$$\eta_{th}(BB) = \Psi_{th}\ \{1 - \exp[-16\ SF_t\ (D * \tau(BB))^{1.15/2}]\} \quad (1.2)$$

where Ψ_{th} is ar empirical correction factor derived from Cohen et al. (1990) with a value of $1 + 80\ \exp\{-[\log_{10}(80 + 10/d_{th}^{0.6})]^2\}$

$\tau(BB)$ is a time constant for conduction of air through the trachea and bronchi (in s) with a value of $V_D(BB)\ (1 + 0.5\ V_T / FRC) / Q$.

$$DE(BB) = \eta_I\ \phi(ET)\ [1 - \eta(ET)]\ \eta(BB) \quad (1.3)$$

where $\phi(ET)$, a volumetric correction factor for extrathoracic dead space, equals $[1 - V_D(ET) / V_T]$.

Bronchiolar Deposition:

$$\eta_{ae}(bb) = 1 - \exp(-\beta\ \Psi_{ae}\ d_{ae}^{\gamma}) \quad (1.4)$$

where $\beta = 0.009 + 0.165\ \tau(bb)^{1.5}$

$\gamma = \tau(bb)^{-0.25} + 0.17\ (1 - \Psi_{ae})$

$\tau(bb)$ = time constant for conduction of air through the bronchioles (in s)

$= V_D(bb)\ (1 + 0.5\ V_T / FRC) / Q$

$$\eta_{th}(bb) = 1 - \exp[-(70 + 12\ SF_{bb}^5)\ (D\ \tau(bb))^{1.05/2}] \quad (1.5)$$

$$DE(bb) = \eta_I\ \phi(ET+BB)\ (1 - \eta[ET])\ (1 - \eta[BB])\ \eta(bb) \quad (1.6)$$

where $\phi(ET+BB)$, a volumetric correction factor for the combined dead space of the extrathoracic airways, trachea, and bronchi, is given by $(1 - (V_D[ET] + V_D[BB]) / V_T)$.

Table 1. (contd)

Alveolar-interstitial Deposition:

$$\eta_{ae}(AI) = 1 - \exp[-0.14\ SF_{AI}\ \Psi_{ae}^{1/3}\ (d_{ae}^{2}\ \tau(AI))^{2/3}] \quad (1.7)$$

where $\tau(AI)$, a time constant for residence of air in the alveolar-interstitial airways (in s), is given by $(V_T - V_D(ET) - [V_D(BB) + V_D(bb)]\ (1 + V_T / FRC)) / Q$.

$$\eta_{th}(AI) = 1 - \exp[-(-450 + 1000\ SF_{AI})\ (D\ \tau(AI))^{2/3}] \quad (1.8)$$

$$DE(AI) = \eta_I\ \phi(total)\ (1 - \eta[ET])\ (1 - \eta[BB])\ (1 - \eta[bb])\ \eta(AI) \quad (1.9)$$

where $\phi(total)$, a volumetric correction factor for total respiratory dead space, is given by $(1 - V_D(total) / V_T)$.

(a) Values of parameters for substitution in the formulae are given in Table 2.

Table 2. Values of Anatomical and Physiological Parameters for Substitution in the Task Group's Model of Regional Deposition in the Respiratory Tract[a].

Parameter		Subject: Man	Woman	Child/10y	Child/5y	Infant/1y	Infant/1mo
FRC	(cm^3)	3300	2660	1500	770	250	110
V_D(ET)	(cm^3)	50	40	26	14	5	2
V_D(BB)	(cm^3)	49	39	28	16	7	4
V_D(bb)	(cm^3)	48	39	31	17	9	7
SF_t		1	1.075	1.247	1.543	2.221	2.989
SF_{bb}		1	1.075	1.103	1.260	1.6	2.0
SF_{AI}		1	1.075	1.301	1.719	2.0	2.0
Sleep:			F(normal) = 1.0		F(mouth) = 0.7		
V_E	(m^3/h)	0.45	0.32	0.31	0.24	0.153	0.079
V_T	(cm^3)	625	450	305	190	75	33
Q	(cm^3/s)	250	180	173	133	85	44
Rest:			F(normal) = 1.0		F(mouth) = 0.7		
V_E	(m^3/h)	0.54	0.39	0.38	0.32	0.22	-
V_T	(cm^3)	750	460	330	210	100	-
Q	(cm^3/s)	300	214	209	175	120	-
Light Exercise:			F(normal) = 1.0		F(mouth) = 0.4		
V_E	(m^3/h)	1.5	1.26	1.11	0.57	0.35	0.12
V_T	(cm^3)	1250	1000	580	245	125	39
Q	(cm^3/s)	833	700	619	318	192	65
Heavy Exercise:			F(normal) = 0.47		F(mouth) = 0.3		
V_E	(m^3/h)	3	2.7	2.1	-	-	-
V_T	(cm^3)	1920	1610	760	-	-	-
Q	(cm^3/s)	1667	1503	1140	-	-	-

(a) Different values are recommended for some non-Caucasian subjects.

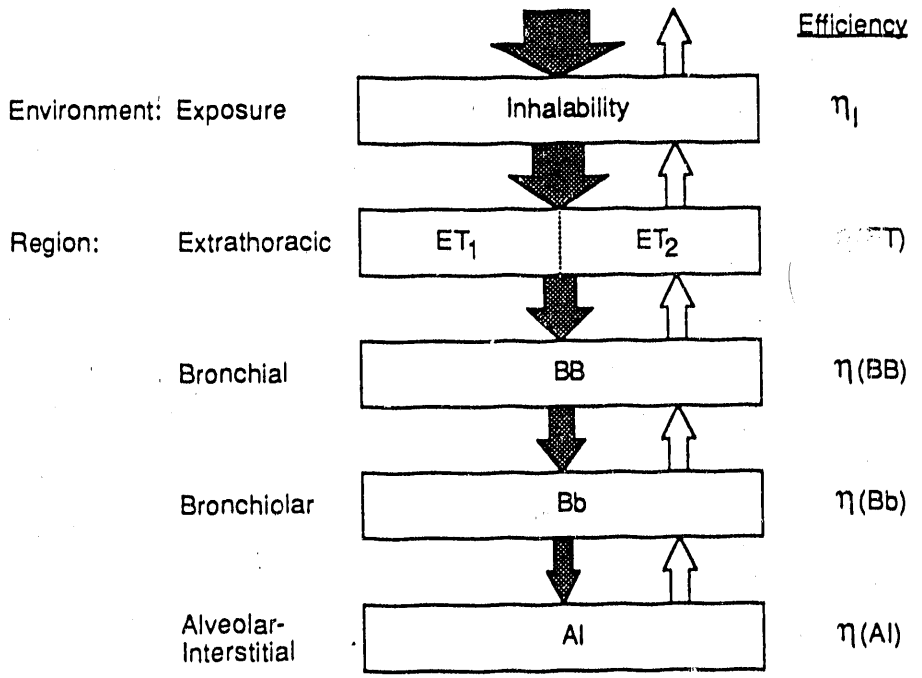

Figure 1. Empirical Representation of the Inhalability of Particles and their Deposition in Regions of the Respiratory Tract During Inhalation and Exhalation by Transport Through a Series of Filters.

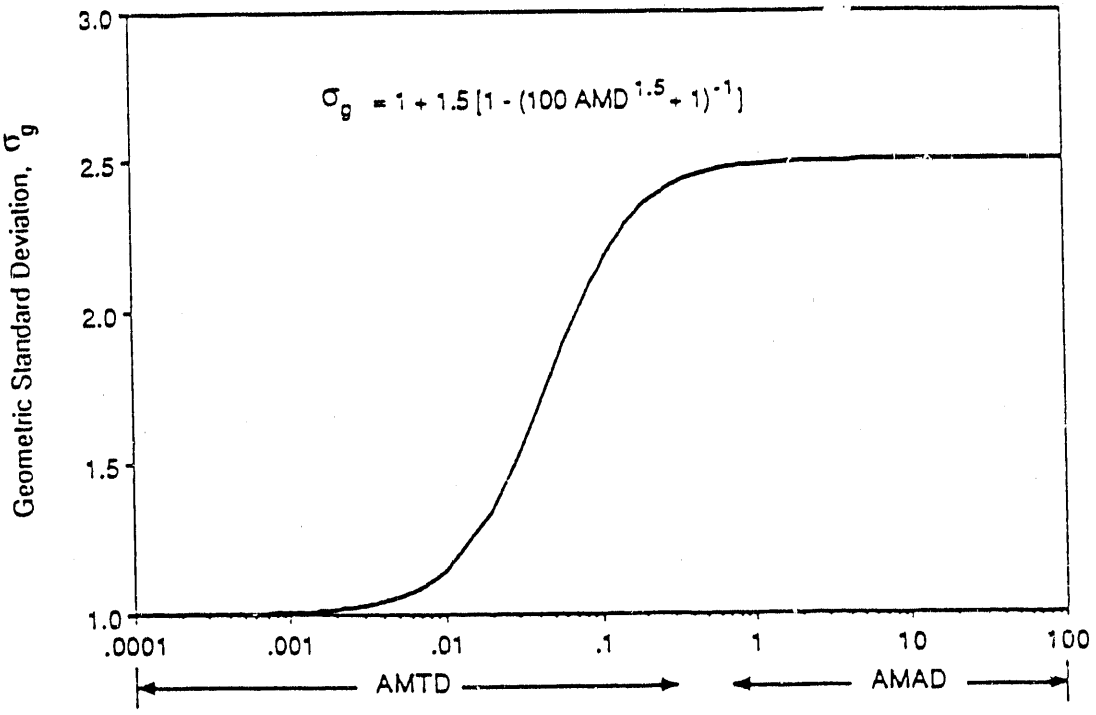

Figure 2. Assumed Relationship between the Geometric Standard Deviation of Particle Size and the Median Size of Polydisperse Aerosols.

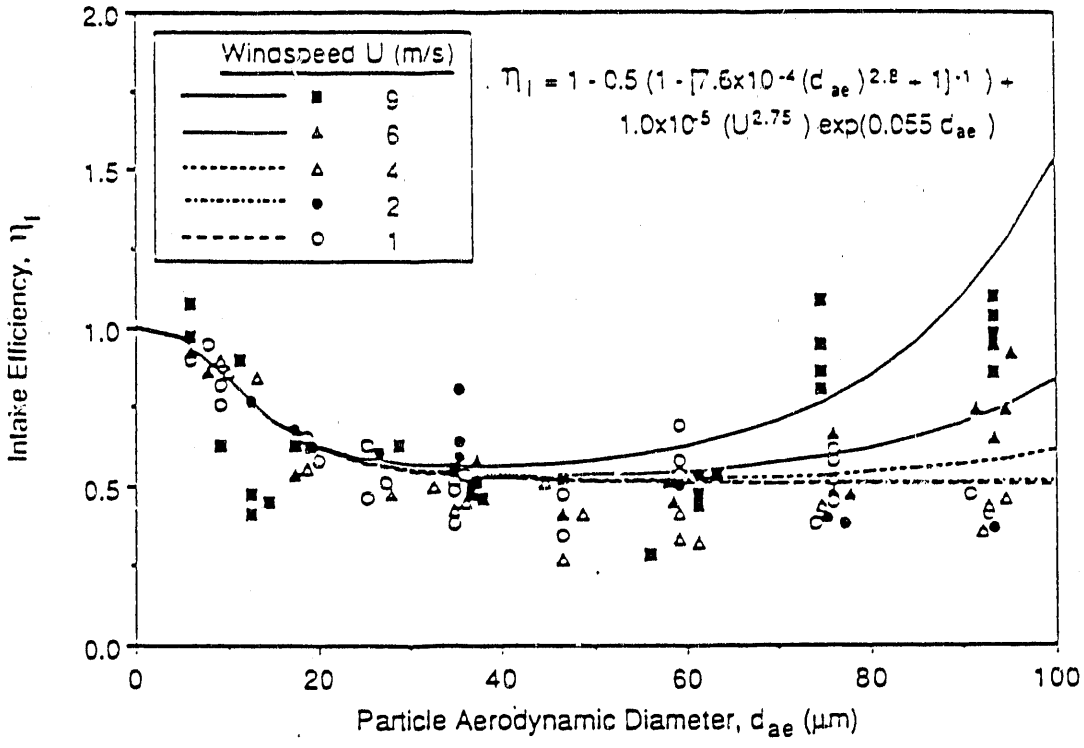

Figure 3. Aspiration Efficiency of the Human Head at Random Orientations to Moving Air. The data were obtained by Vincent et al.[6], using a mannequin placed at various angles in a large wind tunnel. The curves show the representative empirical function recommended by the Task Group for various windspeeds.

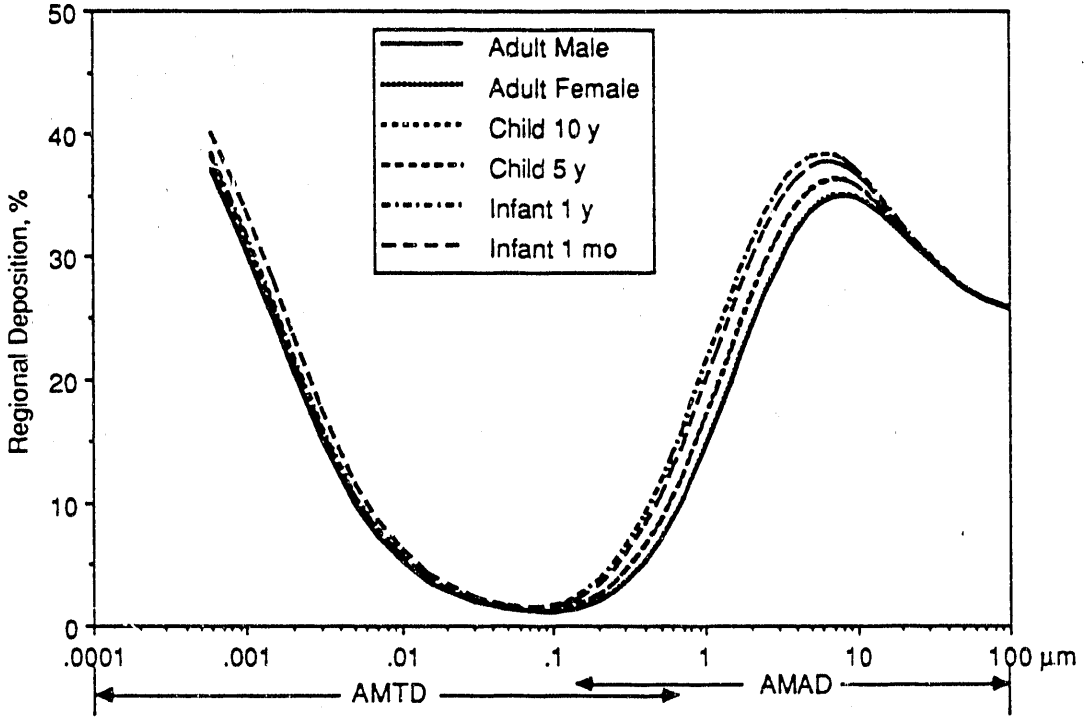

Figure 4. Fractional Deposition in Each Extrathoracic Region (ET_1 and ET_2) Given by the Task Group Model for Various Subjects Exercising Lightly and Breathing Through the Nose.

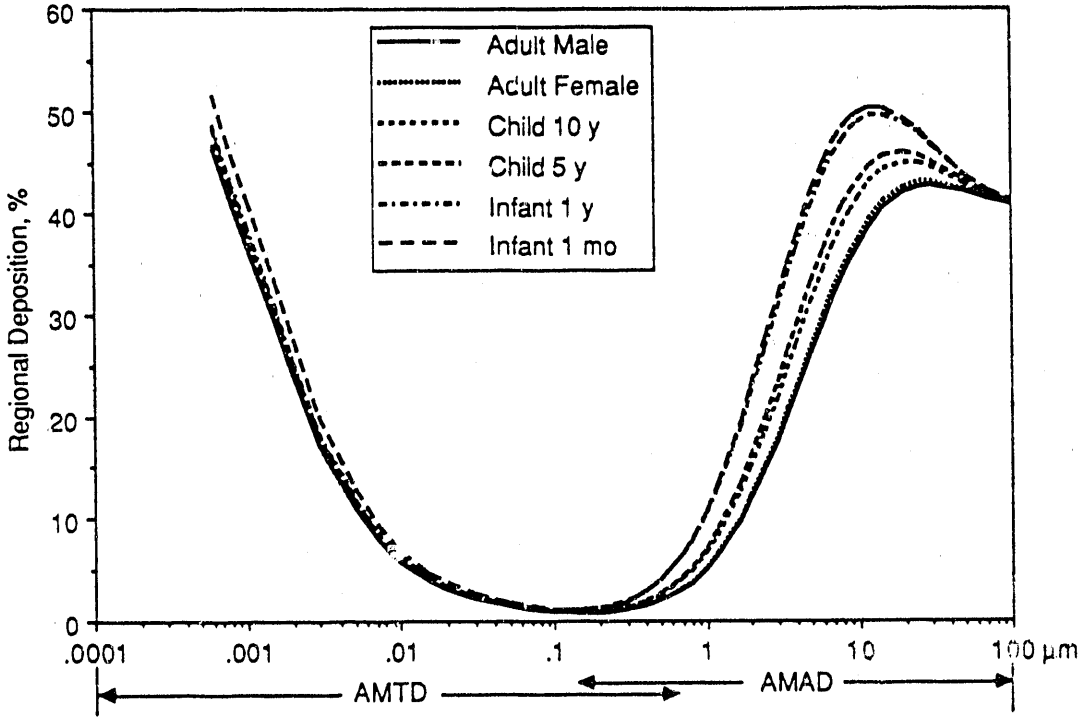

Figure 5. Fractional Deposition in the Main Extrathoracic Airways (Region ET_2) Given by the Task Group Model for Nominal "Mouth Breathers" Undergoing Light Exercise.

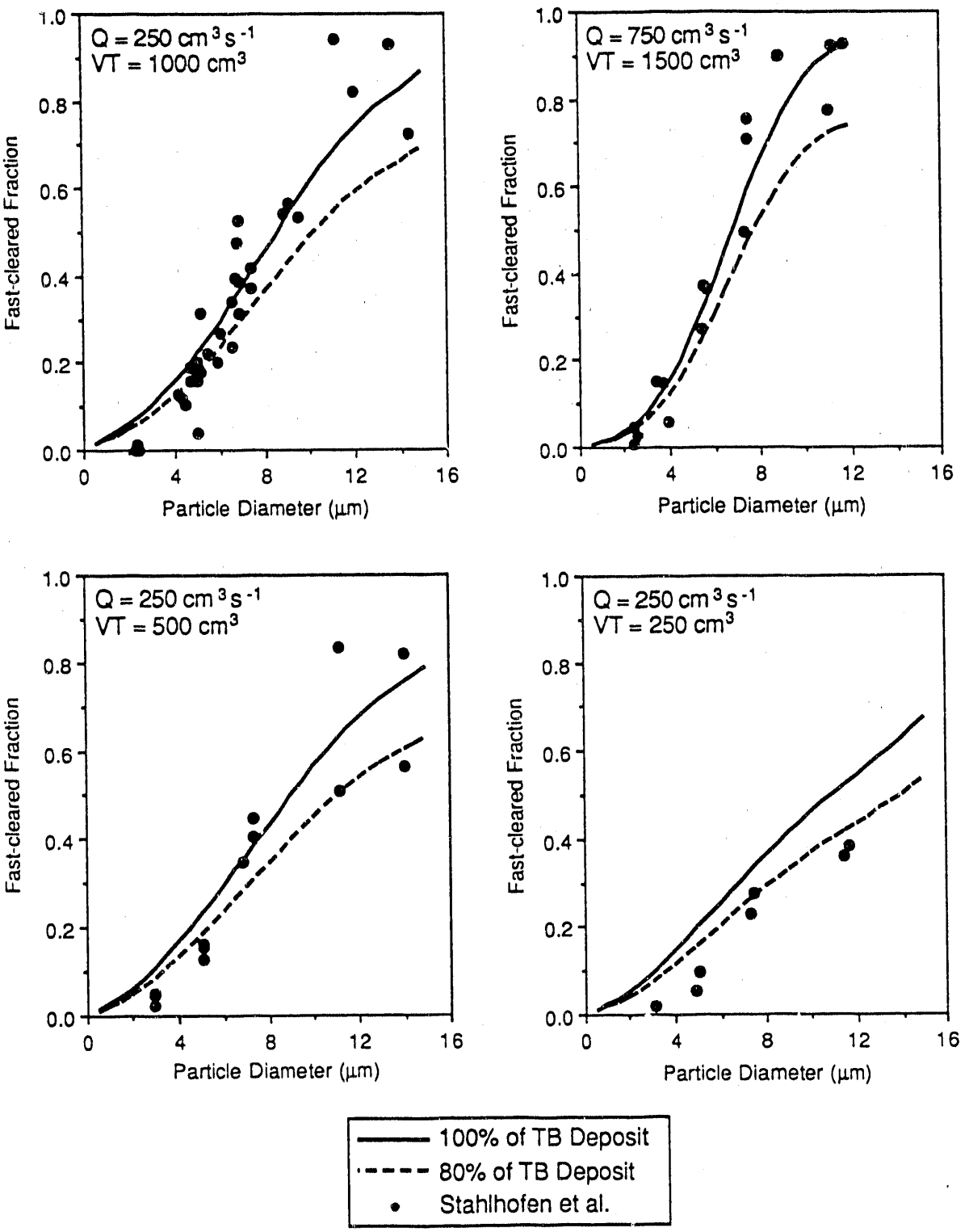

Figure 2. Comparison of Tracheobronchiolar Deposition Given by Egan and Nixon's Theoretical Model with Observations of Stahlhofen et al. on the Fraction of Inhaled Particles Deposited in the Thorax and Cleared Fast (After Removing the Effect of Extrathoracic Deposition).

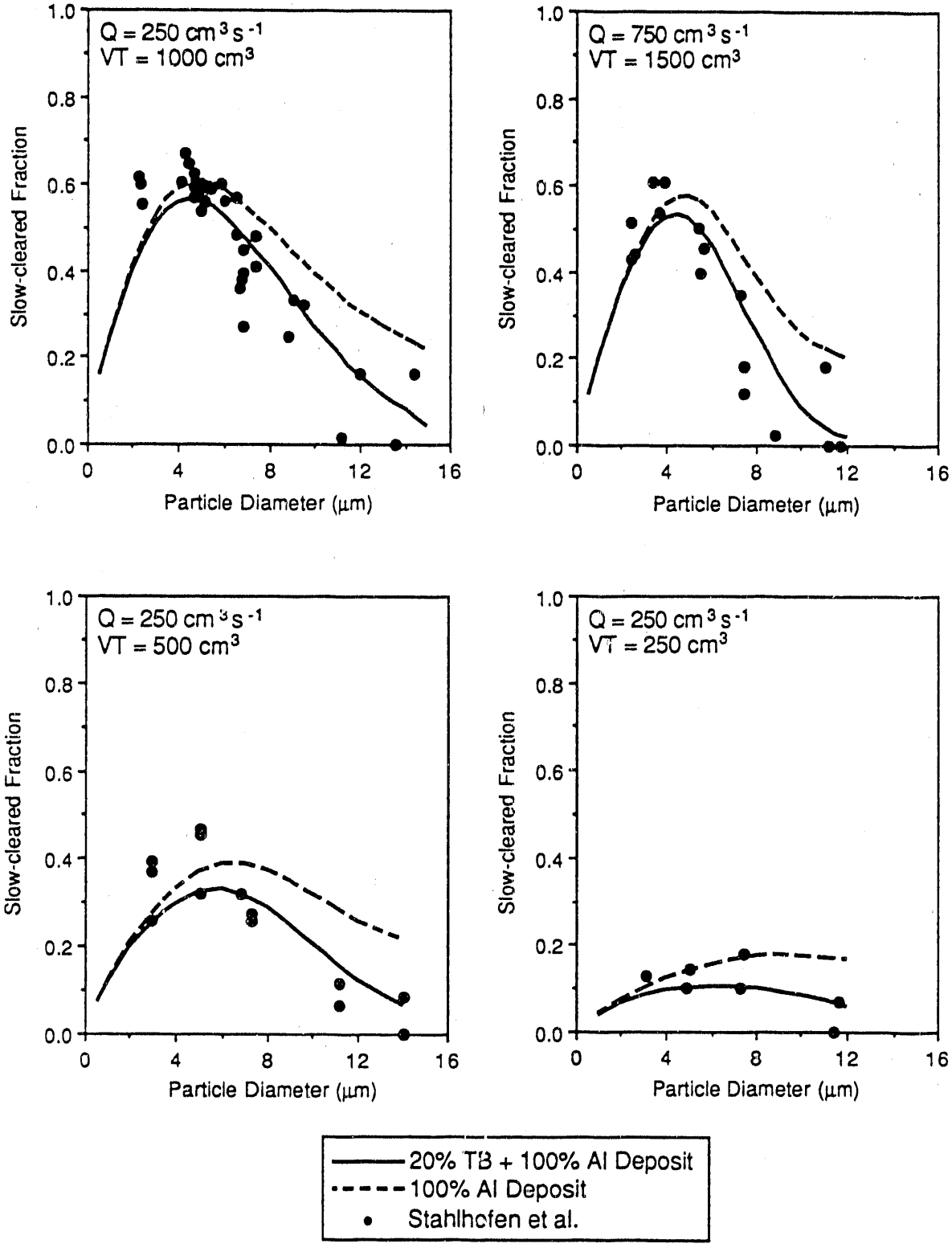

Figure 7. Alveolar-interstitial Deposition (With and Without an Additional Fraction of Tracheobronchiolar Deposition) Given by Egan and Nixon's Theoretical Model Compared with Observations of Stahlhofen et al. on the Fraction of Inhaled Particles Deposited in the Thorax and Cleared Slowly (After Removing the Effect of Extrathoracic Deposition).

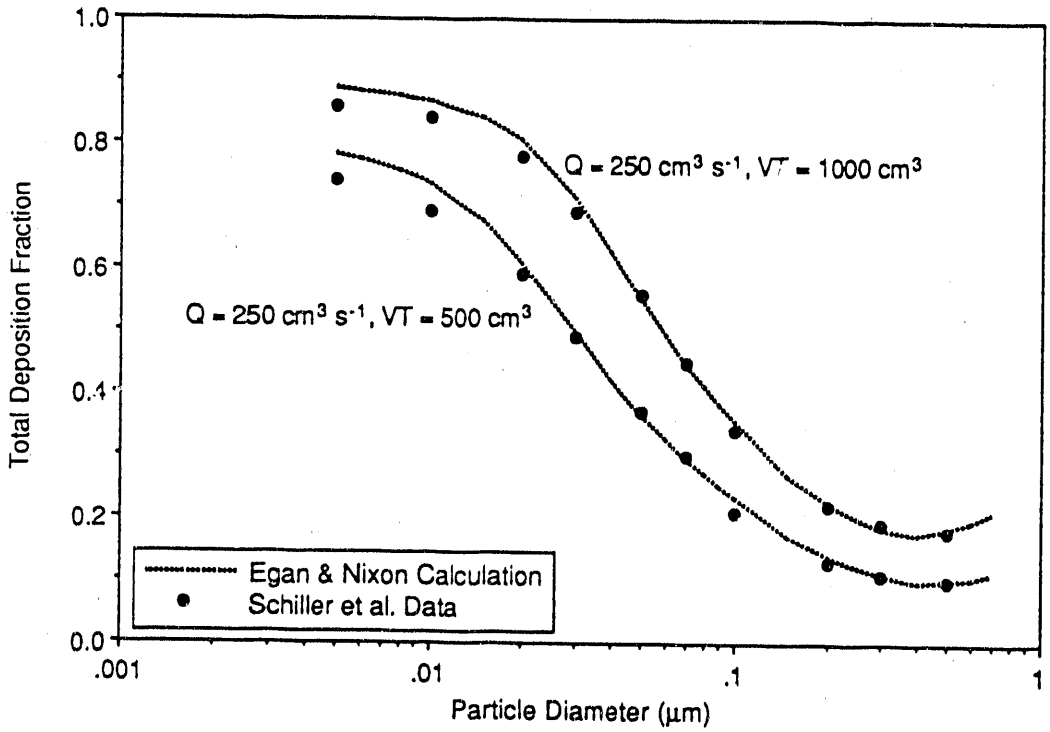

Figure 8. Total Thoracic Deposition Given by Egan and Nixon's Theoretical Model with Compared with Observations of Schiller et al. on the Fraction of Inhaled Sub-micron Sized Particles that is Deposited in the Thorax (After Removing the Effect of Extrathoracic Deposition).

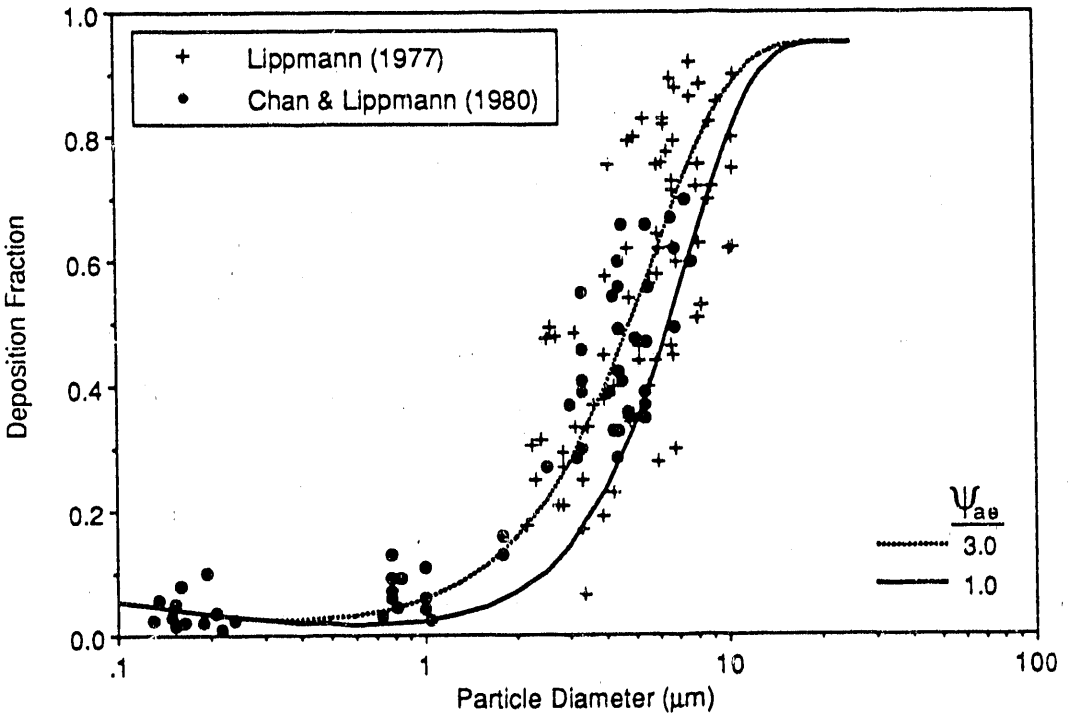

Figure 9. Tracheobronchiolar Deposition Given by the Task Group's Model Compared with Experimental Observations Published by Lippmann[32] and Chan and Lippmann[33]. Values given by Egan and Nixon's theoretical results are shown as a solid curve (denoted by $\psi_{ae} = 1$). Adjusted values recommended by the Task Group (obtained by setting $\psi_{ae} = 3$) are shown by the broken curve.

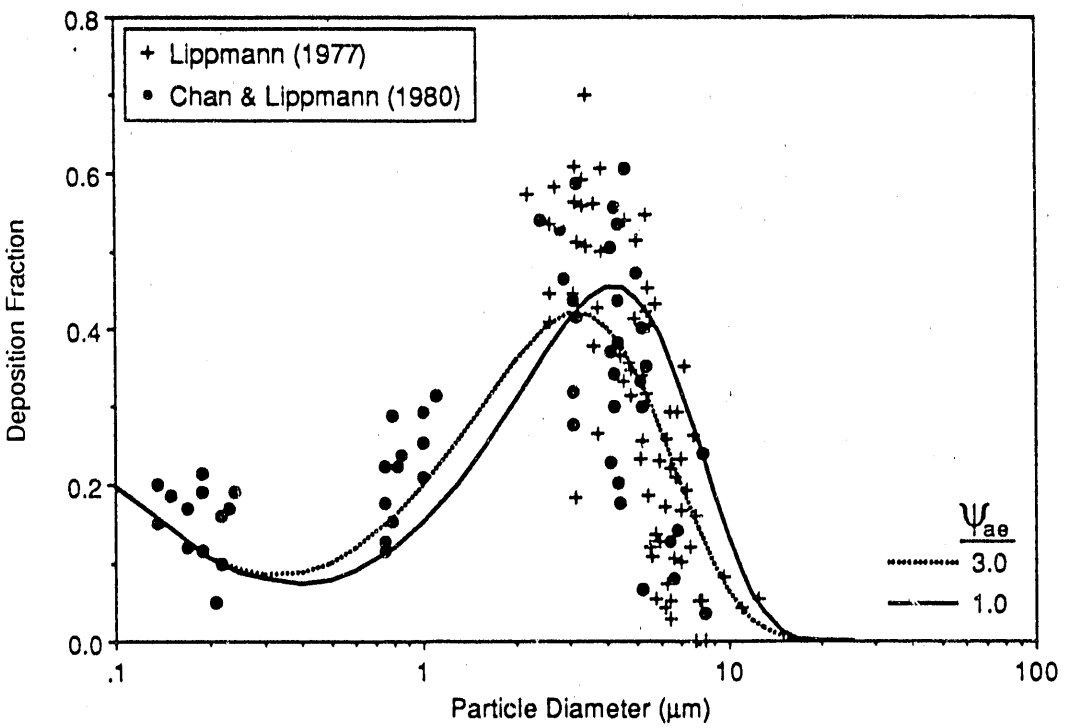

Figure 10. Alveolar-interstitial Deposition Given by the Task Group's Model Compared with Experimental Observations of Lippmann and Chan and Lippmann (details as in Figure 9.)

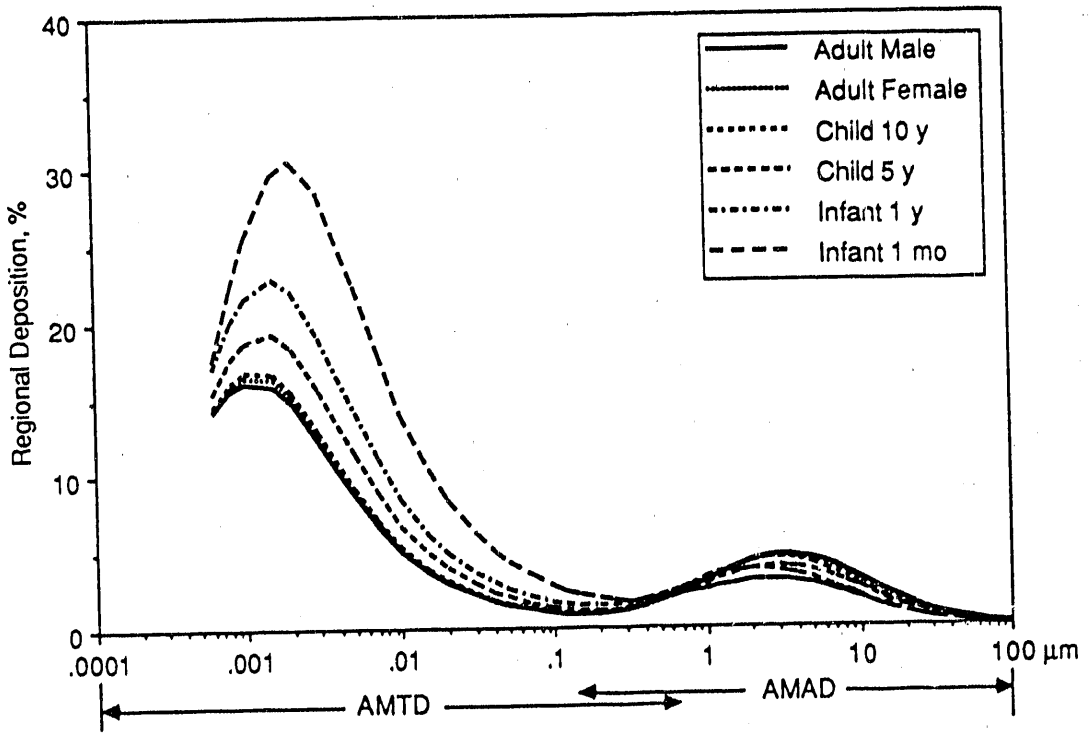

Figure 11. Fractional Deposition in the Bronchial (BB) Region Given by the Task Group's Model for Nose-breathing Subjects Engaged in Light Exercise.

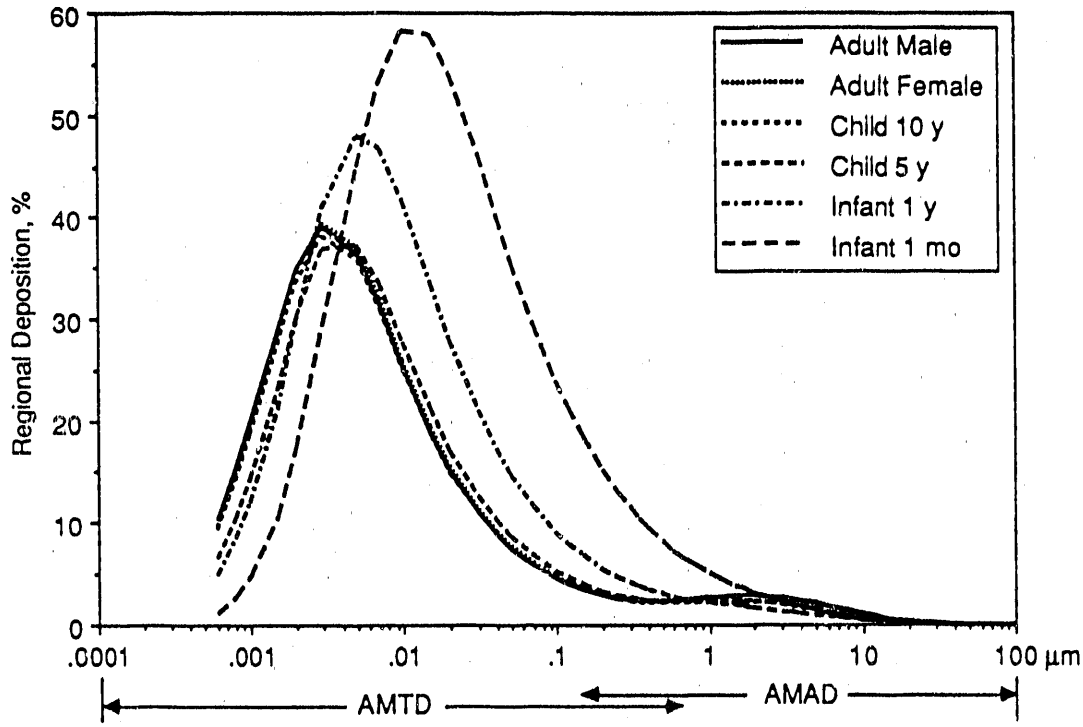

Figure 12. Fractional Deposition in the Bronchiolar (bb) Region Given by the Task Group's Model for Nose-breathing Subjects Engaged in Light Exercise.

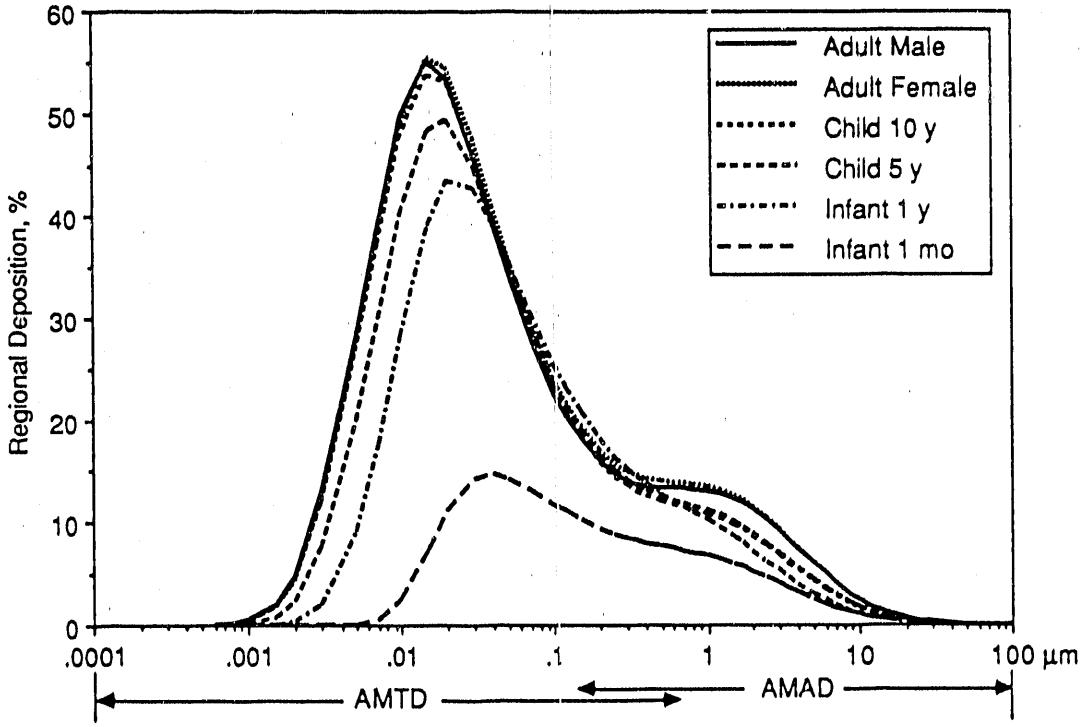

Figure 13. Fractional Deposition in the Alveolar-interstitial (AI) Region Given by the Task Group's Model for Nose-breathing Subjects Engaged in Light Exercise.

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