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ANNEXE E. CLEARANCE OF PARTICLES FROM THE RESPIRATORY TRACT

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Contents

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GLOSSARY

This Glossary supplements the Glossary at the beginning of the report with terms used specifically in this Annexe.

α_s: Surface shape factor $= s/D^2$, where s is the surface area and D is the particle diameter.
α_v: Volume shape factor $= m/\rho D^3$, where m is the particle mass and ρ is the particle density.
χ_{50}, σ_g: Median and geometric standard deviation of a log-normal distribution.
Φ_u: Parameter representing uncertainty in the reference value, such that there is a 95% probability that the true mean value lies within a factor Φ_u of the chosen reference value.
Φ_m: Modifying factor. Amount by which a parameter should be multiplied in order to calculate doses for a specific individual or group for which the modifying factor is recommended. Transient factors apply only during exposure to the factor and are relevant only to acute intakes. Permanent factors are relevant to chronic intake.
a_1: Fraction of initial alveolar deposit in compartment AI_1.
A: Fraction of material deposited in the thorax cleared slowly.
AM: Alveolar macrophage.
CB(τ): Bronchial clearance from intake to time τ.
CF: Cystic fibrosis.
CMD: Count median diameter.
COLD: Chronic obstructive lung disease.
COPD: Chronic obstructive pulmonary disease.
CT(τ): Total lung clearance from intake to time τ.
CZ: Central lung zones measured using a gamma camera.
FAP: Fused aluminosilicate particles.
IAD: Initial alveolar deposit.
ICS: Immotile-cilia syndrome.
ILD: Initial lung deposit.
IND: Initial nasal deposit.
IZ: Inner lung zones measured using a gamma camera.
k: Dissolution rate constant (dissolved mass per unit area per unit time).
[L]: Concentration of material in the lung.
LMC: Lung mucociliary clearance.
[LN]: Concentration of material in lung-associated lymph nodes.
MMD: Mass median diameter.
MPG: Magnetopneumography.
MZ: Intermediate lung zones measured using a gamma camera.
NS: Nonsmoker.
PSL: Polystyrene latex particles.
PZ: Peripheral lung zones measured using a gamma camera.
T_{50}: Time for retention to reach 50% of its initial value.
T_{avg}: Average retention time based on the area under the retention versus time plot.
t_b: Breathholding time.
TB: Tracheobronchiolar region (trachea, bronchi, and bronchioles).
TMTR: Tracheal mucociliary transport rate.
TBLN: Tracheobronchial lymph nodes.
V_F: Bolus front depth.

E.1. Introduction

(E1) This Annexe is not intended to provide a complete review of all aspects of clearance of inhaled materials from the respiratory tract, since that would be too great a task, and comprehensive reviews of specific aspects are available in the literature. The primary objective is to review the information on which the clearance model (Chapter 6) is based. As an introduction, Section E.2 provides an outline of the clearance mechanisms involved. Section E.3 aims to provide support for, and indicate the limitations of, the general approach used in the model. Sections E.4 to E.7 review the information on which the individual parameters in the particle transport model for the human respiratory tract were chosen, with information relating to the uncertainty and variability associated with each value, and the effects of factors that might alter it significantly for specific groups of the population.

E.1.1. *Selection of Reference Values for Particle Transport*

(E2) As far as possible the parameters in the model are based on observations on humans, since particle transport rates are known to vary markedly between species (Felicetti *et al.*, 1981; Snipes *et al.*, 1983; Bailey, 1989; Bailey *et al.*, 1989; Kreyling, 1990a). Ideally each reference value would be based on carefully conducted studies designed to measure that parameter. The uncertainty in the reference value would then be given by the 95% confidence interval on the mean and the variability by the 95% limits on intersubject variation. However, few human lung clearance parameters have been measured directly in this way. It should be noted that the particle transport model is not intended to be used for fibres or other materials, such as quartz, whose physicochemical characteristics might interfere with normal clearance mechanisms. (See Section E.3.3.2.)

E.1.1.1. *Variability*

(E3) Three clearance rates for which the distributions have been obtained in humans are described in the relevant sections: mucociliary transport in the posterior nasal passage (Fig. E.1); mucociliary transport in the trachea (Fig. E.2); and alveolar clearance at 200 d after inhalation (Fig. E.3). In each case most measurements conformed well to a log-normal distribution, with similar geometric standard deviations (σ_g): 1.6, 1.8, and 1.7, respectively. (Note, however, that, for nasal and alveolar clearance, about 20% of cases showed clearance slower than predicted by such a distribution.) It is not surprising that a similar degree of variation should be seen in mucociliary clearance rates in the nasal passage and trachea, since similar mechanisms are involved. It is interesting, however, that a similar distribution occurs for alveolar clearance, which is determined by the behaviour of alveolar macrophages. This result gives support to the proposition, made below, that a similar distribution be assumed for those clearance rates that have not been measured directly.

(E4) For a log-normal distribution with median χ_{50}, approximately 95% of values lie between χ_{50}/σ_g^2 and $\chi_{50}\sigma_g^2$. The observed distributions of human particle transport rates suggest a typical value for σ_g of 1.7, and hence a value for σ_g^2 of about 3. It is therefore proposed that, in the absence of specific information, intersubject variation in any clearance rate be represented by a log-normal distribution with χ_{50} equal to the reference value, and $\sigma_g = 1.7$. This gives 95% confidence limits at $\chi_{50}/3$ and $3\chi_{50}$.

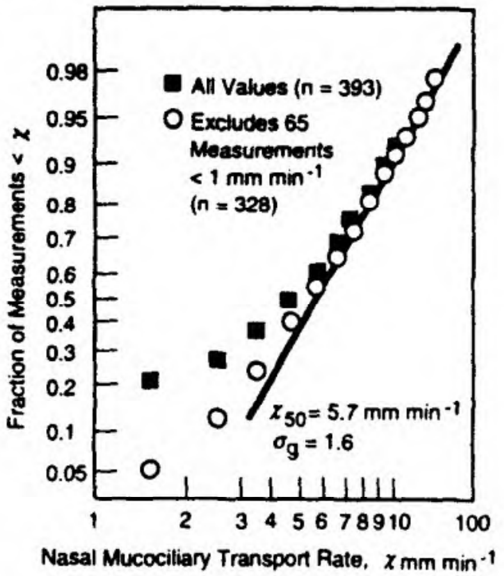

Fig. E.1. Distribution of measurements of nasal mucociliary transport rates (Proctor, 1977, 1982a).

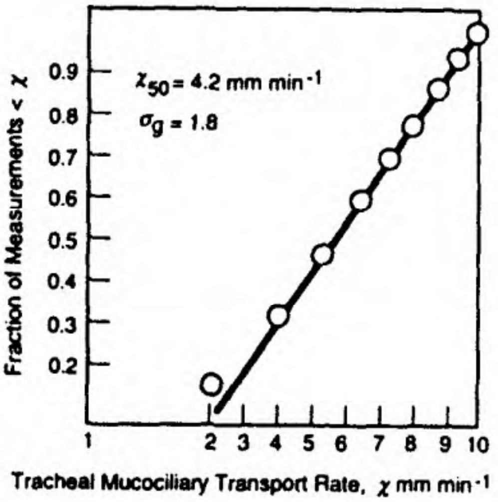

Fig. E.2. Distribution of measurements of tracheal mucociliary transport rates (Yeates *et al.*, 1982).

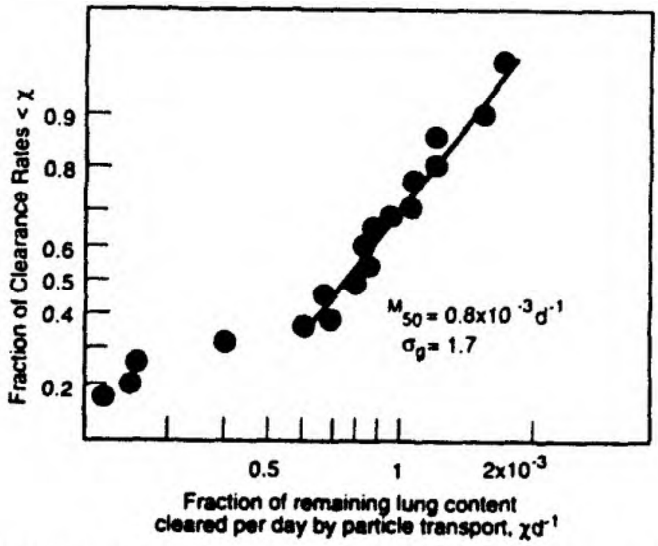

Fig. E.3. Intersubject variation in particle transport rates from the human lung at 200 d after inhalation.

E.1.1.2. *Uncertainty*

(E5) In general, reference values are based on indirect information and therefore involve a considerable element of judgement. Some rates are based entirely on data from animal studies, and extrapolating results to humans involves a possible systematic error, which could be large. For example, the alveolar clearance rate at 100 d after inhalation in humans is about 5 times greater than in dogs, and 5 times lower than in mice (Bailey, 1989; Kreyling, 1990a). Maximum mucociliary transport rates in the trachea ranged from 2 mm min^{-1} in rats to 10 mm min^{-1} in dogs (Felicetti *et al.*, 1981). These are all, however, within a factor of 2.5 of the human value (5 mm min^{-1}, Section E.5.2.3). Thus the combination of a high degree of intersubject variation and possible systematic errors means that the uncertainties in the reference values are large and difficult to quantify. It is therefore assumed that the uncertainty in the reference value is log-normally distributed, and thus that there is a 95% probability that the true mean value lies within a factor Φ_u of the chosen reference value.

(E6) The values selected for Φ_u depend on the quality of information available, and are in general derived in the relevant sections. However, the two examples of interspecies differences described above suggest that a factor of 3 is reasonable whenever a rate is based entirely on animal data.

E.1.1.3. *Modifying factors*

(E7) While it would be expected that many of the parameters in the clearance model will be altered by factors such age, smoking, and disease, only in a few cases have the effects of such factors been measured. Moreover, it would not be expected that a particular agent or condition would affect all clearance rates equally, and therefore they are discussed for each parameter individually in the relevant section. In cases where it is possible to quantify an effect on a parameter, a modifying factor Φ_m is recommended by which the parameter should be multiplied in order to calculate doses for specific individuals or groups. However, it should not be applied to the parameter(s) describing absorption into blood, since any effect on absorption could be quite different.

(E8) It is also necessary to distinguish between two general types of modifying factors: (1) transient factors, such as exercise, which apply only during exposure to the factor, with a time-scale of days or less, and are relevant only to acute exposures; (2) permanent factors, such as sex or a chronic disease, which are relevant to chronic exposures.

E.2. Clearance Mechanisms

(E9) Inhaled substances deposited in the airways are cleared by several mechanisms and pathways, which lead mainly to the GI tract, the lymphatic system, and the blood. These mechanisms have been, and continue to be, intensively studied. Only an outline description is given here, since a number of comprehensive reviews of the literature exist (e.g. Brain *et al.*, 1977; Lauweryns and Baert, 1977; Green *et al.*, 1977; Lippmann *et al.*, 1980; Pavia *et al.*, 1980a; Camner, 1980, 1984; Raabe, 1982; Stuart, 1984; Brain, 1985, 1986; Schlesinger, 1985; Sturgess, 1985; Bowden, 1987; Cuddihy and Yeh, 1988; Morrow, 1988; Oberdörster, 1988; Peterson, 1989; Snipes, 1989). These clearance mechanisms can be grouped into two general processes, which are competitive and complementary:

(E10) *Particle transport.* These mechanisms transport material to the GI tract and lymph nodes, and from one part of the respiratory tract to another. Particles are removed from the extrathoracic airways, trachea, bronchi, and bronchioles by secretions and ciliary action, and from the respiratory airways by free phagocytic cells. The mechanisms operate primarily on particulate material, but the term includes the transport of dissociated material along these routes, which can arise through binding to fluids or uptake by cells.

(E11) *Absorption.* This term is used to refer to the transport of material to the blood, regardless of the mechanism involved. Generally it applies to the dissociation of particles, and the uptake into blood of soluble substances and material dissociated from particles. Important factors in determining absorption rates may include: particle dissolution rates in lung fluids, in secretions, and in phagocytic cells; biochemical reactions; and binding to tissue components.

(E12) The rates of the clearance processes and the relative amounts of material following each pathway depend on the physicochemical properties of the inhaled particles, and also on their site of deposition in the respiratory tract. In the upper airways (posterior nasal passage and large bronchi), particle clearance by mucociliary action toward the oropharynx is generally rapid. Mucociliary clearance is slower in the smaller, more peripheral airways. In the respiratory unciliated airways and alveoli, particle clearance results mainly from transport by macrophages and is slower still; particles can either move toward the ciliated airways or to lymphatic vessels and the pulmonary lymph nodes. Slower particle transport allows greater time for dissolution and biochemical transformations to occur.

(E13) Respiratory-tract models enable these processes to be linked and represented mathematically, so that the fate of an inhaled material under particular circumstances of exposure can be determined from the underlying clearance-rate parameters.

E.2.1. *Particle Transport*

E.2.1.1. *Particle transport in the conducting airways*

(E14) Mucociliary clearance is the most important clearance mechanism throughout the conducting airways, moving particles from the nasal passage and tracheobronchiolar (TB) region (trachea, bronchi, and bronchioles, down to the terminal bronchioles) to the pharynx, where they are swallowed. It may be assisted at times by coughing and sniffing. However, not all particles deposited on the ciliated airways are removed promptly by mucus. There is growing evidence that some are taken up by airway macrophages, and that a very small fraction is retained in the epithelium itself. (See below here and Section E.5.4.) Clearance of insoluble particles from the oral passage occurs, of course, by swallowing, and it is thought that particles are cleared from the anterior nasal passage (ET_1) mainly by nose blowing and wiping (Fry and Black, 1973; Swift and Proctor, 1988; Fig. E.4).

(E15) *Mucociliary clearance.* In parts of the extrathoracic airways (ET_2, posterior nasal passage and larynx) and throughout the TB, the ciliated epithelium moves airway secretions, prevents most particles from reaching airway surface cells, and is the main mechanism for their removal to the GI tract. The structure of the epithelium and the mucociliary transport mechanism are described in Annexe A, Section A.2.5.

(E16) While a traditional view has developed of a continuous mucous sheath covering the airways and moving toward the pharynx, it has long been recognised that the flow is not uniform around the circumference of each airway, particularly at bifurcations. Hilding (1932, 1957a,b, 1959, 1963) has described mucociliary streaming in the nasal passage, larynx, trachea, and bronchi. Van As and coworkers observed,

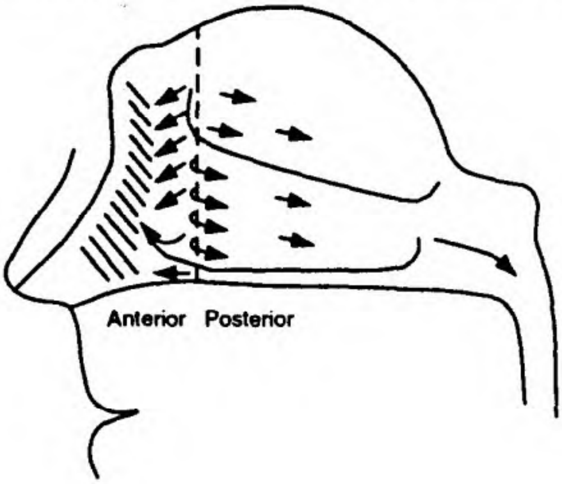

Fig. E.4. Clearance pattern in the nasal passage. Hatched area is nonciliated. (Reprinted from Swift and Proctor, 1988, with permission from Elsevier Science Ltd., Oxford.)

using *in vitro* preparations of rat airways, that, in the small airways, mucus consisted of sparse, discrete particles (4–10 μm). In the bronchi it formed flakes 100 μm across, which aggregated to form streams in the main bronchi. Even in the trachea, the streams did not form a continuous layer (Iravani and van As, 1972; van As and Webster, 1974; van As, 1977, 1980). Other workers could not confirm the discontinuous nature of the mucous layer. Luchtel (1976, 1978) reported that it forms a continuous layer in the rabbit and the rat, from the trachea to the bronchioles, but becomes progressively thinner distally. Sturgess (1977a,b, 1985) also reported it to be continuous in the human and rabbit trachea, but with a more open network in the bronchi. Wolff (1986), in discussing the question, reported his own observation that on 25% of the surface area of the trachea of normal rats there was little or no mucous glycoprotein.

(E17) *Coughing.* Coughing aids mucociliary clearance that is impaired by abnormal or pathological conditions, although the mechanism is only effective when secretions are increased (Camner, 1984). To expel secretions effectively from the walls of airways, coughing must produce a linear air velocity of 5 $m\ s^{-1}$. After the 7th and 8th generation, the airflow is theoretically too low to produce effective coughing (Leith, 1968). There are probably no cough receptors at this level (Camner, 1981). In healthy dogs, repeated coughing impaired normal tracheal clearance markedly for several hours (Smaldone *et al.*, 1979).

(E18) *Airway macrophages.* Recent observations indicating that a significant fraction of particles deposited in the TB may be subject to delayed clearance (Section E.5.3) have focused attention on the airway macrophage as a possible mechanism involved in this pathway (Brain *et al.*, 1984a; Geiser *et al.*, 1990a,b). Sorokin and Brain (1975) observed many macrophages in the bronchial tree of mice. While some were suspended in the mucus, others were beneath it, attached to the bronchial epithelium. The concentration of macrophages per unit surface area in the airways is similar to that in the alveoli (Lehnert and Sanz-Rodrigues, 1988). Oberdörster (1988) considered that particle phagocytosis by airway macrophages might therefore be a more likely explanation for a slow phase of TB clearance than endocytosis by epithelial cells, discontinuities in the mucous blanket, or lack of epiphase in the bronchioles. Brain (1988) has discussed the possible protective functions of airway macrophages.

(E19) Stirling and Patrick (1980) reported that at 2 h after instillation of $BaSO_4$ particles onto the trachea of rats, most particles remaining on the epithelial surface were within macrophages. Geiser *et al.* (1990a,b) found that in the intrapulmonary airways of hamsters that inhaled 6-μm-diameter polystyrene latex (PSL) particles (a size expected to deposit mainly in the airways), 40% of retained particles were in macrophages at 20 min after inhalation, and 90% at 24 h. Many other particles were in close contact with epithelial cells, and it was suggested that surface tension forces may draw particles through the mucus onto the epithelial surface (Schürch *et al.*, 1990; Gehr *et al.*, 1990a,b).

(E20) *Retention in airway walls.* There is evidence that a small fraction of particles deposited in the nasal passage, and the TB, are retained in the airway wall, from studies on several species, including humans, and for a variety of materials. Details are given in Sections E.4.3 and E.5.4. At 1–7 d after instillation onto the rat trachea, $BaSO_4$ particles retained in the airway wall were within macrophages (Stirling and Patrick, 1980; Patrick, 1983) and were mainly concentrated just beneath the basement membrane (Gore and Patrick, 1982). There is also evidence for phagocytosis of inhaled iron oxide particles by tracheal epithelial cells in the mouse (Watson and Brain, 1979). After intranasal instillation of PSL into dogs, Whaley *et al.* (1986) found particles located in the submucosa of the turbinate epithelium. They noted that the mechanism by which the particles moved there was not understood.

(E21) Takahashi and Patrick (1987a) found that between 1 week and 6 months after instillation of ^{133}Ba-labelled $BaSO_4$ particles onto the rat trachea, the ^{133}Ba cleared from the tracheal wall with a half-time of 88 d. By injecting colloidal carbon into the tracheal wall, they determined that it drains into the internal jugular and cervical lymph nodes (Takahashi and Patrick, 1987b). Bryant *et al.* (1953) and Berg *et al.* (1954) measured the uptake of ^{198}Au-labelled colloidal gold (3- to 4-nm diameter) into the hilar lymph nodes of dogs following instillation into the lumen, or injection into the submucosa of a bronchus. Masse *et al.* (1974), following observations of the retention of tantalum and iron oxide particles by monkeys, considered that particles phagocytosed in the bronchial lumen were ultimately removed by lymphatic clearance.

(E22) The route of clearance of particles retained in the nasal epithelium has not been established. In a study with fused aluminosilicate particles (FAP), Snipes *et al.* (1983) noted that the material retained in the nasal passage was "apparently subject to dissolution only as a significant clearance mechanism." There is, however, evidence for the existence of clearance pathways from the extrathoracic airways to regional lymph nodes. Oghiso and Matsuoka (1979) reported that at 1 d after intranasal instillation of colloidal carbon into mice, the greatest accumulation was found in the cervical lymph nodes. Welsh and Welsh (1963) investigated uptake by cervical lymph nodes following instillation of radiolabelled gold into the human larynx.

E.2.1.2. *Particle transport in the alveolar-interstitial region*

(E23) In the respiratory bronchioles and alveoli many structures contribute to clearance: airway secretions, alveolar surfactant, and epithelial cells (Green *et al.*, 1977; Lauweryns and Baert, 1977; Camner, 1980; Brain, 1985). Deposited substances may be moved toward the mucociliary escalator, the interstitium, lymphatics, and blood capillaries, or may be retained in the tissues and lymph nodes.

(E24) The most important clearance mechanism, however, involves the alveolar macrophage (AM), whose main function is phagocytosis, which keeps the alveolar surface free of foreign substances (see, e.g. Brain, 1985, 1986, 1988). Alveolar macrophages are large mononuclear cells that make up more than 95% of the free cell population of the alveolar region. They originate from bone marrow precursor cells and arrive as monocytes in the lungs, where they can mature and multiply in the interstitium or in the alveolar space (Oberdörster, 1988).

(E25) Alveolar macrophage phagocytosis is the intake of large particles, including bacteria and cell fragments. It is one of the processes by which a cell internalises material; the others, according to current conventions, are endocytosis and pinocytosis. With endocytosis, a small region of the plasma membrane folds inward until it has formed a new intracellular, membrane-limited vesicle (endocytic vesicle) about 0.1 μm in diameter. This mechanism is used for the specific internalisation of macromolecules that are bound to cell surface receptors. Pinocytosis refers to the nonspecific uptake of small droplets of extracellular fluid to form pinocytic vesicles. Following these processes, bacteria and particulate matter can be absorbed very rapidly (in 2–20 min) (Sorokin, 1977; Brain *et al.*, 1984b).

(E26) The rate of phagocytosis of particles by AM depends upon properties such as size, surface composition, and density. Hahn *et al.* (1977) reported that rabbit AM phagocytised 2.2-μm FAP *in vitro* more rapidly than 0.3-μm FAP, and denser PuO_2 particles more rapidly than FAP of the same size. Camner and Lundborg (1977) demonstrated, *in vitro*, a higher rate of phagocytosis for carbon-coated than for silver-coated Teflon particles. They also showed a toxic effect of beryllium particles that resulted in inactivation and death of the macrophages. However, Camner *et al.* (1977) found similar lung clearance of carbon-, silver-, and beryllium-coated particles between 1 and 8 d after inhalation by rabbits, suggesting that the differences in rate of phagocytosis observed *in vitro* did not affect clearance *in vivo*.

(E27) After ingestion of particles, and lysosomal digestion (Lundborg *et al.*, 1984), the macrophage may store the particles or release them into intercellular fluids. The loaded macrophages may be removed from the alveolar region via the mucociliary escalator, a pathway that is possibly oriented by chemotaxis to the bronchial lumen, but this has not been established (Lauweryns and Baert, 1977; Oberdörster, 1988). Some researchers consider that AM may penetrate into the interstitium, and hence reach the lymphatics and the lymph nodes, resulting in very long-term retention (Corry *et al.*, 1984; Harmsen *et al.*, 1985; Gillett *et al.*, 1989). However, others believe that it is mainly free particles that follow this route. (See below.)

(E28) Following inhalation exposure, AM in the alveoli can recruit more by passing chemotactic factor through epithelial cells (Adamson and Bowden, 1981). The number of AM increases within a day following a moderate exposure, and the increase is related to the particles' chemical form, number, and surface area (Brain and Corkery, 1977). Bowden (1987) reported that the increase in the number of macrophages was greater for 0.1-μm than for 1.0-μm PSL, and twice as much for 0.03-μm carbon dust, for the same mass.

(E29) Many studies of alveolar clearance of insoluble particles from the lungs of animals have shown that excessive dust burdens progressively reduce AM-mediated clearance until it is completely inhibited, a phenomenon known as overload (Ferin, 1977; Ferin and Feldstein, 1978; Chan *et al.*, 1981; Oberdörster *et al.*, 1984; Muhle *et al.*, 1990). Reduced clearance rates are related to the loss of macrophage mobility and to alterations in their metabolism. Morrow (1988) made the hypothesis that dust overload is better correlated with particle volume than with particle mass, and that the critical volume of particulate was around 600 μm^3.

(E30) Some researchers consider that it is mainly free particles that penetrate into the interstitium (Lauweryns and Baert, 1977; Lehnert *et al.*, 1986). Particles may reach the interstitial space by endocytosis and subsequent exocytosis by type I, and to a lesser extent type II, epithelial cells (Sorokin and Brain, 1975; Lauweryns and Baert, 1977; Oberdörster, 1988).

(E31) Movement to the interstitium may be greater for very small particles. Takenaka *et al.* (1986) found that, after chronic inhalation by rats, fly ash particles (1-μm to 2-μm diameter) were mostly in AM, while TiO_2 (primary particles 0.02–0.03 μm) was mostly in interstitial macrophages. Ferin *et al.* (1990, 1991) found, with both titanium and aluminum oxides, greater lung retention in rats for particles with diameters of 0.02–0.03 μm than for particles of 0.2–0.5 μm. They suggested that this might be due to greater penetration of the ultrafine particles to the interstitium, and that one function of AM phagocytosis is to reduce toxic effects resulting from particles entering the interstitial space.

(E32) Particles may move through the interstitium under the influence of concentration gradients, and of the flow of tissue fluids, which is normally towards lymphatics (Le Bouffant, 1971; Lauweryns and Baert, 1977; Leak, 1977, 1980). Large molecules and particles enter lymphatics through the lymphatic endothelium by means of its discontinuous basement membrane. The open intercellular junctions act as one-way flap valves, allowing fluids and particulate matter to enter but not to leave the lymphatic capillary lumen (Lauweryns and Baert, 1977). Interstitial macrophages may take up particles that have entered the interstitium, and transport them towards, and possibly into, lymphatics (Lauweryns and Baert, 1977).

E.2.2. *Absorption into Blood*

(E33) In addition to particle transport, deposited material is cleared from respiratory tract tissues by biochemical processes. Absorption into blood is essentially a two-stage process: (1) the dissociation of the particles, and (2) the uptake of the dissociated material. Absorption rates tend to change with time since the process of dissociation inevitably alters the physicochemical form of the material. Of particular importance for bioassay is that a rapid phase of uptake to blood is often observed immediately after inhalation, even with relatively insoluble materials (TGLD, 1966). This may be due to the presence of (1) a more soluble component in a mixture (Stradling *et al.*, 1987, 1989); (2) a relatively unstable particle surface (Eidson and Mewhinney, 1983); (3) small particles with relatively high specific surface area; (4) particles small enough to pass directly into the blood (see below); or (5) transformation of the deposited material into a form that is less readily absorbed. Conversely, it is possible for the dissolution rate to increase, if the surface-to-volume ratio of the particles increases as they dissolve (Mercer, 1967). Generally uptake to blood is effectively instantaneous, but, for a number of important elements, a significant fraction of the dissociated material is absorbed slowly as a result of binding to respiratory tract components (Cuddihy, 1984; Oberdörster, 1988).

(E34) The term absorption as used here also includes any transport of particulate material to the blood, although this appears to be important only for particles smaller than a few nanometres. Smith *et al.* (1977) and Stradling *et al.* (1978a,b) found that 1-nm particles of $^{239}PuO_2$ or $^{238}PuO_2$ were readily translocated from the lungs to the blood in rats, but there was negligible translocation of particles larger than 25 nm. This is consistent with observations that the intercellular clefts in pulmonary blood capillaries do not exceed 4 nm (Lauweryns and Baert, 1977). Particles with diameters between a few nanometres and a few microns that were to enter the bloodstream would be expected to deposit predominantly in liver and spleen and be retained there (Berg, 1951; Smith *et al.*, 1977; Kreyling *et al.*, 1986). The absence of marked accumulation of activity in these organs following inhalation has been interpreted by a number of authors as evidence for the low rate of particle penetration of lymph nodes (Section E.7.4), but it similarly indicates a lack of significant direct movement of particles from the respiratory tract itself to the bloodstream. In some species, e.g. calves, sheep, pigs, goats, and cats, particles reaching the bloodstream are retained in pulmonary capillaries by intravascular macrophages. This does not seem to be an important mechanism in rodents, or in humans (Warner and Brain, 1986, 1990; Winkler, 1988).

E.2.2.1. *Particle dissolution*

(E35) The term dissolution is normally taken to mean that a solid in contact with a liquid dissociates, and the ions or molecules produced mix freely with the liquid. The process is reversible, and the solubility is defined as the concentration in the liquid at equilibrium, i.e. when the rate of dissolution equals the rate of precipitation. In the respiratory tract, renewal of the lining fluids is continuous, and therefore particle dissolution does not reach equilibrium. Furthermore the chemical reactions that result in dissociation will not generally be reversible. Other mechanisms may also be involved, notably particle fragmentation as a result of alpha decay, which has been suggested as the reason for the higher dissolution rate of $^{238}PuO_2$ compared with $^{239}PuO_2$ (Fleischer and Raabe, 1977; Stradling *et al.*, 1978a; Diel and Mewhinney, 1983). Nevertheless, the term dissolution is used here for the process, regardless of the mechanisms involved. Moss and Kanapilly (1980) reviewed the mechanisms of dissolution of inhaled particles and *in vitro* methods designed to estimate dissolution rates in the respiratory tract.

(E36) Mercer (1967) suggested that particle dissolution is the major determinant controlling the rate of absorption into blood for material retained in the respiratory tract, and that the dissolution rate is proportional to the particle surface area, and to specific constants and factors controlling particle dissolution. Following Mercer (1967), if dissolution at the particle surface is the rate-determining step, then the rate at which the particle loses mass is proportional to the surface area:

$$\frac{\mathrm{d}m}{\mathrm{d}t} = -ks = -k\alpha_s D^2 = \frac{-k\alpha_s m^{2/3}}{(\rho\alpha_v)^{2/3}} \tag{E.1}$$

where m, s, and D are the particle mass, surface area, and diameter at time t, and ρ is the particle density; k is the dissolution rate constant (dissolved mass per unit area per unit time); $\alpha_s = s/D^2$ = the surface shape factor; $\alpha_v = m/\rho D^3$ = the volume shape factor. The fractional dissolution rate is given by:

$$\mathrm{f} = -\frac{\mathrm{d}m/\mathrm{d}t}{m} = \frac{k\alpha_s}{\rho\alpha_v D}. \tag{E.2}$$

The model thus predicts that the dissolution rate is inversely proportional to particle diameter, and that, if the shape does not change, the fractional dissolution rate will increase with time, as the particles become smaller. There is experimental support for the model, for some compounds at least. Morrow (1974) noted that it predicted the clearance half-time of UO_2 well. Kreyling (1990a) found a good correlation between the initial absorption rate from the lungs of dogs, and the specific surface area, for Co_3O_4 particles of various sizes and densities.

(E37) In principle, the dissolution rate of a particular material could be predicted from knowledge of its size and shape and the value of k for the compound. However, that cannot be determined with confidence except from *in vivo* measurements, and the model has not been widely applied. Furthermore, dissolution at the surface may not be the rate-determining step. Other possible factors include diffusion within the particle and diffusion through a stagnant layer around the particle (Moss and Kanapilly, 1980).

(E38) Dissolution rates, like chemical reaction rates in general, are potentially very sensitive to conditions, making it difficult to simulate respiratory tract dissolution *in vitro*. This sensitivity is well illustrated by recent studies on uranium tetrafluoride (Stradling *et al.*, 1985a; André *et al.*, 1989; Ansoborlo *et al.*, 1990). A wide range of dissolution rates had been reported previously, due partly to differences in *in vitro* technique and partly to differences in the method of production of the material. All three groups found that, following deposition in the lungs of rats, most of the material was absorbed into blood with a half-time of several days. André *et al.* (1989) found a much lower dissolution rate *in vitro* using a serum simulant (Gamble solvent), but a rate similar to that *in vivo* when oxygen was bubbled through the medium, or with cultured alveolar macrophages *in vitro*. Ansoborlo *et al.* (1990) used eight different media and found dissolution half-times ranging from 285 d (Gamble solvent alone) to 2–3 d (pyrogallol + bubbled oxygen), and, like André *et al.* (1989), inferred that dissolution in the lung is mediated by oxygen.

(E39) Solubility in aqueous media may not be even a qualitative guide to absorption *in vivo* (Rhoads and Sanders, 1985). Oberdörster (1988) compared the observed lung clearance in rats of the oxides of cadmium, nickel, and zinc, which are all of low solubility in water. Nickel oxide is cleared mainly by particle transport, with a retention half-time of about 2 months, which is typical for insoluble particles in rats. Zinc oxide dissolves rapidly and is retained with a half-time of about 6 h. Cadmium oxide also dissolves rapidly in the lungs, but the cadmium is retained with a half-time of about 2 months as a result of chemical binding.

(E40) Dissolution rates in the respiratory tract could well differ according to whether the particles are in the liquid lining the epithelium, or phagocytosed by macrophages. Intracellular particle dissolution in AM may well be the rate-determining step in absorption of material from particles that do not dissolve rapidly, and there is growing interest in the use of *in vitro* cultures of AM to study particle dissolution (Lundborg *et al.*, 1984; André *et al.*, 1989). Dissolution rates of compounds of beryllium, cobalt, and manganese were found to be greater in AM cultures than in a lung fluid simulant such as the culture medium (Lundborg *et al.*, 1985; André *et al.*, 1987; Kreyling *et al.*, 1990). Marafante *et al.* (1987) found that the dissolution rate of lead arsenate was higher, but that of arsenic trisulphide was lower, in AM culture than in the medium alone, from which they inferred that the relatively low pH (4–5) in the phagosomes (Nyberg *et al.*, 1989) was likely to be an important factor. Nyberg *et al.* (1991) found that the phagolysosomal pH remains at about 5 during at least the first month after particle deposition in the lungs. However, pH alone was not considered sufficient to account for differences in the dissolution rate of Co_3O_4 between AM and saline observed by Kreyling *et al.* (1990). Other cofactors suggested included the chelators, enzymes, and oxygen radicals present in the phagolysosome. Similarly, observed differences between species in the dissolution rate of inhaled Co_3O_4 could not be attributed to differences in phagolysosomal pH (Kreyling *et al.*, 1991a). The dissolved material within the phagolysosome still must cross the membrane separating it from the cell cytoplasm, the cytoplasm itself, and the cell membrane, to reach the epithelial lining fluid.

E.2.2.2. *Uptake into blood*

(E41) To reach the bloodstream, dissolved material must cross the fluid lining the epithelium, the epithelial cell barrier itself, the interstitium, and the vascular endothelium. Little is known about the ability of inhaled substances to cross the barrier presented by airway secretions. For example, bronchial mucus, which is 95% water, can trap water-soluble material. Its protein and glycoprotein content and its electrolyte properties allow it to bind and eliminate foreign bodies, reducing their absorption. Thus, measurements of mucociliary clearance rates have been made using water-soluble compounds such as saccharine (Andersen *et al.*, 1974a) and dyes (Bang *et al.*, 1967; Ahmed *et al.*, 1980). In contrast, alveolar surfactant presents only a minimal barrier to substances that reach the alveoli, and can remove only a small amount *via* the airways, although it does influence absorption by its physical and chemical features. Nevertheless, it has been suggested that the epithelial lining fluid may be a significant factor in determining the clearance rate of diethylenetriamine pentaacetic acid (DTPA) from the lungs, but the issue is not resolved (Peterson, 1989).

(E42) *Transport across the epithelium.* Water-soluble (hydrophilic) substances are absorbed at a rate determined by diffusion and that is inversely related to molecular weight (MW) (Effros and Mason, 1983). Water and small molecules cross the epithelium readily as illustrated by the high resorption of NaCl isotonic solutions used for bronchoalveolar lavage; the volume absorbed by each lung may reach several hundred cubic centimetres. Observed clearance rates of low-MW solutes suggest the existence in the epithelia of 0.6–1.5-nm-diameter pores in the region of the intercellular tight junctions (Oberdörster, 1988). The alveolar epithelium is only slightly permeable to hydrophilic solutes with MW > 15,000 daltons (1 dalton = 1 atomic mass unit) (Bernaudin, 1981; Jones *et al.*, 1982). Transcellular transport by pinocytosis may also occur and be important for solute molecules too large to diffuse through the intercellular pores (Chinard, 1980; Oberdörster, 1988).

(E43) Lipid-soluble (lipophilic) substances (such as most gases and alcohols) are passively transported across the cellular membranes (Effros and Mason, 1983), which provide a much larger surface area for absorption than do the extracellular pathways. This may explain why absorption rates are higher than for hydrosoluble materials. The absorption rate increases with the lipid–water partition coefficient (Brown and Schanker, 1983), but may be markedly reduced by adsorption onto particles (Bond *et al.*, 1986). An important practical example is the plutonium nitrate–tributyl phosphate complex (Pu–TBP) employed in the extraction of plutonium from spent nuclear fuel. Stradling *et al.* (1985b) found that, following inhalation by rats, a large fraction of the initial lung deposit (ILD) was rapidly absorbed into blood: 40% ILD within 30 min. From complementary experiments, Stradling *et al.* (1983) deduced that the absorbed fraction was in the form of a negatively charged colloid that did not react with phospholipids. At relatively high ILDs, the fraction absorbed was much smaller in rats or baboons (Métivier *et al.*, 1983, 1989) possibly because of polymerisation of the plutonium. Nolibé *et al.* (1989) confirmed, in a direct comparison between ^{238}Pu- and

^{239}Pu–TBP, that the uptake of plutonium from the lungs was much greater at low mass loadings, and found a similar result for Pu–trilaurylamine.

(E44) *Transport across the endothelium.* Usually materials move from the interstitium to blood relatively quickly; the rate of absorption through vascular endothelium is 10–100 times higher than through alveolar epithelium. Hydrophilic substances clear by diffusion into blood and to a lesser extent lymph capillaries, depending on their MW. The pores are larger than in the epithelium, in the range of 2–13 nm (Oberdörster, 1988). The main driving force results from the balance between interstitial and intravascular pressures (Starling's exchanges, Fig. E.5). Hydrostatic pressure (HP) within a capillary forces water out towards interstitial fluid, but is opposed by osmotic pressure (OP) from blood proteins and tissue pressure (TP) from tissue around a capillary.

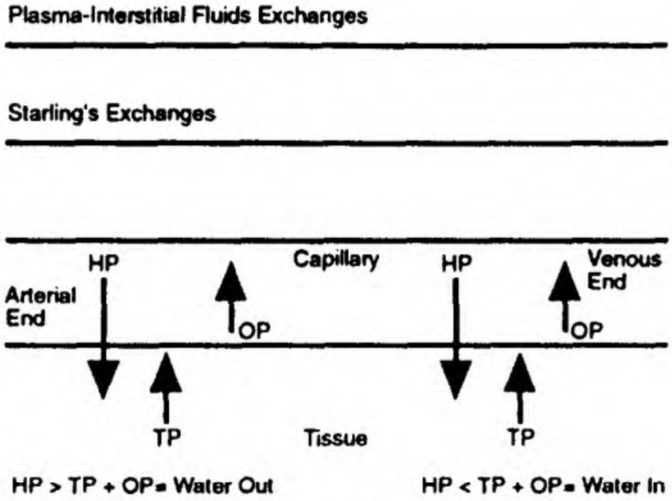

Fig. E.5. Pressure mechanisms of fluid exchanges. HP = hydrostatic pressure; OP = osmotic pressure; TP = tissue pressure.

E.2.2.3. *Determination of absorption rates*

(E45) At present there is insufficient scientific information to model the factors involved in dissolution and uptake, in order to predict the rates of absorption into blood for specific materials. The absorption rate of a given compound may vary greatly. For example, that of plutonium oxide depends on particle size, the method and temperature of formation, history prior to intake, isotopic composition, and presence of other metals (ICRP, 1986). Particles encountered in practice may be complex mixtures of ill-defined compounds, and the radionuclide of concern may be present as a minority constituent of the material, so that the first stage in absorption, particle dissolution, is determined by the main matrix, rather than by the radionuclide itself. Determination of the rate of absorption into blood must therefore be based on a study of the material itself.

(E46) As discussed in Section E.2.2.1 above, *in vitro* dissolution measurements cannot be used with confidence to predict the absorption rate of a material *in vivo.* However, there are practical requirements for relatively rapid and inexpensive techniques to estimate absorption rates of workplace materials, particularly where a large number of samples must be evaluated. Hence there are continuing efforts to develop reliable methods for appropriate circumstances (e.g. Eidson and Griffith, 1984; Ansoborlo *et al.*, 1990; Duport *et al.*, 1991). Cellular dissolution systems (Section

E.2.2.1) offer natural advantages, but do not yet provide results that consistently agree with dissolution *in vivo* (André *et al.*, 1989), possibly because of sensitivity to conditions in the culture medium. Thus if it is demonstrated that a particular *in vitro* method provides results consistent with *in vivo* dissolution for a particular material (i.e. by comparing results *in vivo* and *in vitro*), it can be used to test further samples of that material. Another suitable application arises when a material consists of a mixture of compounds that have distinctly different *in vivo* dissolution characteristics. An *in vitro* test may be used to determine the fraction that is absorbed rapidly (Eidson and Griffith, 1984).

(E47) Material-specific absorption rates thus need to be based on *in vivo* measurements of lung clearance, preferably in humans or in a large animal species (primate or dog), and the study should be of sufficient quality to merit publication in a peer-reviewed journal. The appropriate method of deriving the absorption rate from the experimental data will depend on factors such as the relative values of the absorption rate and the particle transport rate of the material in the animal species used as well as the biokinetic behaviour of the radionuclide following systemic uptake. Ideally a full mass-balance study would be carried out following deposition of the material in the respiratory tract, i.e. sequential measurements of lung retention, urinary and faecal excretion, and accumulation of material in organs outside the respiratory tract. However, often an adequate assessment of the absorption rate can be obtained from a less detailed study.

(E48) On the basis of the model assumptions that (1) particle transport and absorption into blood are independent, and (2) particle transport is independent of material, it may be possible to obtain the absorption rate simply from sequential measurements of the amount retained in the lungs, $R(t)$ at time t (Cuddihy and Yeh, 1988). The overall lung clearance rate, $\lambda(t)$, as a fraction of the amount of material in the lung, is obtained by differentiation:

$$\lambda(t) = -\frac{\mathrm{d}R(t)/\mathrm{d}t}{R(t)} \qquad \text{(E.3)}$$

where $\lambda(t)$ is the sum of the rates due to particle transport, $m(t)$, and absorption into blood, $s(t)$. Hence:

$$s(t) = \lambda(t) - m(t) \qquad \text{(E.4)}$$

where $m(t)$ will have been obtained for the animal species previously, using appropriate, highly insoluble, test particles. This approach can generally be applied to studies with dogs, for which $m(t)$ is particularly low, provided $s(t)$ is not exceptionally low.

(E49) In situations where particle transport is the dominant clearance mechanism, for example in studies with small rodents (rats, hamsters, mice), which have relatively high particle transport rates from the AI region, and for very insoluble materials, it may well be more appropriate to base the assessment of $s(t)$ on the accumulation of material in other organs (Stather *et al.*, 1979) or on urinary excretion (Stradling *et al.*, 1985a; André *et al.*, 1989; Bailey *et al.*, 1989). This approach requires additional information, in particular about the biokinetic behaviour of the radionuclide following systemic uptake, and the fractional absorption of material in the GI tract. It is also normally necessary to assume that the radionuclide absorbed into blood behaves in the same way as it does when administered systemically in a soluble form.

E.3. The Clearance Model

E.3.1. *Requirements of Model*

(E50) For radiological protection purposes, the clearance model is required to provide a quantitative description of retention of radionuclides deposited in the respiratory tract, to calculate doses to radiosensitive tissues, particularly the epithelium of the bronchial and bronchiolar regions. It must also quantify clearance to the GI tract, blood, and regional lymph nodes with sufficient precision for calculating doses resulting from deposition at secondary sites, and for the interpretation of bioassay measurements. The structure of the model should permit parameters to be altered for specific situations. However, for practical application there should be no more complexity than needed to meet these requirements, especially in view of the need to deal with chronic exposures and radioactive decay products.

(E51) Materials deposited in the respiratory tract are cleared by three main routes (see Fig. 19): (1) to the GI tract via the pharynx, (2) to blood by absorption, and (3) to regional lymph nodes (LN_{ET} and LN_{TH}).

(E52) The model provides for clearance by these routes from each region: ET, BB, bb, and AI (Annexe A). In addition, for radioactive substances, the activity in each region is reduced by radioactive decay, but possibly with the formation of radioactive decay products.

(E53) The rates at which deposited materials are cleared by each route in general depend on: (1) the location of the material in the respiratory tract, (2) the physicochemical form of the material, and (3) the time since deposition of the material.

(E54) The general approach used in this model is based on that developed by Cuddihy and his colleagues (Cuddihy, 1976, 1984; Cuddihy *et al.*, 1979; Cuddihy and Yeh, 1988). Clearance from each region of the respiratory tract is treated as competition between particle transport processes and absorption into blood (Section E.2).

E.3.2. *Working Assumptions Made in the Clearance Model*

(E55) Several simplifying assumptions are made to provide a systematic basis for predicting human lung clearance kinetics for the wide range of materials required, on the basis of the limited information available, much of which necessarily comes from animal experiments. Supporting evidence is discussed in Section E.3.3 below. Clearance kinetics are expressed in terms of fractional clearance rates, i.e.:

$$\lambda_i = \frac{-\mathrm{d}A_i(t)/\mathrm{d}t}{A_i(t)} \qquad \text{(E.5)}$$

where $\lambda_i(t)$ is the overall rate of clearance of material from region i and $A_i(t)$ is the amount of material in the region at time t. Thus $\lambda_i(t)$ is the fraction of $A_i(t)$ cleared per unit time, at time t.

(E56) It is assumed in the model that:

1. The clearance rates due to particle transport and absorption are independent. The overall rate of clearance is, thus, the sum of the rates due to the individual processes:

$$\lambda_i(t) = m_i(t) + s_i(t) = g_i(t) + l_i(t) + s_i(t) \qquad \text{(E.6)}$$

where $m_i(t)$ and $s_i(t)$ are clearance rates from region i due to particle transport and absorption, respectively; $g_i(t)$ and $l_i(t)$ are clearance rates to the GI tract and regional lymph nodes.

2. Particle transport rates are the same for all materials.
3. The rate of absorption of a material to blood is the same in all regions of the respiratory tract, including the regional lymph nodes to which the material is cleared (unless information is available from which absorption rates from different regions can be determined). However, it is assumed that material deposited in the anterior nasal passage (ET_1) is not absorbed into blood.

E.3.3. *Justification for the Clearance Model Assumptions*

E.3.3.1. *Independence of particle transport and absorption*

(E57) The independence of particle transport and absorption into blood has been demonstrated particularly clearly by two interspecies comparisons of lung clearance kinetics (Bailey *et al.*, 1988, 1989; Kreyling *et al.*, 1991a). These studies were designed specifically to test aspects of the model proposed here. Lung retention and excretion of ^{57}Co were followed for at least 6 months after inhalation of monodisperse ^{57}Co-labelled cobaltosic oxide ($^{57}Co_3O_4$); the rates of clearance from the lungs by absorption of ^{57}Co into the blood, $s(t)$, and by particle transport to the GI tract, $m(t)$, were assessed. (The terms $s[t]$ and $m[t]$ are the fractions of the lung content remaining at time t after inhalation cleared per day by each process.) In the first study (Bailey *et al.*, 1988, 1989), 0.8-μm- and 1.7-μm-geometric-diameter particles of porous $^{57}Co_3O_4$ were inhaled by human volunteers, baboons, dogs, guinea pigs, hamsters, and rats (three strains: HMT, Fischer-344, and Sprague-Dawley); the 0.8-μm particles were inhaled by mice. In the second study (Kreyling *et al.*, 1991b), 0.9-μm-diameter $^{57}Co_3O_4$ of higher density was inhaled by baboons, dogs, and HMT rats.

(E58) The pattern of particle transport rates in the various species (Fig. E.6) was qualitatively different from that of the absorption rates (Figs E.7A–C). Initial values of $s(t)$ for the 0.8-μm particles were higher than those of the 0.9- and 1.7-μm particles in each species, whereas there was no apparent effect of particle size on $m(t)$. During the first three months after inhalation, $s(t)$ remained constant or initially increased with time in each group, while $m(t)$ decreased monotonically. There was no correlation between the interspecies differences in $m(t)$ and those in $s(t)$. Thus, in HMT rats, both rates were high; in humans and baboons, both were low. Dogs, however, showed rapid absorption of cobalt to blood, but very slow particle transport.

E.3.3.2. *Independence of particle transport on material*

(E59) Particle transport processes are envisaged as being determined by ongoing biological processes, such as the flow of fluids over airway surfaces, which are generally unaffected by the nature of the deposited material or indeed by its presence. In the conducting airways, the principal mechanism is mucociliary clearance, and in the AI region phagocytosis by macrophages and their subsequent migration. There is a growing body of evidence to support the view that particle transport rates are similar for materials of different physicochemical form, under a wide range of conditions. Conversely, there is an increasing amount of information on those particle-specific factors (size, chemical toxicity) that may cause particle transport rates to differ. Individual-specific factors that may alter particle transport rates are considered by region in Sections E.4–E.7.

(E60) *Conducting airways.* Mucociliary clearance (Section E.2.1.1) is the principal particle transport mechanism in the conducting airways. Mucociliary clearance rates in the posterior nasal passage, and in the trachea, have been measured using a wide variety

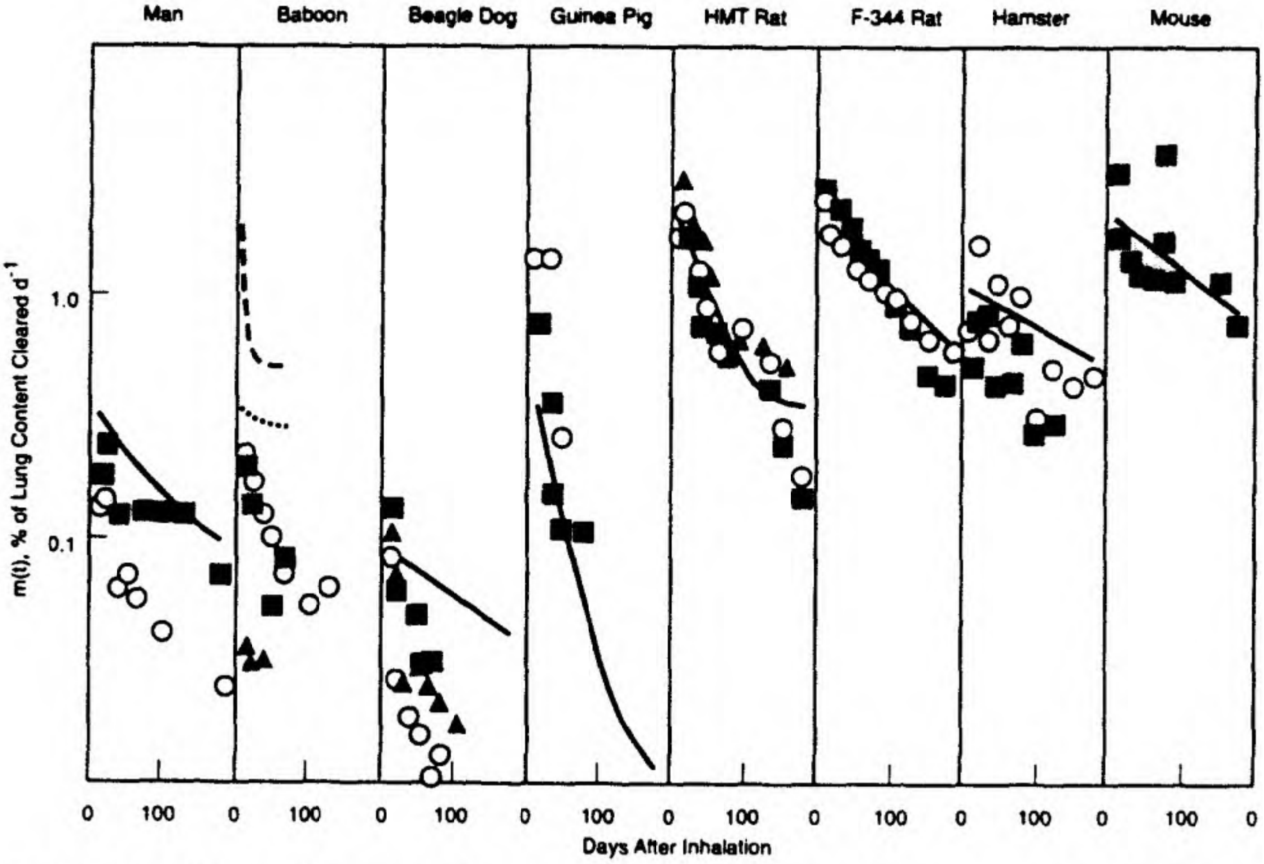

Fig. E.6. Estimated particle transport rates *m*(*t*) from lung to GI tract for 0.8-μm porous Co_3O_4 (■), 1.7-μm porous Co_3O_4 (○), from Bailey *et al.*, 1989; 0.9-μm solid Co_3O_4 (▲), from Kreyling *et al.*, 1991b; and FAP (—). In plotting the results, data for Co_3O_4 were averaged over the following periods: week 2, weeks 3–4, 5–6, 7–8, 9–10, 11–12, 13–16, 17–20, 21–24, 25–28. Values for FAP were taken from Bailey *et al.*, 1985a (humans); Bailey *et al.*, 1985b (HMT rats, hamsters); Kreyling and Schumann, 1987 (dogs); McClellan *et al.*, 1984 (Hartley guinea pigs); Snipes *et al.*, 1983 (F-344 rats, CD-1 mice). (Note that the FAP and Co_3O_4 experiments used different strains of guinea pigs and mice.) No measurements of *m*(*t*) in baboons with other nontoxic materials were found. Lung clearance rates for ^{51}Cr-labelled polystyrene (- -) and ^{198}Au-labelled colloidal gold (. . .) from Métivier *et al.* 1974 are shown, but as they are not corrected for any absorption of the labels to the blood they represent upper limits on *m*(*t*).

of tracers (Sections E.4.1.1 and E.5.2.3), and similar results have been obtained. Studies in which measured mucociliary clearance rates were compared directly are summarised in Table E.1. The measured clearance rates were remarkably insensitive to the size, composition, or amount of particulate material used as a tracer. Several of the studies involved comparison of measurement of mucous velocity in the human posterior nasal passage using insoluble radiolabelled or radio-opaque particles, with measurement of mucous velocity using saccharine or a dye. The latter approach entails measuring the time between deposition and the tracer's taste or appearance at the pharynx. It therefore provides the peak rather than an average velocity and does not allow for changes in different parts of the nose (Andersen *et al.*, 1974a). Furthermore, since the saccharine dissolves in mucus, its movement may represent that of periciliary fluid as well as the mucous gel (Brondeel *et al.*, 1983). Nevertheless, similar results have generally been obtained.

(E61) Patrick (1989) and colleagues measured a similar slow phase of clearance of particles deposited on the distal trachea of rats, for insoluble particles of various compounds and with a wide range of sizes (Section E.5.3.1). Patrick and Stirling (1977)

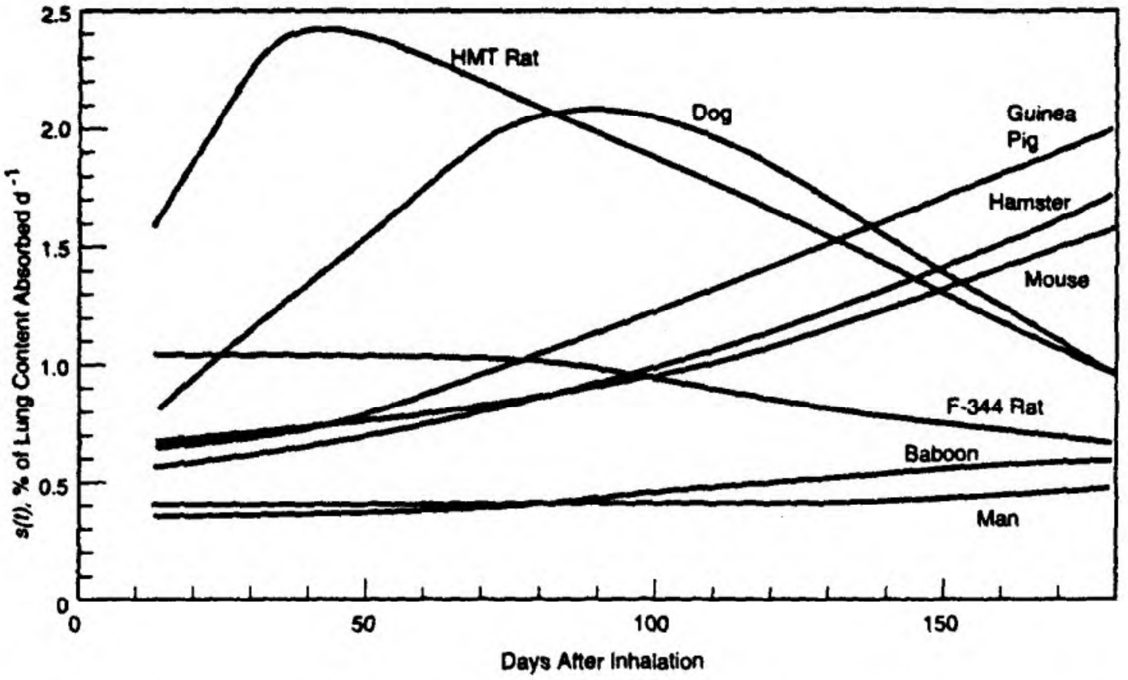

Fig. E.7A. Rate of absorption of ^{57}Co from lung to blood following inhalation of 0.8-μm porous Co_3O_4, $s(t)$, from Bailey *et al.* (1989). Data were averaged as for $m(t)$ in Fig. E.6.

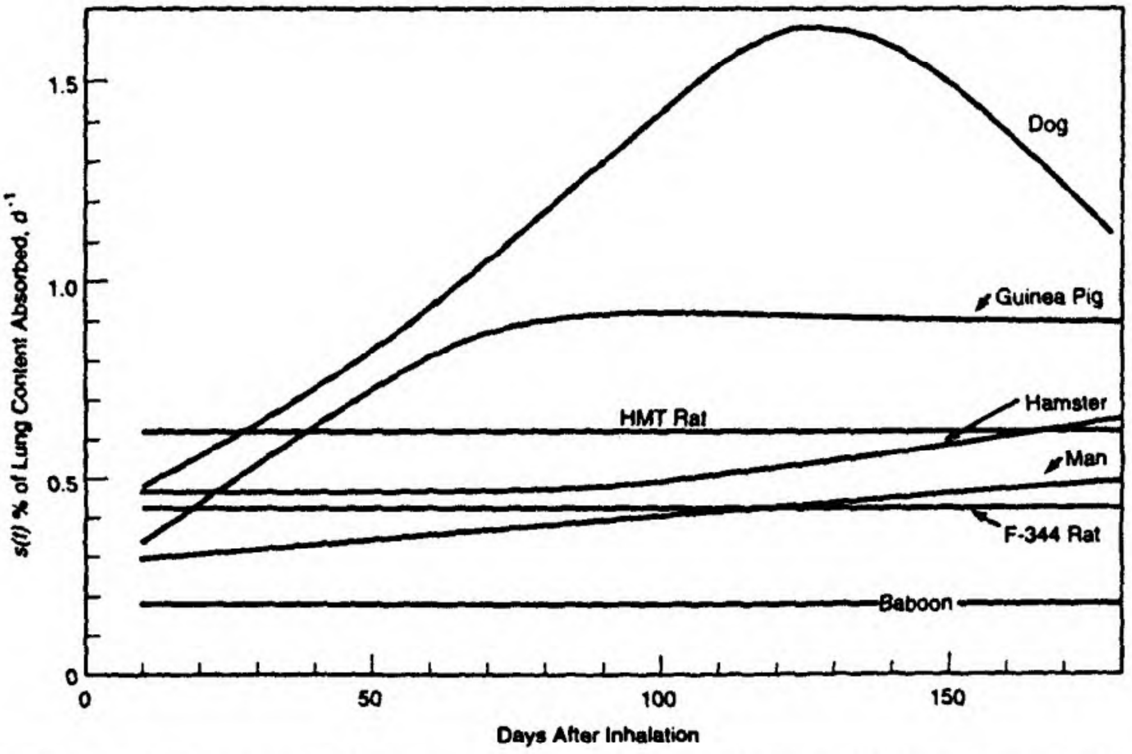

Fig. E.7B. Rate of absorption of ^{57}Co from lung to blood following inhalation of 1.7-μm porous Co_3O_4, $s(t)$, from Bailey *et al.* (1989). Data were averaged as for $m(t)$ in Fig. E.6.

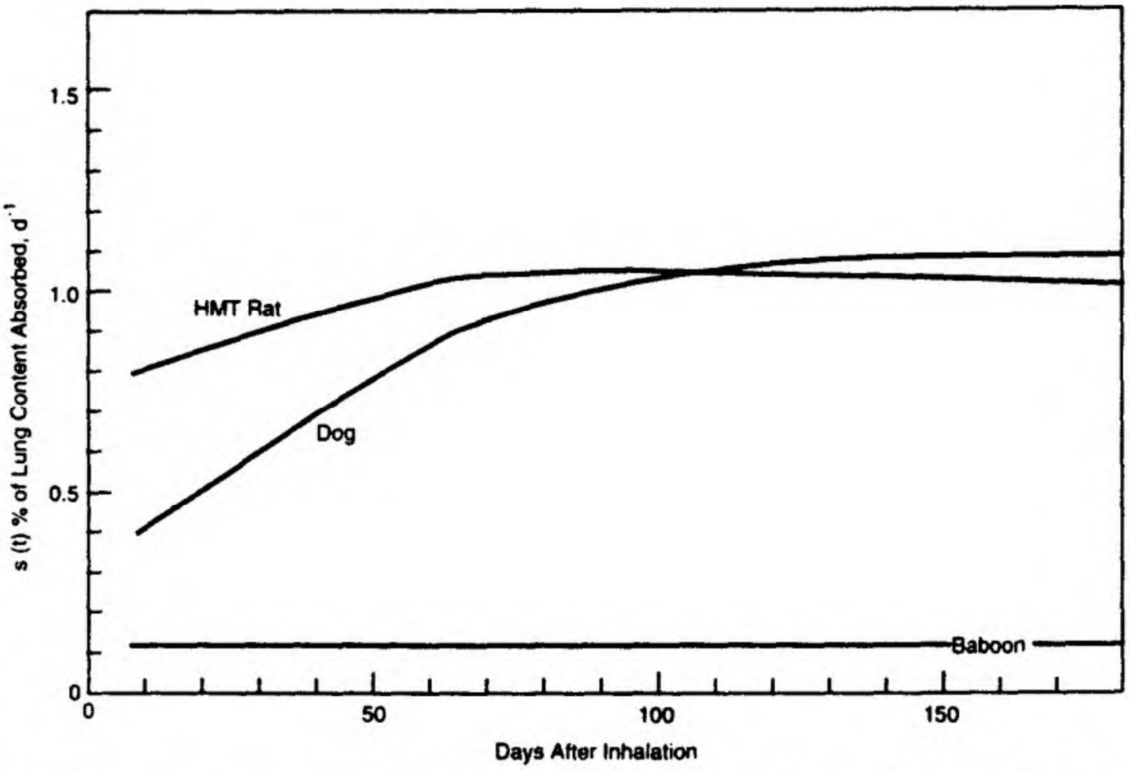

Fig. E.7C. Rate of absorption of ^{57}Co from lung to blood following inhalation of 0.9-μm solid Co_3O_4, $s(t)$, from Kreyling *et al.* (1991b). Data were averaged as for $m(t)$ in Fig. E.6.

found that, for $BaSO_4$ particles (count median diameter [CMD] 0.35 μm), about 80% cleared with a half-time of a few minutes, and 20% with a half-time of about 16 h. They also found that 1% of the deposited material was retained for at least 30 d. (See below.) Patrick (1979, 1983) reported very similar results for UO_2 (CMD 0.35 μm), $BaSO_4$ (CMD 1.0 μm), and for monodisperse FAP (CMD 1.1 μm or 5.7 μm). Wolff *et al.* (1989) found similar retention (80% fast clearance; 20% with a half-time of about 20 d) for 3-μm and 9-μm PSL microspheres deposited in the small ciliated airways of dogs.

(E62) In studies where radiolabelled particles were administered to human volunteers in a manner designed to maximise bronchial deposition, i.e. as a 50-cm^3 bolus introduced at the end of a breath (Section E5.3.2), the fraction of the lung deposit that cleared slowly was similar (50%) for 3-μm-d_{ae} ^{111}In-Teflon, ^{198}Au-Fe_3O_4, or ^{111}In-FAP inhaled under similar conditions (Stahlhofen *et al.*, 1986b, 1987b). However, it has also been found that the slow-cleared fraction decreases with increasing particle size, being 25% for 6-μm-d_{ae} ^{198}Au-Fe_3O_4 (Stahlhofen *et al.*, 1990).

(E63) The retention of particles in the nasal epithelium (Section E.4.3) has been observed qualitatively, for particles ranging from carbon ($\leq$1.5-μm diameter) to pollen granules (40–50 μm) (Strömme, 1955). Snipes *et al.* (1983, 1988) obtained quantitative data for a range of particle sizes and several species. There was no clear difference in the fraction retained for particles with geometric diameters from 0.35 to 15 μm, or between FAP and PSL. However, faster clearance of the particles retained in the nasal epithelium was observed for particles $\geq$ 3 μm than for smaller particles (Section E.4.3).

(E64) The fraction of material deposited onto the distal trachea of rats by intratracheal instillation, which was retained in the airway wall, was similar (0.4–1.0%)

Table E.1. Direct comparisons of mucociliary transport rates measured with different materials

Respiratory tract region	Species	Material	Particle size (μm)	Comment	Reference
Posterior nasal passage	Human	^{131}I-iodofluorescein, various dyes, charcoal		No significant difference	Bang *et al.* (1967)
Posterior nasal passage	Human	^{99m}Tc-resin Saccharine	~ 500 ~ 500	Significant correlation	Andersen *et al.* (1974b)
Posterior nasal passage	Human	Teflon disc Saccharine	1000 ~ 500	Similar rates, but no correlation	Yergin *et al.* (1978)
Posterior nasal passage	Human	^{99m}Tc-resin Saccharine		Significant correlation	Sakakura *et al.* (1980)
Posterior nasal pasage	Human	^{99m}Tc-resin Saccharine Aluminium	250–350 'powder' 600	Correlation between resin and saccharine, but not with aluminium	Puchelle *et al.* (1981)
Posterior nasal passage	Human	^{99m}Tc-resin Saccharine	500–1000	Similar rates in 25 subjects, saccharine faster in 19	Brondeel *et al.* (1983)
Posterior nasal passage	Human	$BaSO_4$ Saccharine		Similar rates	Hady *et al.* (1983)
Palate	Frog, toad	Charcoal, licopodium, glass, steel, mercury		No effect of composition or size	Sadé *et al.* (1970)
Trachea	Dog	Ion exchange resins	3, 110, 180	No effect of composition or size	Connolly *et al.* (1978)
Trachea	Dog	Resin Corn pollen Ragweed pollen Chrysotile Silica Talc	180 ± 50 85–90 19–20 20 × 20–400 2–25 2–25	Resin used as standard. No difference in tracheal transport except for ragweed pollen (+ 15%)	Man *et al.* (1980)
Trachea *in vitro*	Dog	Teflon disc Methylene blue	1000 solution	No difference in transport rate	Ahmed *et al.* (1980)

for UO_2 (CMD 0.35 μm), $BaSO_4$ (CMD 0.34 μm, 0.35 μm, or 1.0 μm), and for FAP (CMD 1.1 μm or 5.7 μm) (Section E.5.4). The retention time in the airway wall has only been determined for $BaSO_4$ (CMD 0.34 μm) (Takahashi and Patrick, 1987a).

(E65) *Alveolar clearance*. Table E.2 summarises the results of studies in which rates of particle transport, $m(t)$, from the lungs to the GI tract measured over periods of weeks to years were compared for different materials, or for different-sized particles of the same material. In some cases the comparison is made simply on the basis of lung retention of materials that are relatively insoluble *in vivo*, i.e. for which clearance would have been determined by particle transport. In several of the papers cited the authors have compared the clearance measured in the experiment they were reporting with published clearance rates for other materials. Monodisperse, radiolabelled PSL or FAP have often been used as nontoxic, relatively insoluble, tracers to measure normal particle transport rates.

(E66) Lung retention similar to that of monodisperse PSL or FAP has been observed for a remarkably wide range of relatively insoluble materials of different physical and chemical forms (Table E.2). This includes $^{239}PuO_2$, provided the ILD is relatively low. Reduced clearance was observed for ILDs > 1 kBq alpha activity in rats and hamsters. Similar reductions in clearance with increasing ILD have been observed for potentially harmful mineral dusts such as quartz and amosite fibres (Vincent, 1990).

(E67) Reduced clearance is also observed at high lung loadings, greater than about 1 mg dust per gram of lung tissue, with insoluble dusts in general, including nuisance dusts, which do not show specific harmful effects. This is currently termed the overload phenomenon (Morrow, 1988; Oberdörster, 1988; Vincent, 1990; Muhle *et al.*, 1990; Section E.2.1.2).

(E68) While most comparisons of particle transport have been made with relatively insoluble compounds, extensive comparisons have been made with several different forms of Co_3O_4, which have different *in vivo* dissolution rates, up to 3% d^{-1}. In several species the particle transport rates determined up to 6 months after inhalation for the different forms of Co_3O_4 were very similar to each other and also to values for the same species based on measurements with FAP (Bailey *et al.*, 1989; Kreyling, 1990a; Kreyling *et al.*, 1991a; Fig. E.6; Table E.2).

(E69) Similar particle transport rates have been measured for particles with geometric diameters between about 0.4 μm and 4 μm, but they may well be different for larger and smaller particles. Clearance was found to be slower for 9-μm particles from rat lung, and too slow to be measured for 15-μm particles from rat lung and for 7-μm and 13-μm particles from dog lung (Snipes and Clem, 1981; Snipes *et al.*, 1984). Similarly long fibres (> 5 μm) are cleared less readily than short ones, and fibres longer than 50 μm are not cleared (Morgan *et al.*, 1978).

(E70) Guilmette *et al.* (1984) measured faster clearance for 0.17-μm than for 0.4-μm or 0.9-μm $^{239}PuO_2$, which they attributed to faster particle transport to the GI tract, because of the lack of accumulation of plutonium in the skeleton, liver, or lymph nodes. There is, however, evidence that particles that are smaller still may be cleared more slowly. Ferin *et al.* (1990, 1991) found with both titanium and aluminum oxides greater lung retention in rats for particles with diameters of 0.02–0.03 μm, than for particles of 0.2–0.5 μm, and suggested that this might be due to greater penetration of the ultrafine particles to the interstitium. Particles smaller than a few nanometres are readily transported into the blood (Section E.2.2).

Table E.2. Comparisons of rates of particle transport $m(t)$ from the alveolar-interstitial region to the GI tract for different materials and/or particle sizes

Species	Material[a]	Particle size[b] (μm)	External comparison[c]	Comment	Reference
Rat	^{141}Ce-PSL ^{85}Sr-PSL ^{46}Sc-PSL	3 9 15		Particles instilled. $m(t)$ for 3 μm similar to inhaled 3 μm particles. 9 μm slower, 15 μm no clearance	Snipes and Clem (1981)
Dog, rat, mouse	^{134}Cs-FAP	0.35, 0.9, 1.8, and polydisperse	PuO_2 (dog)	$m(t)$ similar for different sizes in each species	Snipes *et al.* (1983)
Dog	$^{239}PuO_2$	0.17 0.41 0.87	FAP	$m(t)$ for 0.41 and 0.87 μm similar to inhaled FAP, but faster for 0.17 μm	Guilmette *et al.* (1984)
Mouse	$^{239}PuO_2$	'small' 'medium' 'large'		No difference in lung retention between the 3 fractions with AMADs 0.8, 1.5, and 2.2 μm	Morgan *et al.* (1984)
Dog	^{141}Ce-PSL ^{85}Sr-PSL ^{46}Sc-PSL	3 7 13	FAP	Particles instilled. $m(t)$ for 3 μm similar to inhaled FAP. No clearance of 7 or 13 μm	Snipes *et al.* (1984)
Man	^{85}Sr-FAP ^{88}Y-FAP	1.2 3.9	Polystyrene Teflon	$m(t)$ similar for the two sizes. Similar retention to other insoluble materials	Bailey *et al.* (1985a); Bailey (1989); Section E.6.2
Rat	^{85}Sr-FAP	1.2	U/PuO_2, TiO_2, synthetic fibres	Similar lung retention of various insoluble materials	Bailey *et al.* (1985b)

Hamster	^{85}Sr-FAP	1.2	U/PuO$_2$ (ILD[d] 0.8, 1.5 kBq)	Mixed oxide similar to FAP at ILD 0.8 kBq, increased retention at ILD 1.5 kBq	Bailey *et al.* (1985b)
Rat	^{57}Co-FAP U/PuO$_2$	1.2		Mixed oxide similar to FAP at ILD 0.1 kBq, increased retention at ILD 2 and 9 kBq	Collier *et al.* (1988)
Dog	^{57}Co$_3$O$_4$ (solid) ^{57}Co-FAP	1.6 1.5	FAP	$m(t)$ similar for Co$_3$O$_4$ and FAP	Kreyling *et al.* (1988)
Man, dog, baboon, guinea pig, rat, mouse, hamster	^{57}Co$_3$O$_4$ (porous)	0.8 1.7	FAP (all species except baboon)	$m(t)$ similar for the two sizes, and similar to FAP	Bailey *et al.* (1989); Kreyling (1990b)
Rat	^{54}Mn-tourmaline	Polydisperse	U/PuO$_2$, PuO$_2$, Fe$_2$O$_3$	$m(t)$ similar for various materials	Batchelor (1989)
Baboon, dog, rat	^{57}Co$_3$O$_4$ (solid)	0.9	FAP (dog, rat) porous Co$_3$O$_4$ (all species)	$m(t)$ similar for all forms of Co$_3$O$_4$ and FAP	Kreyling *et al.* (1991b)
Rat	TiO$_2$ Al$_2$O$_3$	0.03, 0.25[e] 0.02, 0.50[e]		Instilled. Similar clearance of 0.25 μm TiO$_2$ and 0.5 μm Al$_2$O$_3$. 0.03 μm TiO$_2$ and 0.02 μm Al$_2$O$_3$ slower	Ferin *et al.* (1990)

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[a] PSL = polystyrene latex microspheres; FAP = fused aluminosilicate particles.

[b] Values given are count median diameters for monodisperse particles, unless stated otherwise.

[c] Comparisons with published results for the materials listed were made by the authors of the papers cited.

[d] ILD = initial lung deposit.

[e] Primary particle size.

E.3.3.3. *Independence of absorption rate on respiratory tract region*

(E71) It is assumed in the model that the rate of absorption into blood of a material is the same in all respiratory tract regions, except the anterior nasal passage, where it is assumed that no absorption takes place. The assumed absence of absorption from the anterior nasal passage is based, not on any direct measurements, but on consideration of the structure of the epithelium, which is much like skin (Annexe A).

(E72) The assumption that the rate of absorption to blood is the same in all other regions may well be an over-simplification immediately after deposition. It might be expected that uptake of dissociated material into blood would be more rapid in the AI region, where the air–blood barrier is thinnest, than elsewhere; there is some experimental support for this view. Schanker *et al.* (1986), for example, found that for 12 different drugs, with widely varying properties such as molecular size, lipid solubility, degree of ionisation, and chemical structure, absorption into blood was about twice as rapid following administration by inhalation than it was following intratracheal injection. They concluded that absorption was probably more rapid from the alveolar region than from the tracheobronchial region of the lung. However, according to Effros and Mason (1983), it is by no means clear whether the flat alveolar epithelium is more, or less, permeable to solutes than the cuboidal or columnar epithelium of the airways. In any case, the absorption into blood from individual respiratory tract regions has only been measured for a few compounds. Thus it is not in general possible to specify different rates for each region, nor to recommend a general factor by which the absorption rate should be increased or reduced for any particular region.

(E73) The results of studies in which solutions or suspensions of radionuclides have been instilled into each region of the respiratory tract are summarised in Table E.3. In Table E.3 and below, the TGLD (1966) terminology for respiratory tract regions (nasopharynx [NP], tracheobronchial [TB], and pulmonary [P]) is used for consistency with the publications cited, and since instillation into TB would not distinguish between bronchial and bronchiolar airways. These experiments were primarily designed to determine the fraction of activity deposited in each region that was absorbed into blood (for comparison with those assumed by the ICRP 30 Lung Model), and therefore do not generally provide sufficiently detailed information at early times to quantify the absorption rates. In most cases the first measurements were made at least 1 d after the instillation. For most of the compounds studied, the fraction of the deposit in the pulmonary region absorbed into blood by this time was more than twice the fraction absorbed from NP or TB. (Exceptions are ^{241}Am- and ^{242}Cm-nitrates, for which the fractions absorbed from P and TB are similar.) However, this does not in itself indicate that the absorption rates are greater in the pulmonary region. Even if the absorption *rates* were the same in the different regions, it would still be expected that the *fraction* absorbed into blood would be smallest in NP and greatest in P, because competing particle transport is fastest in NP and slowest in P.

(E74) Stather and Howden (1975) also measured tissue distributions at 30 min after instillation of ^{239}Pu-citrate and nitrate into P. The fractions absorbed by this time were similar to the fractions eventually absorbed from NP and TB. Since it is likely that much of the absorption from NP and TB would have occurred in the first 30 min, this suggests that the initial absorption rates from each region are not markedly different.

(E75) The absorption of DTPA from different regions has been studied particularly intensively, because of interest in its use in chelation therapy for plutonium, and also because the rate of absorption from the AI region is sensitive to changes in the lung epithelium, and its measurement has potential as a diagnostic tool (Peterson, 1989). For both applications, it is important to take account of regional differences in absorption rate. Thus, Bennett and Ilowite (1989) found that in healthy nonsmokers the average rate of absorption of ^{99m}Tc-DTPA from the alveolar region ($t_{1/2} = 107$ min) was three times that from the bronchi ($t_{1/2} = 296$ min). However, Wolff *et al.* (1988) measured similar rates of clearance of ^{99m}Tc-DTPA instilled into the nasal passage, trachea, fifth generation airway, and peripheral airway (approximately 10th generation) of dogs.

(E76) The assumption that the rate of absorption into blood is the same in all regions is more reasonable at times later than a few hours after inhalation. By that time most particles are likely to be within macrophages, whichever region they are in (Section E.2.1), and dissolution within macrophages could well be the rate-determining step in the absorption of activity into blood. There is some direct evidence to support the assumption, at least with regard to the AI region and lymph nodes. Kreyling *et al.* (1989) used a gamma camera to follow retention of ^{57}Co in the lungs and lymph nodes of dogs up to 400 d after inhalation of $^{57}Co_3O_4$. The ^{57}Co activity in lymph nodes reached a maximum at 100 d to 150 d after inhalation. Subsequently, the rate of clearance from lymph nodes was very similar to that from the lungs, and it was considered that both were determined by absorption into blood.

E.4. The Extrathoracic Airways

E.4.1. *The Nasal Passage*

(E77) Nasal clearance of insoluble particles and human nasal mucociliary function have been comprehensively reviewed (Proctor *et al.*, 1977a; Proctor, 1977, 1982a). The main features relevant to dosimetry have been summarised by Swift and Proctor (1988) and are shown in Fig. E.4.

E.4.1.1. *Observations of mucus flow*

(E78) Hilding (1932) studied the flow of nasal secretions in humans by placing drops of india ink on the mucosa and observing their removal. He reported that the anterior third of the nose (both the lateral wall and the septum) was relatively inactive with respect to ciliary action. There the drops were removed intermittently as fine streaks, at speeds of millimeters per hour. An hour or more was required to remove a drop completely. The drainage from the inactive areas appeared to be due almost entirely to traction from the cilia farther back. Although from some areas, such as the anterior ends of the turbinates, the initial direction might be anterior, the drops ultimately cleared to the pharynx, mainly through the meatuses. However, he also noted that moisture condensed from expired air in the anterior region moves forward into the nasal vestibule, where it evaporates (Hilding, 1932; Fig. E.4). Tremble (1948) reported similar rates of clearance in the inactive (nonciliated) area: on the lateral wall the mucus is renewed every hour or two, and in the corresponding area of the septum particles move at a few millimeters per hour.

(E79) Many measurements of mucociliary clearance in the posterior nasal passage have been made by a variety of techniques, which all involve placing particles or a solution directly onto the ciliated epithelium (Puchelle *et al.*, 1981; Andersen and Proctor, 1983). The time taken to reach the pharynx may be determined by visual observation of the tracer in the pharynx, such as a dye or tiny coloured discs (van Ree and van Dishoeck, 1962; Puchelle *et al.*, 1981) or by the subject's awareness of its taste,

Table E.3. Retention and absorption to blood following instillation into the three respiratory tract regions

Species	Radionuclide	Chemical form	Region[a]	Time (d)	% Instilled activity			Reference
					Head	Lungs	Absorbed[b]	
Rat	^{239}Pu	Citrate	NP	7	11.1	0.7	17.6	Stather and Howden (1975)
			TB	7	—	1.3	18.9	
			P	0.021	—	69	30	
			P	1	—	27	62	
			P	7	—	17.5	80	
		Nitrate	NP	7	15.2	<0.5	11.5	
			TB	7	—	2.1	12.5	
			P	0.021	—	77	12	
			P	1	—	57	35	
			P	7	—	48	43	
Rat	^{241}Am	Citrate	NP	7	14.3	1.0	9.4	Crawley and Goddard (1976)
			TB	7	—	7.2	20.6	
			P	1	—	18.5	81	
			P	7	—	7.2	92	
		Nitrate	NP	7	5.4	1.0	5	
			TB	7	—	18.5	16	
			P	1	—	79.9	9	
			P	7	—	71.5	19	
	^{242}Cm	Citrate	NP	7	14.8	1.0	9.5	
			TB	7	—	7.2	28.1	
			P	7	—	10.0	81.4	
		Nitrate	NP	7	7.2	1.2	4.8	
			TB	7	—	17.5	16.8	
			P	7	—	61.5	24.5	

Rat	^{14}C	DTPA	NP	7	—	—	16	Stather *et al.* (1976)
			TB	7	—	—	33	
			P	7	—	—	100	
Hamster	^{239}Pu	Oxide	NP	30	0.1	0.007	0.028	Stather *et al.* (1979)
			TB	30	—	3.3	0.064	
			P	30	—	41.6	0.092	
Dog	^{111}In	DTPA	NP	2	0.1	0.02	16	Dudley *et al.* (1980)
			NP[c]	2	0.5	0.0	23	
			TB	2	—	0.04	48	
			P	2	—	2.2	90	
Rat	^{233}U	Nitrate	NP	1	1.8	—	8.9	Ellender (1987)
			NP	3	0.6	—	6.4	
			TB	1	—	0.1	30	
			TB	3	—	0.3	42	
			P	1	—	8.5	70	
			P	3	—	8.4	69	
		Bicarbonate	NP	1	4.6	—	6.8	
			NP	3	3.0	—	6.9	
			TB	1	—	0.04	27	
			TB	3	—	0.13	29	
			P	1	—	27	58	
			P	3	—	8.1	71	

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[a] NP = nasopharyngeal; TB = tracheobronchial; P = pulmonary (TGLD, 1966).

[b] For ^{239}Pu, ^{241}Am, and ^{242}Cm amount absorbed into blood = deposits in tissues other than lungs and GI tract × 1.15 to correct for excretion.

[c] Inhalation of aerosol with AMAD = 11.3 μm, giving deposition mainly in the nasal passage.

using for example saccharine (Andersen *et al.*, 1974a). The particles may be radiolabelled and their movement followed by external collimated detectors or a gamma camera (Proctor and Wagner, 1965; Quinlan *et al.*, 1969), providing more information about clearance rates at different locations. The movement of radio-opaque discs has also been followed radiographically, with an image intensifier (Yergin *et al.*, 1978). Andersen and Proctor (1983) noted that the use of insoluble particles, such as radioactive beads, measures mucous transport, whereas use of a soluble dye may also measure the movement of periciliary fluid. However, they obtained similar results with the two methods.

(E80) Results for normal subjects are summarised in Table E.4. The radiolabelled particles and radiographic methods generally give results in terms of mucus velocities, whereas the saccharine and dyes yield transit times. (Some investigators converted these to velocities on the basis of the measured or estimated length of the nasal passage.) Similar values of the mean velocity (5 mm min^{-1}) or of transit time (10 min) have been obtained by many different groups of researchers using a variety of techniques. However, considerable variation was generally observed even amongst normal subjects. Andersen, Proctor, and colleagues carried out an extensive series of experiments to investigate the effects of environmental factors on nasal mucociliary clearance. They followed the clearance of a gamma-tagged resin particle placed in approximately the same point on the ciliated nasal epithelium in each subject. However, they found that it was difficult to characterise the normal range (Proctor, 1982a). Large variations were found between different areas in the same subject and between similar areas in different subjects. Repeated measurements on the same subject often gave different results. Andersen *et al.* (1971) noted three main types of behaviour in apparently normal subjects, studied under closely controlled environmental conditions: (1) constant flow (2–24 mm min^{-1}); (2) steady movement initially, then slowing or stopping; (3) very slow movement, or none at all during the period of observation (30 min). On examining such cases after a further hour, it was invariably found that the particle had been cleared to the stomach (Proctor *et al.*, 1977b).

(E81) Proctor (1977, 1982b) noted from nearly 400 measurements on apparently healthy subjects that about 20% showed slow clearance, i.e. a flow rate < 1 mm min^{-1}. As shown in Fig. E.1, the remaining measurements conform to a log-normal distribution with a median of 5.7 mm min^{-1} and σ_g of 1.6. Puchelle *et al.* (1981) similarly found that 5 out of 20 healthy subjects studied consistently showed slow clearance, using three different techniques. Lioté *et al.* (1989) investigated inter- and intrasubject variation in nasal mucociliary clearance. They found slow clearance (transit time > 30 min) in about 30% of trials on healthy nonsmokers. Mucus from *in vivo* slow movers showed significantly lower transport rates measured *in vitro* by the frog depleted-palate test than that from fast movers. There was some indication that slower clearance might be associated with a higher level of atmospheric pollution (SO_2).

(E82) Andersen *et al.* (1971) occasionally observed anterior movement of the particle. Anterior mucociliary clearance has also been reported by Bryant (1914), Bang *et al.* (1967), and Naessen (1970). Proctor *et al.* (1973, 1977a) concluded that, in a band between the anterior inactive area and the main ciliated passage, there is rapid mucociliary clearance forward (Fig. E.4). This band corresponds to a region of high particle deposition, and they suggested that this is a defence mechanism to bring material that would otherwise be carried through the nasal passage into the body, into a region from which it would be removed by nose blowing and wiping.

Table E.4. Human nasal mucociliary transport rates (normal values)

Mucus velocity (mm min^{-1})		Transit time (min)			
Mean	Range	Mean	Range	Factors investigated	Reference
	4–6		4–10	Mucous flow and ciliary activity patterns	Hilding (1932)
5.0				Ionizing radiation	Frenckner (1939)
		10	6–16	Gravity, airflow, medication, temperature (air or skin), allergy	van Ree and van Dishoeck (1962)
4.2	0–12			Humidity, smoking, tracheostomy, sex	Ewert (1965)
6				Technique (radiotracer)	Proctor and Wagner (1965)
		5	0.5–12	Normal range, technique, disease, medication, smoke, smog, dust, hot drinks	Bang *et al.* (1967)
8	0–15			Humidity, smoking, infection, tracheostomy	Quinlan *et al.* (1969)
8.4	0–24			Normal range, intrasubject variation	Andersen *et al.* (1971)
6	2–9		20–30	Technique (radiotracer) medication	Guillerm *et al.* (1971)
4.8	0–24			Normal range, humidity	Andersen *et al.* (1972)
7.5	1–15			Normal range, infection, vitamin C, nasal morphology	Sakakura *et al.* (1973)
4.6	2–7			Technique, genetics (twins)	Andersen *et al.* (1974a)
3.9	0.5–7			Comparison with TB clearance, genetics (twins)	Andersen *et al.* (1974b)
6.1	0–23			Humidity, exercise	Andersen *et al.* (1974c)
4.5	0–17			SO_2	Andersen *et al.* (1974d)
6.8	1.9–19			Exposure to wood dust	Black *et al.* (1974)
	0–21			Temperature	Proctor *et al.* (1977b)
4.5				Disease (cystic fibrosis)	Rossman *et al.* (1977)
3.6	0–16			Technique, diseases, medication	Simon *et al.* (1977)
8	± 3 (SD)			Medications	Saketkhoo *et al.* (1978)
8.4	0–22			Technique, age, sex	Yergin *et al.* (1978)
	0.5–20			Exposure to inert dust	Andersen *et al.* (1979)
4.6	2–13			Aerosol hair spray, propellant	Borum *et al.* (1979)
7.6	4–13			Exercise	Saketkhoo *et al.* (1979)
			5–30	Septal deviation, and treatment	Ginzel and Illum (1980)
6.4	± 3.4	15	± 3	Normal range, technique, diseases	Sakakura *et al.* (1980)
		10	± 2 (SD)	Disease	Rutland and Cole (1981)
3.8	0–14		7–35	Technique (disc, saccharine, radiolabelled particle), smoking	Puchelle *et al.* (1981)
9	6–14			Technique, age	Kärjä *et al.* (1982)
3.6	0–13			Comparison with TB clearance	Puchelle *et al.* (1982)
		12	7–25	Medications (nasal drops)	van de Donk *et al.* (1982)
5.3		10	4–16	Technique (saccharine/radiolabelled particle), abnormal morphology	Brondeel *et al.* (1983)
		9	7–11	Technique (saccharine/radiography) diseases, abnormal morphology	Hady *et al.* (1983)
		13	6–23	Disease, inhaled saline	Majima *et al.* (1983)
5.8	0–15			Normal range, technique, age, diseases	Sakakura *et al.* (1983)
			2–19	Normal range, mechanisms	Duchateau *et al.* (1985)
		12	± 4 (SD)	Disease (rhinitis, rhinosinusitis)	Stanley *et al.* (1985)
		11	± 4 (SD)	Smoking	Stanley *et al.* (1986)
10.2	5–17			Comparison with TB clearance	Millar *et al.* (1986)
		14[a]		Normal range, mechanisms	Lioté *et al.* (1989)
	0–5			Disease	Takeuchi *et al.* (1989)

[a] 13.6 ± 6.1 min in 13 subjects, but > 30 min in 7 others.

E.4.1.2. *Clearance of inhaled particles from the nasal passage*

(E83) In contrast to the many measurements of clearance of material placed directly onto the ciliated nasal epithelium, there have been remarkably few studies of the clearance of particles deposited during inhalation.

(E84) Lippmann (1970a) measured nasal retention following inhalation of gamma-tagged monodisperse iron oxide particles (d_{ae} 1.3–7.3 μm). Clearance rates varied considerably, but for particles of 1.2–2.4 μm, 20% were removed in the first hour, a further 30% in the next 3 h, and very few during a further 7 h of observation. Cleaning the anterior nasal passages at 4 h removed most of the remaining activity.

(E85) Fry and Black (1973) used collimated detectors to measure separately the activity retained in the anterior nasal passage (possibly including some ciliated epithelium), the posterior nasal passage, and the oropharynx, for up to 6 h after inhalation of ^{99m}Tc-labelled PSL particles (^{99m}Tc-PSL) (d_{ae} 2.5–10 μm). Clearance from the anterior region showed considerable inter- and intrasubject variation, which masked any effect of particle size. In some experiments a rapid clearance phase was seen, while long-term retention was always observed, often too slow for the clearance half-time to be measured (Table E.5). Clearance from the posterior nasal passage was not discussed in detail, but seemed to occur rapidly and quantitatively, at rates consistent with the mucous velocities given in Table E.4.

Table E.5. Clearance of particles from the anterior nasal passage (Fry and Black, 1973)

Number of experiments	Rapid phase %	Rapid phase $t_{1/2}$ (min)	Slow phase $t_{1/2}$ (h)
2	40 ± 30	12 ± 11	6 ± 3
6	34 ± 18	9 ± 5	> 12
10	–	–	7 ± 3
4	–	–	> 12

E.4.1.3. *Clearance by nose blowing*

(E86) Hounam (1975) and Hounam *et al.* (1983) measured the amount of activity removed by nose blowing and/or swabbing, following inhalation of ^{99m}Tc-PSL. In three subjects, nose blows made immediately after inhalation, and then after 0.5 h and 1 h removed on average 15%, 3%, and 1% of the initial nasal deposit (IND). There was no correlation with particle size (1.5-μm to 9.5-μm d_{ae}) or inhalation flow rate (10–40 L min^{-1}) but there was a consistent difference between subjects. In 10 subjects who inhaled 5-μm d_{ae} particles, the first nose blow (10 min after exposure) removed 17% ± 9% IND, and swabbing immediately afterward removed a further 11%. When the procedures were reversed, the fractions were 18% ± 7% and 13%. Delays of several hours had little effect on the fraction of IND removed by the first nose blow.

(E87) Thus clearance from the anterior nasal passage has not been well defined. The experiments of Lippmann (1970a) and Fry and Black (1973) both showed that particles were retained there for at least 6 h. Both groups concluded that particles deposited in the nonciliated anterior region are probably removed mainly by nose blowing and wiping. The studies by Hounam *et al.*, however, do not seem to account for removal of all the material by nose blowing. Morrow (1974) suggested that the anterior nasal passage could be arbitrarily assigned a clearance half-time of 24 h on the basis of a personal communication from Hounam that particulate deposits in that area were effectively removed in most individuals within 1 d or 2 d after exposure.

E.4.2. *Oral Passage, Pharynx, and Larynx*

(E88) Swift and Proctor (1988) noted that clearance from the oral passage and pharynx is by swallowing, and suggested a clearance half-time of 2 min, as representing a period for salivary accumulation and swallow. They stated that clearance from the larynx is by mucociliary movement towards the oesophagus, and considered that the mucous velocity could be assumed equal to that in the trachea, but pointed out that the laryngeal epithelium is not ciliated over its entire circumference. The main flow from the trachea passes through the interarytenoid region, avoiding the vocal chords (Hilding, 1956, 1959).

(E89) In many studies of particle deposition and clearance in the lungs, labelled particles have been inhaled through the mouth. There has often been substantial deposition in the mouth, pharynx, and larynx, which investigators have followed to a varying degree. Stahlhofen *et al.* (1980) followed retention in the extrathoracic airways, i.e. the mouth, pharynx, and larynx, and about 30 mm of the upper trachea, using collimated detectors. For three subjects who inhaled 2-μm d_{ae} to 5-μm d_{ae} particles, clearance from these airways was complete in about 15 min (Heyder, 1984). Emmett (1979) and Emmett *et al.* (1982), using a profile scanner, observed significant deposition in the region of the larynx, which was undetectable after about 10 min.

E.4.3. *Particle Retention in the Airway Wall*

(E90) The penetration of particles into the nasal epithelium and their subsequent retention have been observed in several species. Strömme (1952, 1955) observed uptake of carbon particles (< 1.5-μm diameter) and pollen granules (40–50 μm) through the nasal mucosa of guinea pigs.

(E91) Snipes *et al.* (1983, 1988) obtained quantitative data on particle retention in the nasal passage for a range of particle sizes and several species. Snipes *et al.* (1983) followed retention up to 850 d after inhalation by mice, rats, and dogs of ^{134}Cs-labelled FAP (0.7-μm-d_{ae}, 1.5-μm-d_{ae}, or 2.8-μm-d_{ae} monodisperse particles or a polydisperse aerosol with AMAD of 1.5–2.0 μm). The presence of particles in the maxillary turbinates of dogs killed up to 2 y after inhalation was confirmed by autoradiography. Snipes *et al.* (1988) followed retention up to 200 d after inhalation of 3-μm, 9-μm, or 15-μm ^{46}Sc-PSL by rats and guinea pigs. The fraction of the IND retained long-term in the two studies ranged from 0.004–2.5%, with no clear dependence on species or particle size (Table E.6). The values have therefore been pooled and, as shown in Fig. E.8, conform approximately to a log-normal distribution with median 0.06% IND and $\sigma_g = 4.7$.

(E92) Bailey *et al.* (1985b) similarly found that for 1.2-μm-d_{ae} FAP inhaled by rats and hamsters, < 0.1% IND was retained for more than 2 d. Whaley *et al.* (1986) followed retention of 3-μm PSL instilled onto the epithelium of the maxillary and ethmoid turbinates of dogs. At both sites 0.1% IND was retained at 30 d, and autoradiographs showed particles located in the submucosa of the turbinate epithelium.

(E93) Snipes *et al.* (1983, p. 358) noted that after the early clearance phase the material retained in the nasal passage was "apparently subject to dissolution only as a significant clearance mechanism." Since the estimated dissolution rate of the FAP *in vivo*

Table E.6. Long-term particle retention in the nasal passage (Snipes *et al.*, 1983, 1988)

Material	Animal species	Particle size (μm) AMAD	Particle size (μm) Geometric	Retained (% IBB)	IND/IBB[a]	Retained (% IND)
FAP	Dog	0.7	0.35	0.0087	0.3	0.029
		1.5	0.90	0.026	0.4	0.065
		2.8	1.8	0.164	0.4	0.41
		Poly[b]	—	0.072	0.4	0.18
	Rat	0.7	0.35	0.030	0.55	0.055
		1.5	0.90	0.017	0.62	0.027
		2.8	1.8	0.039	0.67	0.058
		Poly[b]	—	0.011	0.63	0.017
	Mouse	0.7	0.35	0.054	0.45	0.12
		1.5	0.90	0.039	0.62	0.063
		2.8	1.8	0.0027	0.67	0.004
		Poly[b]	—	0.017	0.62	0.027
PSL	Rat	3	3	1.7	0.67	2.5
		9	9	0.6	1.0	0.6
		15	15	0.6	1.0	0.6
	Guinea pig	3	3	0.09	0.67	0.13
		9	9	0.02	1.0	0.02
		15	15	0.02	1.0	0.02

[a] Values for FAP taken from Snipes *et al.* (1983) Table 1. Value for 3-μm PSL assumed to be the same as for 2.8-μm FAP. For 9-μm and 15-μm PSL, 100% nasal deposition assumed, since Snipes *et al.* (1988) noted that no activity associated with these particles was detected in the lungs.

[b] Polydisperse aerosol with AMAD of 1.5–2.0 μm and geometric standard deviation 1.5–2.0.

FAP = fused aluminosilicate particles; PSL = polystyrene latex microspheres; AMAD = activity median aerodynamic diameter; IBB = initial body burden. Values taken from Snipes *et al.* (1983) Figs 2–5, and Snipes *et al.* (1988) Figs 3 and 4; IND = initial nasal deposit.

was between 0.2 and 1.5×10^{-3} d^{-1}, this suggests a particle transport rate from the region of $< 10^{-3}$ d^{-1}. Faster clearance of the retained particles was however observed by Whaley *et al.* (1986): 4×10^{-2} d^{-1}; and by Snipes *et al.* (1988): 3×10^{-3} d^{-1} for the 3-μm particles and 5×10^{-2} d^{-1} for the 9-μm and 15-μm particles.

(E94) Proctor *et al.* (1977b) and Proctor (1982a, p. 33) noted that the adenoids are in the direct line of inspired air and are also bathed by part of the mucociliary stream, and concluded that their crypts accumulate samples of inhaled material. Similar considerations apply to the tonsils with respect to swallowed material. However, information could not be found on which to assess the amount of inhaled material retained at either site, or its retention time.

(E95) There is evidence for the existence of clearance pathways from the extrathoracic airways to regional lymph nodes. Oghiso and Matsuoka (1979) reported that at 1 d after intranasal instillation of colloidal carbon into mice, the greatest accumulation was found in the cervical lymph nodes.

E.4.4. *Conclusions for Modelling*

E.4.4.1. *Reference values and uncertainties*

(E96) *Anterior nasal passage (ET_1).* On the basis of the information reviewed in Section E.4.1, the reference value for clearance of particles deposited in the anterior nasal passage is taken to be 1 d^{-1}, corresponding to a mean retention time of 24 h.

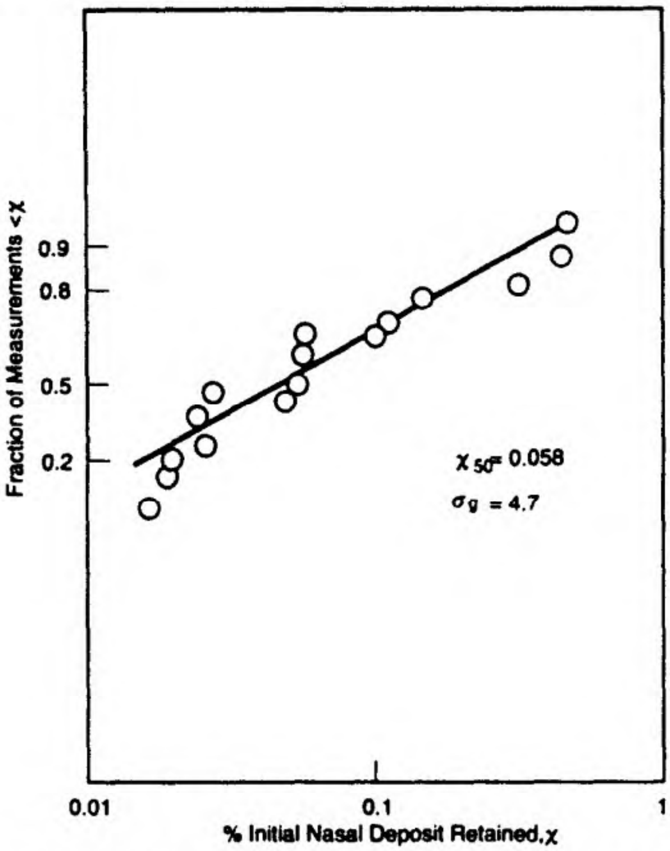

Fig. E.8. Distribution of measurements of the fraction of inhaled particles deposited in the nasal passage that are retained in the airway wall (Snipes *et al.*, 1983, 1988).

Because there have not been experiments of sufficient duration to measure the mean retention time, there is considerable uncertainty associated with this number, but it seems likely that the true value lies within a factor of 3. In Lippmann's (1970a) experiments with 1-μm to 2-μm particles, 50% of the deposit showed little clearance up to 10 h after inhalation, when observations ended. So the mean retention time must be at least 5 h. It therefore seems unlikely that it is less than 8 h. Similarly it seems unlikely to be more than 2 d or 3 d. It is therefore proposed that $\Phi_u = 3$.

(E97) Posterior nasal passage, oral passage, pharynx, and larynx (ET_2). The reference value of the clearance rate from the remaining extrathoracic airways is taken to be 100 d^{-1}, corresponding to a mean retention time of about 15 min. This is a rounded value, representing clearance from the posterior nasal passage, the oral passage, the pharynx, and the larynx, or a combination, according to circumstances. Of these, the clearance rate from the posterior nasal passage is very well defined (Table E.4; Fig. E.1), but for the other parts the retention time cannot be stated more precisely than "a few minutes." Furthermore the pharynx and larynx are considered to be more sensitive to radiation than the nasal passage. In view of this, the uncertainty factor Φ_u is taken to be 3 (although it would be much smaller for the posterior nasal passage alone).

(E98) *Retention in the airway wall.* It has been observed in animal studies that a small fraction of particles deposited in the posterior nasal passage is subject to prolonged retention, located near the basement membrane of the epithelium. There is no direct evidence that particles are retained in the epithelia of the oropharynx and larynx, which are regarded as the principal tissues at risk in ET_2, and are therefore treated as the target tissues. It cannot be readily assumed that retention does also occur in them, because, whereas the lining of the posterior nasal passage is mainly respiratory epithelium, that of the oropharynx and larynx is mainly stratified squamous epithelium. Nevertheless, a retention compartment in ET_2 is included in the model. This ensures that account is taken of detriment arising from retention of particles in the posterior nasal passage. For long-lived alpha emitters in particular, the dose to the basal cells of the epithelium from retained particles can be much greater than that from the material on the surface that is cleared rapidly, because, although the fraction retained is so small (0.05%, see below), its retention time is so much greater (10^3 d compared with 10^{-2} d). Applying it to ET_2 in the model will tend to overestimate the detriment, since the oropharynx and larynx are regarded as being of higher sensitivity than the posterior nasal passage, but this is unlikely to affect the overall estimated detriment, and avoids the complication of including a separate compartment for the posterior nasal passage.

(E99) The retained particles are represented by a sequestration compartment (ET_{seq}). The reference value of the fraction of the deposit retained in the airway wall is taken to be 0.05% (Section E.4.3). This is rounded from the median value of the fraction of the deposit in the nasal passage that is retained (0.06%, Fig. E.8), which is well defined, being derived from 15 sets of results, each of which involved measurements on several animals. However, since it is based entirely on animal data, and on retention in the nasal passage, the uncertainty factor Φ_u is taken to be 3. Figure E.8 shows considerably greater variability ($\sigma_g = 4.7$) than is generally assumed ($\sigma_g = 1.7$, Section E.1.1.1). However, it is based on data from several species, and the data points include uncertainty in the estimated initial deposits in the nasal passage, which may have added to the scatter in the results.

(E100) The reference value for the clearance rate from the airway wall to lymph nodes is taken to be 10^{-3} d^{-1}. This is an order-of-magnitude estimate, since the results of some experiments indicate a value $< 10^{-3}$ d^{-1}, and others indicate values $> 10^{-2}$ d^{-1}. Since it is based entirely on animal data, the uncertainty factor Φ_u is taken to be 3, but the variability of the available data does not in any case indicate greater certainty.

E.4.4.2. *Modifying factors*

(E101) The only aspect of clearance from the ET region for which the effects of modifying factors have been studied is mucociliary clearance in the posterior nasal passage. This has been extensively studied, because of the relative ease with which it can be measured, especially by the saccharine test, and because of interest in its relationship to respiratory tract diseases. Modifying factors are listed in Tables E.7A and E.7B. Since nasal mucociliary clearance can be readily represented by a single number, either the mucous velocity or the transit time, many factors have been quantified.

(E102) Of particular interest, in view of the objective of providing a model relevant to the general population, is that this is the one aspect of particle clearance from the respiratory tract that has been measured in healthy children. Kärjä *et al.* (1982) measured mucociliary transport velocities in four children (aged 2 y, 5 y, 6 y, and 15 y) and obtained rates of 6–10 mm min^{-1}, well within the range they measured in adults. Passàli and Ciampoli (1985) measured transit times in a larger group (33 girls and 21 boys, aged from 3 to 12 y). They did not report a direct comparison with adults, but the average transit time measured (10 min) was very similar to those measured in adults (Table E.4). They found no difference in clearance between boys and girls, and similarly none was observed between men and women (Ewert, 1965; Yergin *et al.*, 1978). Although ethnic origin was not examined explicitly as a factor in any study, most would

Table E.7A. Factors modifying nasal mucociliary transport rate: Transient

Modifying factor	Φ_m[a]	Reference
Aerosol propellant	=	Borum *et al.* (1979)
Air pollution	−	Lioté *et al.* (1989)
Cigarette smoke	=	Bang *et al.* (1967)
	=	Frances *et al.* (1970)
	=	Stanley *et al.* (1986)
Dust (20 min)	=	Bang *et al.* (1967)
2, 10, 25 mg m^{-3}/5 h	=	Andersen *et al.* (1979)
Exercise (20 min)	1.7	Saketkhoo *et al.* (1979)
(20 min)	=	Andersen *et al.* (1974c)
Hair spray	0.7	Borum *et al.* (1979)
Humidity		
RH < 70%	−	Ewert (1965)
RH < 30%	0.7	Quinlan *et al.* (1969)
RH > 30%	+	Guillerm *et al.* (1971)
RH 70%, 50%, 30%, 10%	=	Andersen *et al.* (1972)
RH 9% (78 h)	=	Andersen *et al.* (1974c)
Ionising radiation	−	Frenckner (1939)
Nasal surgery	−	Brondeel *et al.* (1983)
Nasal drops	=	van Ree and van Dishoeck (1962)
	0.8	van de Donk *et al.* (1982)
(Otrivine)	0.4	Simon *et al.* (1977)
Nasal flushing	3	Bang *et al.* (1967)
Nasal sprays	1.7	Saketkhoo *et al.* (1978)
Humid spray	+	Guillerm *et al.* (1971)
Tragacanth (oil)	−	van Ree and van Dishoeck (1962)
Posture	=	Passàli and Ciampoli (1985)
Rhinovirus infection	−	Sakakura *et al.* (1973)
	−	Andersen *et al.* (1977)
	0.5	Simon *et al.* (1977)
SO_2 (5, 25 ppm)	−	Andersen *et al.* (1974d)
(5 ppm)	−	Andersen *et al.* (1977)
Temperature		
Heat (42°C)	=	Bang *et al.* (1967)
Heat (23–39°C)	=	Proctor *et al.* (1977b)
Cold (−6°C)	−	van Ree and van Dishoeck (1962)
Cold (< 23°C)	−	Proctor *et al.* (1977b)
Hot drink	2	Bang *et al.* (1967)

[a] Where a number is given, this is the factor by which the clearance rate should be multiplied. The symbol = indicates no effect. The symbols + and − indicate unquantified increased and decreased clearance, respectively.

have been carried out in Caucasians, but some certainly involved other ethnic groups, with no apparent differences in results. The results of Bang *et al.* (1967) included Indians, and presumably those of Sakakura *et al.* (1980) and Majima *et al.* (1983) were carried out in Japanese.

(E103) However, mucociliary clearance in the posterior nasal passage is only one component of clearance from ET_2, and it is not the most important one, since it is considered that the pharynx and larynx are more sensitive to radiation. It is not likely that clearance from the oral passage, pharynx, and larynx would be similarly affected by these factors. Therefore, it is not suggested that these modifying factors should be applied to clearance from ET_2 at this time. Tables E.7A and E.7B is included to illustrate the effects various factors can have on a clearance process. It is unfortunate that the only parameter for which such information is available is not one which is generally important for dose calculations.

Table E.7B. Factors modifying nasal mucociliary transport rate: Permanent

Modifying factor	Φ_m[a]	Reference
Cold skin	=	van Ree and van Dishoeck (1962)
Vitamin C	=	Sakakura *et al.* (1973)
Age (y) (19–27/54–75)	=	Yergin *et al.* (1978)
(2–15/23–46)	=	Kärjä *et al.* (1982)
(18–39/40–59)	=	Sakakura *et al.* (1983)
(60–100/18–59)	−	
(3–12)	=[b]	Passàli and Ciampoli (1985)
Bronchiectasis	0.3	Rutland and Cole (1981)
Cigarette smoking	0.8	Ewert (1965)
	=	Quinlan *et al.* (1969)
	=	Simon *et al.* (1977)
	0.5	Stanley *et al.* (1986)
Cystic fibrosis	=	Rossman *et al.* (1977)
	0.3	Rutland and Cole (1981)
Deviated septum	−	Ginzel and Illum (1980)
	0.5	Brondeel *et al.* (1983)
	0.3	Hady *et al.* (1983)
Immotile-cilia syndrome	0.0	Rossman *et al.* (1980)
	−	Kärjä *et al.* (1982)
Kartagener's syndrome	0.0	Sakakura *et al.* (1983)
Laryngectomy	2	Simon *et al.* (1977)
	=	Quinlan *et al.* (1969)
	=	Sakakura *et al.* (1980)
	=	Sakakura *et al.* (1983)
Leprosy	=	Bang *et al.* (1967)
Morphology abnormal	0.5	Sakakura *et al.* (1973)
Nasal allergy/atopic	−	van Ree and van Dishoeck (1962)
	−	Simon *et al.* (1977)
	0.7	Brondeel *et al.* (1983)
Rhinitis	−	Simon *et al.* (1977)
	3	Hady *et al.* (1983)
	0.6	Stanley *et al.* (1985)
Rhinosinusitis	0.5	Stanley *et al.* (1985)
Sex	=	Ewert (1965)
	=	Yergin *et al.* (1978)
	=	Passàli and Ciampoli (1985)
Sinusitis	0.6	Rutland and Cole (1981)
	0.5	Sakakura *et al.* (1980)
	2	Hady *et al.* (1983)
	−	Majima *et al.* (1983)
	0.3	Sakakura *et al.* (1983)
Sjögren's syndrome	0.3	Sakakura *et al.* (1980)
	0.3	Sakakura *et al.* (1983)
	−	Takeuchi *et al.* (1989)
Tracheostomy	2	Ewert (1965)
Wood dust (> 10 y)	< 0.1	Black *et al.* (1974)

[a] Where a number is given, this is the factor by which the clearance rate should be multiplied. The symbol = indicates no effect. The symbols + and − indicate unquantified increased and decreased clearance, respectively.

[b] No direct comparison with adults was reported, but the average transit time measured (10.0 min; $N = 54$) was similar to those measured in adults (Table E.4).

E.5. The Bronchial and Bronchiolar Regions

E.5.1. *Introduction*

(E104) Although the trachea, bronchi, and bronchioles are treated separately in this model because of differences in sensitivity (Annexe C), it is convenient in discussing aspects of particle transport to consider the tracheobronchiolar (TB) region as a unit. Particle clearance from TB has been studied extensively. (See, for example, reviews by Wanner, 1977; Pavia *et al.*, 1980a, 1983; Yeates *et al.*, 1981a; Lippmann and Schlesinger, 1984; Pavia, 1984; Wolff, 1986.) However, it has not been well characterised and is the subject of some controversy (Foster, 1988). There is general agreement that mucociliary clearance is the principal transport mechanism, that the main flow is towards the pharynx, and that mucous velocities decrease distally, but there is not agreement about the rate at which the decrease occurs, or the pattern of mucous flow, such as the degree of streaming (Section E.2.1.1). The region is inhomogeneous: from the trachea to the terminal bronchioles the airways decrease in length and diameter, and the structure of the epithelium and its lining fluid change. It has proved very difficult even to distinguish TB clearance completely from alveolar clearance, and measurements of transport velocity in an individual airway generation are almost exclusively confined to the trachea (Section E.5.2.1).

(E105) Following deposition of insoluble radiolabelled particles in the thorax, two distinct phases of clearance are usually observed. It has been generally assumed that the fast phase, which is complete within about a day, represents mucociliary clearance of particles deposited in TB, and the slow phase represents clearance of the alveolar deposit (Albert and Arnett, 1955). This assumption forms the basis of experimental measurements of regional deposition (e.g. Lippmann *et al.*, 1980; Stahlhofen *et al.*, 1980). It is supported by observations that the magnitude and speed of the fast phase increase with increasing particle size (Lippmann and Albert, 1969), and with increasing inhalation flow rate (Heyder *et al.*, 1980; Foster, 1988).

(E106) There is also, however, increasing evidence to suggest that there may be a significant slow phase of clearance from part, at least, of TB and that, as in the nasal passage, a small fraction of particles deposited in TB may be sequestered in the airway wall. Although representing minor pathways of clearance, these mechanisms can have significant effects on the doses to the sensitive cells in the epithelium, and are therefore included in the model. They are considered in detail in Sections E.5.3 and E.5.4. The fast phase of particle clearance from the lung is here termed lung mucociliary clearance (LMC).

E.5.2. *Lung Mucociliary Clearance (Fast Phase)*

E.5.2.1. *Measurements of whole-lung clearance*

(E107) In most studies of bronchial clearance, total lung retention of inhaled gamma-tagged particles may be followed in one lung or both. As noted above (Section E.5.1) the lung clearance pattern depends greatly on exposure parameters (particle size, breathing pattern). It also depends upon individual parameters (lung size, age, disease) (Agnew *et al.*, 1986a; Gerrard *et al.*, 1986). Considerable intersubject variation is observed, but clearance in an individual is relatively constant, as it is in pairs of monozygotic twins (Albert *et al.*, 1973; Camner *et al.*, 1972). Lung mucociliary clearance shows several phases: a rapid phase during the first hour; most of the remaining clearance during the next 6 h; but some detectable up to 2 d (Stahlhofen *et al.*, 1981). It cannot in general be well represented by a single exponential function (ICRP, 1979); the use of three components (Yeates *et al.*, 1982) or a power function (Morrow, 1969) is more appropriate, but clearance following an acute intake is often observed to be a discontinuous process, which is not well represented by any simple function (Lippmann, 1969). This behaviour has been utilised to measure tracheal mucous velocities, by following the movement of boluses of particles up the trachea (Section E.5.2.3).

(E108) Since the mucociliary clearance pattern depends so much on exposure parameters and individual characteristics, and is not easily quantified (see below), no attempt is made here to collate measurements in normal healthy subjects. Effects of modifying factors are considered in Section E.5.5.2, since in any particular experiment clearance in the study group is compared with similarly exposed controls.

(E109) A wide variety of endpoints has been used to measure LMC. This may be simply lung retention as a fraction of the initial lung deposit: $R(\tau) = L(\tau)/L(0)$ at time τ. $R(\tau)$ may be given as a function of time, usually up to a few hours after inhalation, since most of the mucociliary clearance is complete in that period; or at one or more specific times (typically 2 or 3 h). Often the activity associated with the slow phase (assumed to be alveolar or pulmonary) is subtracted (e.g. by deducting 24-h retention), to give "bronchial" retention. This is clearly preferable, especially when investigating factors that can lead to differences in regional deposition as well as clearance. However, if large particles are used so that alveolar deposition is small, total lung retention may still be useful. Alternatively, clearance (1 minus retention) may be presented, and this is used in Section E.5.5.2, where $CT(\tau)$ and $CB(\tau)$, respectively, represent total and bronchial clearance up to time τ. Characteristic (lung or bronchial) retention times are also employed:

T_{avg} the average retention time based on the area under the retention versus time plot;

$t_{1/2}$ the retention half-time based on fitting a single exponential function to the retention over some specified time;

T_{50} the time for retention to reach 50% of its initial value (without fitting any function).

E.5.2.2. *Measurements of zonal lung clearance*

(E110) Retention of inhaled gamma-tagged particles in different parts of the lung has been followed using collimated detectors and gamma-cameras. The fields viewed do not, however, correspond to morphologically distinct regions, except in the largest airways, and observed retention is affected by material clearing from more distal airways. Morrow *et al.* (1967a) observed clearance half-times of 2.5–3 min, and 20–30 min with detectors over the trachea and main bifurcation, respectively, and three phases ($t_{1/2}$ 1–2 h, 5 h, and 1–2 months) with detectors over the rest of the lungs.

(E111) In studies with gamma cameras, the lungs are generally divided into concentric zones about the hilum, but different workers have made different divisions and use different terminology. Most often each lung has been divided into three zones: perihilar (inner), intermediate, peripheral (outer) (Sanchis *et al.*, 1972); central (I), intermediate (II), and peripheral (III) (Short *et al.*, 1979); I, II, III (Wilkey *et al.*, 1980). Würtemberger *et al.* (1987), however, divided each lung into two: central and peripheral, but designated the trachea and main bronchi as a third zone. Agnew *et al.* (1984a) divided each lung into three zones: inner, intermediate, and peripheral, with the trachea and main bronchi as a fourth (central). Since this terminology is the most comprehensive, it is used here.

(E112) All lung zones contain some small bronchi, bronchioles, and alveoli, but some of the largest airways are only included in the inner zone; the intermediate zone includes some airways larger than those in the peripheral zone. There are, however, large differences in the zonal clearance patterns of healthy nonsmokers reported by different investigators, because of differences in initial deposition patterns, definition of zones and possibly materials (Wilkey *et al.*, 1980). For example, Sanchis *et al.* (1972), using 3-μm-d_{ae} albumin particles, observed three clearance phases in zone I ($t_{1/2}$ 0.5 h, 4.5 h, 23 h); two in zone II ($t_{1/2}$ 8 h, 23 h) and in zone III an initial increase in activity followed by clearance with $t_{1/2}$ 23 h. Wilkey *et al.* (1980), using 7-μm-d_{ae} iron oxide, observed similar patterns in all three zones, with 50% of mucociliary clearance complete in about 2 h.

(E113) Because of the problems noted for whole-lung clearance (Section 5.2.1), and with the additional problem of different definitions of zones by different authors, no attempt is made to correlate zonal lung clearance in healthy subjects. The effects of modifying factors are, however, considered (Section E.5.5.2). As with whole-lung clearance, a variety of endpoints has been measured, but, where possible, "bronchial" clearance has been determined. It should be noted that Agnew *et al.* (1984a,b, 1986a,b) employed a model that corrects retention in the inner zones for material cleared from the more peripheral zones.[1]

E.5.2.3. *Measurement of local mucous velocities*

(E114) Measurements of tracheal mucociliary transport rate (TMTR) have been made by following the movement of individual particles or boluses. Several techniques have been used, but all tend to measure the maximum, rather than the average, clearance rate. Tracer particles have been deposited via a bronchoscope, and their movement measured by cine-photography, or externally by radiography or gamma-camera. Tracheal mucociliary transport rate has also been measured by following the clearance of boluses of inhaled gamma-tagged particles along the trachea with a gamma-camera or collimated detectors (Yeates *et al.*, 1981b). Since the results should not depend on the initial deposition pattern, and there is a simple, common endpoint, mean velocities measured in healthy subjects are given in Table E.8. Measurement techniques involving bronchoscopes have given results in healthy subjects, which are more variable and higher than those involving inhalation, perhaps because of the effects of the trauma and anaesthetics (Yeates *et al.*, 1981a; Pavia, 1984).

(E115) Yeates *et al.* (1982) found that TMTRs in 74 healthy subjects measured with inhaled particles were log-normally distributed with a median of 4.2 mm min^{-1} and $\sigma_g = 1.8$ (Fig. E.2). Yeates *et al.* (1975) found that for TMTR the intraindividual short-term coefficient of variation (25%) was considerably less than that between subjects (75%). The latter could result from a combination of genetic and environmental factors.

(E116) The study by Foster *et al.* (1980, 1982), who followed clearance of inhaled particles with a gamma camera, is unique in that mucous velocities were also measured in the main bronchus. For healthy nonsmokers, these averaged 2.4 ± 0.5 mm min^{-1} compared with 5.5 ± 0.4 mm min^{-1} in the trachea. Tracheal and bronchial velocities measured in the same trial were correlated. The ratio was greater than would be predicted from the ratio of the circumferences of the airways, assuming continuity of flow and mucus of constant depth.

E.5.2.4. *Radiographic measurements of tracheobronchiolar clearance*

(E117) Gamsu *et al.* (1973) insufflated tantalum powder into the TB tree of 26 patients. In 18 it was deposited in a sample of all airways (bronchography), and in the

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[1] In Tables E.16 and E.17 (Section E.5.6.2) zonal clearance parameters are distinguished by the suffixes CZ, IZ, MZ, PZ for central, inner, intermediate, and peripheral zone, respectively.

others only in the trachea and main bronchi (tracheography). Radiographs were taken immediately and at times up to 15 months. The opacified TB tree was divided into regions, and the amount in each was estimated as a fraction of that on the first radiograph. The clearance time determined for each region of the TB (Table E.9) is greater than that of the region itself, because of the movement into it of material originally deposited in more distal airways, as shown by the shorter times measured by tracheography. Aspects of the technique may have led to results that are not representative of normal clearance: the introduction of the catheter; lung disorders in the subjects; the large amount of powder deposited; and possible toxic effects specific to

Table E.8. Tracheal mucociliary transport rates in healthy humans

Technique	Material	Particle size (μm)	Velocity (mm min⁻¹ ± SD)	Reference
Bronchoscope Cine-photography	Teflon	680	21.5 ± 5.5	Santa Cruz *et al.* (1974)
	Teflon	680	22.9 ± 6.4	Sackner *et al.* (1975)
	Teflon	1000	11.3 ± 3.2	Wood *et al.* (1976)
	Polyethylene	1000	18.5 ± 6.0	Toomes *et al.* (1981)
Bronchoscope (radiography)	Teflon		9.8 ± 2.4	Goodman *et al.* (1977)
	Teflon	1000	11.2 ± 3.6	Friedman *et al.* (1977)
	Teflon	1000	10.1 ± 3.5	Goodman *et al.* (1978)
	Teflon	1000	11.6 ± 3.6	Mezey *et al.* (1978)
	Teflon		6.5 ± 2.1	Sackner *et al.* (1979)
Bronchoscope (radiotracer)	Albumin	3–7	15.5 ± 1.7	Chopra *et al.* (1979)
Radioaerosol	Albumin	0.5	4.7 ± 3.1	Yeates *et al.* (1975)
	Albumin	0.5	4.4 ± 1.3	Wong *et al.* (1977)
	Sulphide	0.02–5	9	Ross *et al.* (1979)
			4.2 ± 2.5	Yeates *et al.* (1979)
	Fe_2O_3	~2	5.5 ± 1.0	Foster *et al.* (1980)
	Fe_2O_3	~4	4.3 ± 1.9	Leikauf *et al.* (1981)
	Fe_2O_3	~2	5.1 ± 2.9	Yeates *et al.* (1981b)
	Fe_2O_3	~4	6.7 ± 3.0	Gerrity *et al.* (1983)
	Fe_2O_3	~2	5.7 ± 1.4	Leikauf *et al.* (1984)
	Fe_2O_3	~4	4.8 ± 1.6	Gerrard *et al.* (1985)
	Albumin	~2	4.3 ± 1.1	Katz *et al.* (1987)
	Albumin	~2	4.7 ± 1.3	Zwas *et al.* (1987)
	Fe_2O_3	~4	4.9 ± 1.3	Mussatto *et al.* (1988)

Table E.9. Times for lung regions to clear tantalum dust (Gamsu *et al.*, 1973)

Region	50% clearance time		100% clearance time
	Mean	Range	
Trachea and large bronchi[a]	2.5 h	1–4 h	20 h
Trachea and large bronchi	5.5 h	2–9 h	4 d
Small bronchi (1–6 mm dia)	14 h	6–22 h	12 d
Proximal bronchioles	34 h	24–48 h	17 d
Distal bronchioles (last 2–3 generations)	4 d	2–9 d	21 d
Terminal units	Increase up to 2 d; no observable clearance up to 15 mo		

[a] Tracheography. All other results for bronchography.

tantalum. (Masse *et al.* [1973a] reported toxic effects from inhaled tantalum in rats and monkeys, but Morrow *et al.* [1976] found none in a long-term dog study.) Furthermore the measurements were only semiquantitative. This study is, however, the only one in which clearance in individual airways distal to the main bronchi were directly observed in humans. It supports the view that clearance rates decrease distally and indicates residence times in the terminal and/or respiratory bronchioles of about a week.

E.5.2.5. *Mucociliary clearance models*

(E118) Models of bronchial clearance have been developed to estimate mucous velocities throughout TB. Morrow (1974) associated three observed clearance phases (Morrow *et al.*, 1967b) with hilar, intermediate, and peripheral airways, and deduced a mucous velocity in the terminal bronchioles, v_{tb}, of 0.1 mm min^{-1}.

(E119) Lee *et al.* (1979) assumed that all mucus was produced in the terminal bronchioles and was of constant thickness, and hence predicted the velocity (v_z) in generation z, with diameter D_z to be given by:

$$v_z = v_0 D_0 / 2^z D_z. \qquad \text{(E.7)}$$

For a velocity in the trachea of 5.5 mm min^{-1} this gives v_{tb} (generation 15) of 0.005 mm min^{-1} (Table E.10).

(E120) Yeates *et al.* (1982) refined this model to fit observed retention curves by introducing an individual-specific factor K ($1 < K < 10$):

$$v_z = K^{1/15} v_0 D_0 / 2^z D_z. \qquad \text{(E.8)}$$

This gave v_{tb} ranging from 0.001 to 0.020 mm min^{-1}.

(E121) Yu (1981) treated the TB region as a series of "escalators," one representing each generation z, with an associated velocity v_z. To determine their values, he used a retention curve measured by Lourenço *et al.* (1971) for 7.7-μm-d_{ae} particles inhaled by

Table E.10. Calculated mucus velocities and clearance times

	Mucus velocities (v_z) (mm min^{-1})			
Generation, z[a]	Lee *et al.* (1979)	Yu *et al.* (1986)	Cuddihy and Yeh (1988)	Clearance times (min) (Yu *et al.* 1986)
0 (trachea)	5.5	6.5	5.5	22
1	4.1	6.6	3.5	12
2	3.0	2.5	2.0	10
3	2.2	1.2	1.1	8
4	1.4	0.89	0.9	19
5	0.88	0.69	0.9	29
6	0.55	0.54	0.7	35
7	0.34	0.43	0.6	38
8	0.21	0.36	0.4	35
9	0.13	0.29	0.3	28
10	0.074	0.21	0.2	31
11	0.044	0.15	0.1	48
12	0.025	0.11	0.05	65
13	0.015	0.08	0.02	73
14	0.0082	0.05	0.007	104
15 terminal	0.0046	0.04	0.001	115
16 bronchioles		0.03		207

[a] Cuddihy and Yeh (1988) refer to the trachea as generation 1.

a healthy subject. He calculated deposition in each generation and then solved the set of equations for the time to clear each generation. This gave v_{th} of 0.01 mm min^{-1}. Yu *et al.* (1986) extended the model calculations to 18 healthy subjects who inhaled particles with d_{ae} in the ranges 4.2–4.6 μm or 7.4–8.1 μm, to obtain mean mucous velocities for a population (Table E.10).

(E122) Cuddihy and Yeh (1988) used a similar approach to estimate mucous velocities in each airway generation. They calculated deposition in each airway generation for a series of deposition and clearance studies using particles of d_{ae} 1.1–9.5 μm, two breathing patterns, and three subjects (Stahlhofen *et al.*, 1980). On the assumption that the most proximally deposited material cleared first, they derived clearance times for each generation (Fig. E.9), and hence mucous velocities (Table E.10). These three models were used to estimate representative clearance rates for the bronchial and bronchiolar regions (Section E.5.5.1).

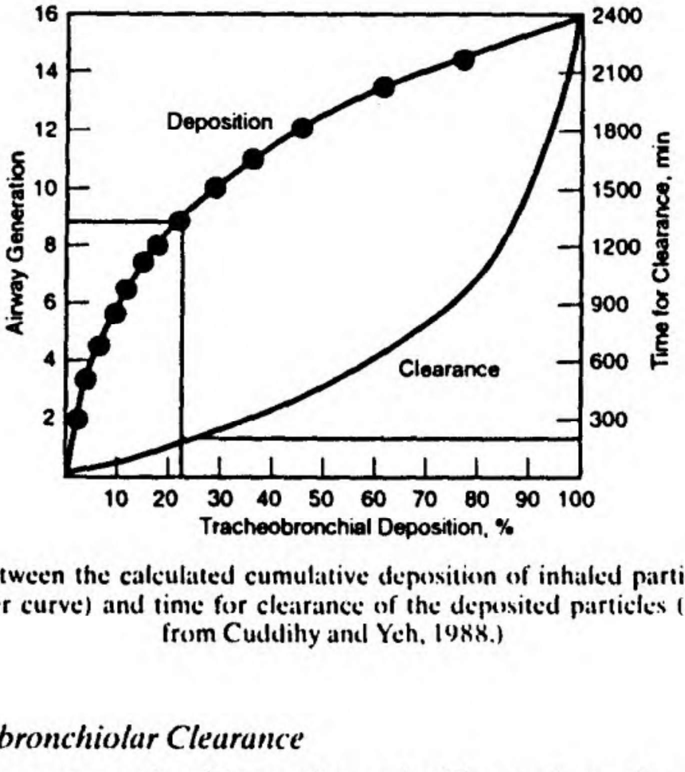

Fig. E.9. Relationship between the calculated cumulative deposition of inhaled particles in tracheobronchial airway generations (upper curve) and time for clearance of the deposited particles (lower curve). (Modified from Cuddihy and Yeh, 1988.)

E.5.3. *Slow Tracheobronchiolar Clearance*

(E123) The main sources of evidence for a significant slow phase of clearance from TB are (1) animal experiments in which particle clearance was measured following deposition at well-defined sites in TB (Section E.5.3.1); (2) human inhalation studies in which the fraction of the thoracic deposit clearing in the slow phase was significantly greater than the fraction expected to deposit in the alveolar region (Section E.5.3.2).

E.5.3.1. *Animal studies indicating slow tracheobronchiolar clearance*

(E124) Patrick and Stirling (1977) measured the clearance kinetics of $BaSO_4$ particles (CMD, 0.35 μm) deposited on the distal trachea of the rat by intratracheal instillation. They found that retention over the first 2 d could be represented by a two-component exponential function: 83% with $t_{1/2}$ 5 min, and 17% with $t_{1/2}$ 16 h. They also found that about 1% of the deposited material was retained for at least 30 d (Section E.5.4). Similar results were obtained for particles administered in suspension in mannitol, or in suspension in mucus. Similar results were also obtained with other materials: UO_2 (CMD 0.35 μm); $BaSO_4$ (CMD 1.0 μm) and monodisperse FAP (CMD 1.1 μm or 5.7 μm) (Patrick, 1979, 1983).

(E125) Svartengren *et al.* (1981) found a significant slow phase of clearance following intratracheal instillation of Teflon particles (CMD 6 μm) into rabbits. For particles deposited in the trachea, 39% cleared with $t_{1/2}$ 19 h; and for particles deposited at the first bifurcation, 71% cleared with $t_{1/2}$ 39 h. In a second study, Svartengren and Camner (1984) found a smaller fraction (37%) of particles deposited on the first bifurcation of rabbits was cleared slowly. They also found that the retention half-time of the slow phase was reduced from 30 h to 10 h by administration of the cholinergic drug bethanecol chloride.

(E126) Felicetti *et al.* (1981) instilled ^{99m}Tc-macroaggregated albumin onto the distal trachea of several species, to measure tracheal mucus velocities. In dogs, an average of 14% of the initial activity remained at the deposition site after 25 min, but in rats, guinea pigs, and rabbits 70–83% remained at an hour.

(E127) Wolff *et al.* (1989) administered a mixed aerosol of 3-μm and 9-μm PSL microspheres via a catheter to give deposition primarily in the 6th–10th generation bronchi of dogs. They found similar retention (80% fast clearance; 20% with a half-time of about 20 d) for both sizes.

(E128) Spoo *et al.* (1991) used a similar technique to administer 3-μm-diameter radiolabelled microspheres into the conducting airways of eight dogs, but on separate occasions deposited them in 15-mm, 8-mm, and 4-mm-diameter airways. Retention was followed for up to 40 d. Some long-term (> 3 d) retention was usually observed, but there was considerable variation between animals exposed in the same size of airway, and also between different airways in the same dog. On average, the fraction retained, and the retention half-time appeared to be greater in the smaller airways. Three dogs exposed in 15-mm airways and one exposed in 8-mm airways apparently cleared all microspheres within 3 d. In other cases the fraction retained varied from 2–84%. The retention half-time was typically on the order of 100 d, but was < 30 d in three cases, while in two others no clearance after 3 d could be measured. In a second study, 1.5-μm mass median diameter polydisperse radiolabelled FAP was administered to 15-mm and 4-mm airways of eight dogs (Snipes *et al.*, 1993). The deposited particles cleared within 3 d from 15-mm sites in seven dogs; and from 4-mm sites in two dogs, with 40–50% of particles retained with half-times on the order of months in the other six dogs. Histological examination of the lungs of three dogs sacrificed 6 d after administration of 3- to 4-μm PSL to 15-mm- and 4-mm-diameter airways showed that some particles had moved to the alveoli and were retained there. One possibility is that the microspheres were displaced by peripheral movement of mucus, a phenomenon ("alveolarisation") previously proposed to account for slow clearance of tantalum dust deposited in the conducting airways of dogs (Friedman and Tisi, 1972), but which may be related to the high surface concentrations of particles employed in these studies.

(E129) There is some evidence supporting slow TB clearance from inhalation studies, but the results are more difficult to quantify because the initial regional deposition pattern is not well defined. In addition, material measured in the airways some time after inhalation will result partly from retention at the site and partly from material clearing in transit. Geiser *et al.* (1990a,b) estimated that, following inhalation by hamsters of 6-μm-diameter PSL (a size expected to deposit mainly in the airways), 14% were retained in the intrapulmonary airways at 24 h. Velasquez and Morrow

(1984), however, reported no evidence for relatively prolonged bronchial retention following inhalation of 8-μm-d_{ae} PSL by guinea pigs.

(E130) Gore and Patrick (1978) found that, at 14 d after inhalation of UO_2 by rats, the mass in the trachea was 10 times the amount estimated to be in transit from the lung lobes. Gore (1983) reported that at 2–35 d after inhalation of UO_2 by rats, the mass concentration in intrapulmonary airway tissue was about 60% of that in pulmonary tissue, a much higher ratio than would be predicted on the basis of complete TB clearance in 24 h. Similarly, Briant and Sanders (1987), who followed lung clearance of a chain aggregate mixed U/Pu oxide for 85 d after inhalation in rats, considered that the amounts found in extrapulmonary airways were much greater than the expected amounts in transit from the pulmonary region. However, in these experiments, particles sequestered in the airway walls (Section E.5.4) may well have contributed to the excess.

E.5.3.2. *Human studies indicating slow tracheobronchiolar clearance*

(E131) The assumption that TB is completely cleared in the rapid phase was challenged by Davies (1980). Following a comparison of experimental results obtained under controlled breathing conditions, with theoretical predictions, he concluded that "the assumption that particles remaining in the lungs after about 30 h are in the alveolated regions" led to "impossibly high values" of alveolar deposition. Bailey *et al.* (1982) reported that, following inhalation of 1.9-μm-d_{ae} and 6.1-μm-d_{ae} particles under controlled conditions, the fractions cleared within 6 d corresponded only to those expected to have deposited in the first 14 airway generations. For both sizes the fractions cleared in the intermediate phase ($t_{1/2}$ about 20 d) were consistent with the predicted deposits in terminal bronchioles. Becquemin *et al.* (1987) and Roy *et al.* (1988) described lung retention in healthy nonsmokers up to 35 d after inhalation, by a three-component exponential function. About 30% cleared with $t_{1/2}$ 1 h, and 40% with $t_{1/2}$ 3 d, while clearance of the remainder was too slow to measure. They attributed the first two phases to proximal and distal airways, respectively. The intermediate (3-d) component was found in patients with sarcoidosis, but in those with silicosis it could not be distinguished from the third phase.

(E132) The main evidence for slow TB clearance in humans comes from a series of experiments conducted by Stahlhofen *et al.* (1986a,b, 1987a,b, 1990, 1994), Stahlhofen (1989), Scheuch (1991), and Scheuch *et al.* (1993). In most of these experiments (Table E.11A) the subject inhaled clean air at a constant rate (250 $cm^3\ s^{-1}$), and tidal volume (1000 cm^3). Radiolabelled particles were administered as a small bolus (50 cm^3) at a predetermined point in the breathing cycle. The breath was completed, a breath-hold imposed to promote deposition by sedimentation at the chosen lung depth, and retention in the thorax measured by external counting for about a week. In one experiment (Table E.11B), the aerosol was inhaled rapidly (700 $cm^3\ s^{-1}$) and was followed by a minimal breath-hold to promote deposition by inertial impaction.

(E133) When the bolus was injected early on in the breath, to deposit it in the alveolar region, the fraction of material deposited in the thorax which cleared slowly, A, was close to unity, as expected. However, when the bolus was injected at the end of the breath, A was surprisingly large: it was still about 0.5 when the bolus front depth, V_F, was only 45 cm^3, about half the volume of the anatomical dead space.

(E134) The experiments were initiated to investigate the assumption that the fast and slow phases of lung clearance corresponded to TB and alveolar deposition, respectively (Stahlhofen, 1989), and the variation of mucociliary clearance velocity with

Table E.11. Fraction, A, of thoracic deposit retained in slow phase following bolus inhalation

Subject	d_{ae} (μm)	V_F[a] (mL)	t_h[b] (s)	Position[c]	Material	A	Reference
(A) Volumetric flow rate of inspired air ~ 250 mL s^{-1}							
25	1.2	45	29	S	Fe_2O_3	0.66	Stahlhofen *et al.* (1986b)
6	1.8	50	36	S	Fe_2O_3	0.70	Scheuch (1991)
1	1.4	70	10	S	Fe_2O_3	0.44	Scheuch (1991)
1	1.8	70	24	S	Fe_2O_3	0.60	Stahlhofen *et al.* (1990)
25	2.9	30	15	L	FAP	0.50	Scheuch (1991)
6	3.0	30	65	S	Fe_2O_3	0.62	Stahlhofen (1989)
4	3.1	35	31	S	Fe_2O_3	0.47	Stahlhofen (1989)
2	3.5	35	9.5	S	Fe_2O_3	0.57	Stahlhofen (1989)
6	2.9	35	52	L	FAP	0.73	Stahlhofen *et al.* (1987b)
31	2.9	40	15	S	FAP	0.57	Scheuch (1991)
1	3.1	45	5	S	Fe_2O_3	0.41	Stahlhofen (1989)
25	3.4	45	4	S	Fe_2O_3	0.57	Stahlhofen (1989)
25	2.9	45	5	S	Fe_2O_3	0.59	Stahlhofen *et al.* (1986b)
25	3.4	45	20	S	Fe_2O_3	0.47	Stahlhofen *et al.* (1986a)
25	2.8	50	10	S	FAP	0.63	Scheuch (1991)
25	3.0	50	40	S	Fe_2O_3	0.62	Stahlhofen (1989)
1	3.4	50	17	S	Fe_2O_3	0.42	Stahlhofen *et al.* (1986a)
6	3.2	50	13	S	Fe_2O_3	0.57	Stahlhofen (1989)
6	3.4	50	14	S	Fe_2O_3	0.56	Stahlhofen *et al.* (1986a)
1	3.5	60	7	S	FAP	0.50	Scheuch (1991)
25	3.7	60	20	L	Fe_2O_3	0.51	Scheuch (1991)
25	3.3	64	12.5	S	FAP	0.60	Scheuch (1991)
25	3.1	65	50	L	FAP	0.80	Stahlhofen *et al.* (1987b)
1	3.2	70	9	S	Fe_2O_3	0.58	Stahlhofen *et al.* (1986a)
1	3.1	70	9	S	FAP	0.54	Stahlhofen *et al.* (1987b)
1	2.9	70	9	S	Fe_2O_3	0.45	Stahlhofen *et al.* (1986b)
4	3.2	70	8.5	S	Fe_2O_3	0.60	Stahlhofen *et al.* (1986a)
30	3.0	70	6	L	FAP	0.72	Stahlhofen *et al.* (1987b)
2	3.0	70	49	L	FAP	0.83	Stahlhofen *et al.* (1987b)
25	3.4	80	1.5	S	Fe_2O_3	0.61	Stahlhofen *et al.* (1986b)
25	3.4	80	8	S	Fe_2O_3	0.55	Stahlhofen *et al.* (1986b)
25	3.0	80	8	S	Teflon	0.59	Stahlhofen *et al.* (1986b)
2	3.0	85	20	S	Fe_2O_3	0.70	Stahlhofen (1989)
25	3.2	120	7	S	Fe_2O_3	0.60	Stahlhofen *et al.* (1986a)
4	3.0	125	38	L	FAP	0.79	Stahlhofen *et al.* (1987b)
4	2.9	135	7	S	Fe_2O_3	0.56	Stahlhofen *et al.* (1986a)
6	3.4	145	16	S	Fe_2O_3	0.57	Stahlhofen *et al.* (1986a)
1	3.4	200	12	S	Fe_2O_3	0.79	Stahlhofen *et al.* (1986a)
4	3.4	275	14	S	Fe_2O_3	0.88	Stahlhofen *et al.* (1986a)
25	3.3	710	6.5	S	Fe_2O_3	0.97	Stahlhofen *et al.* (1986a)
4	6.0	50	20	S	FAP	0.20	Scheuch (1991)
25	6.0	50	20	L	FAP	0.33	Scheuch (1991)
25	5.6	55	5	S	Fe_2O_3	0.30	Scheuch (1991)
1	5.9	70	8	S	Fe_2O_3	0.25	Stahlhofen *et al.* (1990)
4	5.6	76	5	S	Fe_2O_3	0.30	Scheuch (1991)
25	3.7	48	10	S	PSL	0.33	Scheuch *et al.* (1993)[d]
1	3.7	60	10	S	PSL	0.30	Scheuch *et al.* (1993)[d]
4	3.7	75	10	S	PSL	0.25	Scheuch *et al.* (1993)[d]
4	3.7	76	8	S	PSL	0.23	Scheuch *et al.* (1993)[d]
1	3.7	100	8	S	PSL	0.36	Scheuch *et al.* (1993)[d]
2	3.7	120	8	S	PSL	0.42	Scheuch *et al.* (1993)[d]
(B) Volumetric flow rate of inspired air ~ 700 mL s^{-1}							
4	3.8	41	1	S	FAP	0.50	Stahlhofen *et al.* (1994)
6	3.8	54	1	S	FAP	0.40	Stahlhofen *et al.* (1994)
30	3.8	60	1	S	FAP	0.65	Stahlhofen *et al.* (1994)

[a] The bolus front depth, V_F, is the volume of air that passes the larynx, from the time that the leading edge of the bolus passes it to the end of inspiration.

[b] Breath-holding time. Many of these are taken from Stahlhofen (1989).

[c] S = sitting; L = lying down.

[d] Further details from G. Scheuch, personal communication.

lung depth (Stahlhofen *et al.*, 1986a). However, in view of the unexpected initial results, they have continued with the objective of investigating the phenomenon, in particular to try to establish whether it results from slow TB clearance, rather than greater than expected penetration of the bolus to the alveolar region (Stahlhofen *et al.*, 1986a; Sweeney *et al.*, 1988).

(E135) Most of the studies were conducted with iron oxide particles (Fe_2O_3), but similar results were obtained with Teflon or FAP, confirming that the phenomenon is not related to the composition of the particles. Similarly, the results are consistent between subjects.

(E136) In most experiments the subject was seated during inhalation, but in some the subjects inhaled the particles lying down, and took a longer breath-hold after inhaling the bolus, manoeuvres intended to increase the fraction of the bolus deposited in large airways. However, A was even greater, about 0.75 for V_F between 30 cm^3 and 130 cm^3.

(E137) Experiments were carried out to investigate the possibility that a significant fraction of the bolus might reach the alveoli either during inhalation, or during the breath-hold imposed at the end of inhalation.

(E138) Measurements were made of the total particle deposition of inhaled aerosol boluses, as functions of V_F and breath-holding time t_h (Scheuch and Stahlhofen, 1988, 1994). For boluses of 3-μm-d_{ae} particles, which have a gravitational settling velocity of about 0.3 mm s^{-1}, administered at end-inhalation (V_F <55 cm^3), there was <20% deposition during the first 5 s of breath-holding. Since in this time the particles would have fallen more than 1 mm under the action of gravity, all particles that reached alveolar structures, which have dimensions < 1 mm, would have deposited. Since there was some deposition of particles in the TB tree, <20% of the bolus could have reached alveoli during inhalation. In an alternative analysis, the bolus deposition as a function of t_h was used to determine the "effective" diameter of the airways (EAD) reached by the bolus (Scheuch and Stahlhofen, 1988). Results indicated that for V_F <80 cm^3, EAD was > 2 mm, i.e. most of the bolus had not reached the alveolar region.

(E139) Scheuch and Stahlhofen (1991, 1994) investigated the possibility that particles might be transported to alveolar structures during the breath-hold at the end of inhalation, as a result of movement produced by the heart beat. It was shown that such an effect did occur, but only for particles with d_{ae} < 2 μm. It was therefore concluded that this phenomenon is not significant for the 3-μm-d_{ae} particles with which most of the clearance studies were conducted.

(E140) It is notable that there is no obvious effect of front depth on A until V_F > 145 cm^3, beyond which A increases; nor does A vary noticeably with t_h (Table E.11). If the observed retention were mainly due to alveolar deposition, then a continuous decrease in the value of A with decreasing V_F would be expected.

(E141) Gamma-camera images following bolus inhalation in both supine and sitting positions, with $V_F = 55$ cm^3 and 70 cm^3, $d_{ae} = 3$ μm, and inhalation flow rate $Q = 250$ cm^3 s^{-1}, clearly showed particle deposition in the central airways but did not demonstrate peripheral deposition (Scheuch, 1991). However, according to Bennett (1991), gamma-camera analysis has indicated that shallow boluses of radiolabelled particles can penetrate to peripheral airways in humans. He showed an image obtained following inhalation of a 70-cm^3 bolus of 2-μm MMAD particles at 90% total lung capacity, which indicated that deposition was asymmetric and not confined to the conducting airways.

(E142) A high value of A (0.5) was also observed when a bolus of 3.8-μm-d_{ae} particles was inhaled at the end of a rapid breath ($Q = 700$ cm^3 s^{-1}) (Stahlhofen *et al.*, 1994; Table E.11B). In this experiment a greater proportion of deposition is expected to occur by impaction than in those listed in Table E.11A, but the value of A was similar. Since deposition by impaction occurs predominantly in the first five bronchial generations, this result is also consistent with the view that the high values of A are due to a slow phase of TB clearance, and indeed indicates that the phenomenon occurs in the bronchi, not only in the bronchioles, as had been proposed.

(E143) It has therefore not been possible to account for the high retention values (A) on the basis of penetration of a large fraction of the bolus beyond the ciliated airways, either during inhalation or during breath-hold. Taking all the observations above, together with those from animal studies (Section E.5.3.1), such an explanation appears improbable.

(E144) Most experiments were conducted with 3-μm-d_{ae} particles. The few trials with smaller particles (d_{ae} 1.2–1.8 μm) suggest that A may be somewhat greater (about 0.6). Recently, measurements have been made of lung retention following inhalation by human subjects of ^{111}In-labelled indium oxide, with a mass modal diameter of 27 nm (Roth *et al.*, 1994). For such particles, which are deposited mainly by diffusion, it was calculated that TB deposition should be about 20% of thoracic deposition. However, only about 7% of the thoracic deposit was cleared in the rapid phase, suggesting that about two-thirds of the TB deposit is cleared slowly. In this experiment the aerosol was inhaled throughout each breath, not as boluses.

(E145) Initial experiments with 6-μm-d_{ae} particles, however, indicate a significantly lower fraction retained in the slow phase, about 0.25 (Stahlhofen *et al.*, 1990). Furthermore, it has long been known that large (> 10-μm-d_{ae}) particles inhaled at moderate flow rates are practically all cleared in the rapid phase (Lippmann and Albert 1969; Stahlhofen *et al.*, 1983). It was hypothesised (Stahlhofen *et al.*, 1987b) that the apparent decrease in the fraction of the TB deposit cleared slowly, f_s, with increasing size might result from deposition of the larger particles by impaction at sites with efficient clearance. The experiment in which 3.8-μm-d_{ae} particles were inhaled rapidly (Stahlhofen *et al.*, 1994; Table E.11B) was designed to test this, but did not show the lower value of A expected. It has therefore been proposed that f_s depends on the physical size of the particles. This hypothesis was tested in a recent experiment in which subjects inhaled boluses of PSL particles with a nominal geometric diameter, d_p, of 4 μm (Scheuch *et al.*, 1993). This diameter was chosen to be similar to that of the 6-μm-d_{ae} Fe_2O_3 ($\rho = 3.2$ g cm^{-3}; $d_p = 3.4$ μm) and FAP ($\rho = 2.2$ g cm^{-3}; $d_p = 4.0$ μm), for which A was previously found to be about 0.25 (Table E.11). However, since for the PSL, $\rho = 1.05$ g cm^{-3}; d_{ae} would be about 4 μm, similar to that of the FAP and Fe_2O_3 particles for which A was about 0.5. As detailed in Table E.11A, values of A were 0.23 to 0.33, for V_F < 100 cm^3 (the measured value of d_{ae} was 3.7 μm, and hence d_p was 3.6 μm), supporting the view that f_s decreases with increasing geometric diameter.

(E146) Stahlhofen (1989) reported the half-time of the slow phase observed in the bolus clearance studies to be 20 ± 10 d. However, since measurements were only made for up to about a week after inhalation, this might only be representative of part of the retained material.

(E147) Some gamma-camera studies have indicated that TB clearance is not complete within 24 h. Smaldone *et al.* (1988) reported "significant but quantitatively small" retention in central airways at 24 h, notably in those normal subjects with relatively high central deposition, and in patients with "flow-limitation." Foster *et al.* (1982), however, reported that "asthmatic subjects, except only one, had cleared all particles by 24 h, suggesting not only more centralised deposition, i.e. anatomically close to the lung roots, in these subjects, but deposition which could be entirely cleared by mucociliary transport." In the discussion following the paper (p. 244) he further noted that "for some subjects, within 2 h after the initiation of the clearance measurements, the central region of the lung can be virtually free of labelled mucus (< 5%)."

(E148) Bennett *et al.* (1993) found that administration of a beta-adrenergic agent (albuterol) significantly enhanced the rapid phase of particle clearance but not of clearance between 24 h and 48 h. An enhancement of clearance at 24 h would have been strong support for the view that there is substantial particle retention in the airways at 24 h. The authors note, however, that the absence of such enhancement does not rule out the possibility of such retention. One possibility is that the particles are mainly retained in small airways, while albuterol might stimulate clearance mainly in large airways. Another possibility is that the retained particles are in the sol phase or in macrophages and so their retention would not necessarily be affected by an agent that altered mucociliary clearance.

E.5.4. *Particle Retention in the Airway Wall*

(E149) Particle retention in the airway wall of the TB region has been observed qualitatively for a variety of materials and several species (Table E.12). However, there may well be interspecies differences in the extent to which it occurs. Masse *et al.* (1973b) reported that, following inhalation of tantalum powder, retention of particles in bronchial cells was considerably less in cats than in rats or monkeys.

(E150) Little *et al.* (1965) reported high concentrations of ^{210}Po at segmental bronchi bifurcations of smokers. Radford and Martell (1977) inferred long-term retention of ^{210}Pb-enriched particles at bifurcations from observed ^{210}Po:^{210}Pb ratios. However, these results were not confirmed by other investigators (e.g. Robertson and Rogers, 1980; Henshaw *et al.*, 1988). Cohen *et al.* (1980) generally found much lower surface concentrations than Little *et al.*, but a similar level in one sample from a smoker.

(E151) The studies by Churg and his colleagues are of special relevance here, since they demonstrate that particle retention in the airway wall occurs in humans, under normal environmental conditions of exposure, and throughout the airways from the main bronchus (Churg *et al.*, 1990) to the respiratory bronchioles (Churg and Wright, 1988). Churg *et al.* (1990) measured particle number concentration in the mucosa of bronchi (not at bifurcations), and in the parenchyma tissue supplied by those bronchi, in 11 nonsmokers without lung disease or occupational dust exposure. This study appears to be an initial base-line study against which other groups will be compared, but provides several observations relevant to this topic. The concentration of mineral dust particles in the mucosa of most bronchi measured (2×10^8 particles g^{-1} dry tissue) was very similar to that in parenchyma tissue. Differences in the size distribution and composition of particles at different locations suggest that the retained particles result from sequestration of locally deposited particles. Concentrations of larger particles (> 1 μm) were highest in segmental bronchi, where highest deposition would be expected. Silica accounted for 47% of particles in large airways, but only 24% of particles in the parenchyma. Conversely, kaolin and mica accounted for 44% of particles in parenchyma but only 15% of particles in the large airways. In a recently reported similar study on cigarette smokers without emphysema, Churg *et al.* (1992) found considerably

Table E.12. Observations of airway wall retention in the tracheobronchiolar region

Species	Location	Material	Particle size (μm)	Route of administration	Reference
Mouse	Bronchi	Soot	—	Inhalation	Duthie (1930)
Baboon	Bronchi	Iron oxide	95% < 5 μm	Inhalation	Masse *et al.* (1973b)
Monkey, cat, rat	Bronchi	Tantalum	—	Inhalation	Masse *et al.* (1973b)
Guinea pig	Trachea	Horseradish peroxidase, ferritin	—	Instillation	Richardson *et al.* (1976)
Mouse	Trachea, bronchi	Fe_2O_3	0.005	Inhalation	Watson and Brain (1979)
Rat	Trachea	$BaSO_4$	0.35 (CMD)	Instillation	Stirling and Patrick (1980)
Rat	Trachea	$BaSO_4$	0.35 (CMD)	Instillation	Gore and Patrick (1982)
Rat	Bronchi, bronchioles	UO_2	0.34 (CMD)	Inhalation	Gore and Patrick (1982)
Human	Tracheal bifurcation	Mineral		Inhalation	Henshaw and Fews (1983)
Rat	Trachea	FAP	5.7 (CMD)	Instillation	Patrick (1983)
Rat	Trachea	U/Pu oxide	0.7 (AMAD)	Inhalation	Briant and Sanders (1987)
Rat	Trachea	Gold	0.01	Instillation	Takahashi *et al.* (1989)
		Carbon	0.03		
		PSL	0.27		
		PSL	1.24		
Dog	Bronchi, bronchioles	$^{239}PuO_2$	—	Inhalation	Filipy *et al.* (1985, 1986)
Human	Trachea, bronchi	Mineral	—	Inhalation	Henshaw *et al.* (1988)
Human (chrysotile miners)	Bronchi	Mineral	—	Inhalation	Churg and Wright (1988)
Human (lungs with cancer)	Bronchioles	Mineral	—	Inhalation	Churg and Stevens (1988)
Human (normal nonsmokers)	Bronchi	Mineral	—	Inhalation	Churg *et al.* (1990)

lower concentrations in the airways of many, but not all, smokers than had been found in nonsmokers.

(E152) However, the phenomenon has only been well quantified by Patrick (1989) and his colleagues (Table E.13), who followed retention of activity after deposition of radiolabelled particles onto the distal trachea of rats. Between 0.4% and 1.1% of the deposited activity was retained at 1–7 d after instillation. Takahashi and Patrick (1987a; Table E.13) found that between 1 week and 6 months after instillation of ^{133}Ba-labelled $BaSO_4$ the ^{133}Ba cleared from the tracheal wall with a half-time of 88 d. There is evidence that particles are cleared from the TB mucosa to regional lymph nodes (Section E.2.1.1).

Table E.13. Long-term particle retention in the tracheal wall following intratracheal instillation

Material	Particle CMD (μm)	Time (d)	% Retained (mean ± SE)	Reference
$BaSO_4$	0.35	1	1.1 ± 0.1	Patrick and Stirling (1977)
		7	1.0 ± 0.2	
		30	0.9 ± 0.3	
UO_2	0.35	1	0.39 ± 0.09	Patrick (1979)
		14	0.69 ± 0.19	
$BaSO_4$	1.0	7	0.83 ± 0.55	Patrick (1983)
FAP	1.1	7	0.45 ± 0.12	
FAP	5.7	7	0.75 ± 0.35	
$BaSO_4$	0.34	7	0.41 ± 0.13	Takahashi and Patrick (1987a)
		28	0.30 ± 0.09	
		56	0.13 ± 0.05	
		112	0.15 ± 0.10	
		168	0.10 ± 0.03	

E.5.5. *Retention of Particles in Transit*

(E153) Consideration of a slow phase of TB clearance (Section E.5.3), and of airway wall retention (Section E.5.4) of particles *deposited* onto the surfaces of the conducting airways, raises the question of the extent to which particles *cleared* into a region may be subject to similar retention. For example, are particles that were initially deposited in AI, and are being transported towards the GI tract, subject to slow clearance or airway wall retention in BB and/or bb, and if so how much? Information on this is sparse and inconclusive, and it is difficult to predict what might occur from mechanistic considerations.

(E154) Morrow (1972), for example, noted that: "It is logical to assume that materials in transit through the tracheobronchial tree (including mucus) experience absorption, at least to some extent. If this were to occur, the materials would thereafter appear in the peribronchial and perivascular lymphatic drainage and the tracheobronchial nodes." There is also some experimental evidence to support this. Patrick and Stirling (1992, 1994) administered ^{195}Au-labelled colloidal gold particles to rats by microinjection into subpleural alveoli, to confine the initial deposition to alveolar tissue. They followed retention and distribution of the material for 15 months and found that most of the material that was not cleared from the lung remained close to the deposition site. However, they did find some ^{195}Au beneath the bronchial epithelium and also observed it on the luminal surface of the conducting airways more frequently than expected and, remarkably, at times up to 15 months. Filipy *et al.* (1985) studied by autoradiography the distribution of ^{239}Pu in dogs following inhalation of $^{239}PuO_2$. They drew attention to "the high concentrations of plutonium particles observed on bronchial surfaces 400 days after a single exposure."

(E155) Conversely, it seems reasonable to assume that material once in a moving mucous stream keeps going. The very speed of the rapid clearance phase suggests that it is probably not subject to slow clearance. For example, in the experiments by Patrick and Stirling (1977) in which particles were deposited on the distal trachea of rats, about 80% cleared with $t_{1/2}$ of 5 min and about 20% cleared with $t_{1/2}$ of 16 h. There was a very distinct change in the slope of the retention curve between the two phases. The fast phase, $t_{1/2}$ of 5 min, is consistent with mucociliary transport rates of a few mm min^{-1} and a tracheal length of about 3 cm (Gore and Patrick, 1978). If material leaving the deposition site were subject to slow clearance "downstream", then a more gradual transition between the two phases might be expected. Similarly the use of boluses of labelled mucus to measure tracheal mucociliary transport rates (Section E.5.2.3), and the consistency of the results (Table E.8), also suggest that material that is being transported by mucociliary transport generally keeps moving. Furthermore, Churg *et al.* (1990) inferred from measurements of the size distribution and composition of particles in human bronchial mucosa, and differences from those found in the parenchyma, that they resulted from local deposition.

E.5.6. *Conclusions for Modelling*

E.5.6.1. *Reference values and uncertainties*

(E156) *Mucociliary clearance (fast phase) (BB_f and bb_f).* Representative values of the clearance rates from the bronchioles (bb) to bronchi (BB), and from the bronchi to the extrathoracic region (ET) are required. Any single value chosen can only be typical, because the regions are not homogeneous; the clearance time is likely to be different for particles cleared into bb from AI, from that for particles deposited directly within bb; and different for particles cleared into BB from bb from that for particles deposited directly within BB. While there are numerous measurements of the overall pattern of lung clearance, direct measurements of clearance rates are confined to the trachea and main bronchi (Section E.5.2.3). Thus a model of mucociliary clearance must be used to obtain estimated clearance rates for the bronchi and bronchioles separately (Section E.5.2.5). Clearance from the two regions cannot be distinguished experimentally at present.

(E157) Similar mucous velocities were calculated for the first nine airway generations (BB) by the three models for which results are given in Table E.10 (Lee *et al.*, 1979; Yu *et al.*, 1986; Cuddihy and Yeh, 1988). For the example shown in Fig. E.9 (Cuddihy and Yeh, 1988), cumulative deposition in the first nine generations is 22% of total TB deposition, and this fraction is cleared in 170 min. From the airway clearance times calculated by Yu *et al.* (1986; Table E.10), the first nine generations would be cleared in 236 min. On this basis a rounded value of 10 d^{-1} was chosen, which corresponds to a $t_{1/2}$ of about 100 min. Given the many observations that most mucociliary clearance is complete in a few hours, and the agreement between the clearance models, it is considered that this value is relatively well known and proposed that $\Phi_u = 1.5$.

(E158) For the bronchioles, there are greater differences between the model estimates of mucus velocities, especially in the terminal bronchioles, for which Yu *et al.* (1986) predict a rate 40 times faster than Cuddihy and Yeh (1988). Similarly, according to the model of Yu *et al.* the bronchioles are completely cleared in 643 min, and, according to Cuddihy and Yeh's model, in 2400 min. On this basis, a rounded value of 2 d^{-1} was chosen, which corresponds to a $t_{1/2}$ of 500 min. Given the greater uncertainty about clearance from bb compared with BB, it is proposed that $\Phi_u = 2$.

(E159) *Slow clearance.* The main body of evidence from human studies suggesting a significant slow phase of bronchial clearance comes from the bolus experiments of Stahlhofen *et al.* (Section E.5.3.2; Table E.11). These indicate that, for small particles (d_{ae} < 4 μm), the fraction of the deposited material that is subject to slow clearance, f_s, is about 0.5. For larger particles f_s decreases, being about 0.5 at $d_{ae} = 6$ μm, and $< 10\%$ for $d_{ae} > 10$ μm. It remains uncertain as to whether the effect is due to an unexpectedly large fraction of the boluses of small particles reaching alveoli through some unknown mechanism; or to selective deposition of the larger particles in sites within the TB that are cleared effectively; or to a mechanism that depends on the physical size of the particles. However, the information currently available (Section E.5.3.2) suggests that f_s depends on the particle diameter (for the spherical particles tested). For nonspherical particles, it is assumed here that the relevant size parameter is the equivalent volume diameter, d_e, i.e. the diameter of a sphere having the same volume as the particle.

(E160) From Table E.11, the largest particles for which A was about 0.5 were 3.8-μm-d_{ae} FAP. Since for FAP, $\rho = 2.2$ g cm^{-3}, d_e is 2.5 μm. Therefore, it is assumed for modelling purposes that $f_s = 0.5$ for $d_e \leq 2.5$ μm, and then decreases with increasing size. As a simple decreasing function, assume:

$$f_s = 0.5e^{-k(d_e - 2.5)} \qquad \text{for } d_e > 2.5\ \mu\text{m}. \tag{E.9}$$

A was found to be about 0.25 for:

- 5.9-μm-d_{ae} Fe_2O_3, for which $\rho = 3.2$ g cm^{-3}, and therefore $d_e = 3.3$ μm;
- 6.0-μm-d_{ae} FAP, for which $\rho = 2.2$ g cm^{-3}, and therefore $d_e = 4.0$ μm;
- 3.7-μm-d_{ae} PSL, for which $\rho = 1.05$ g cm^{-3}, and therefore $d_e = 3.6$ μm.

Hence assume $f_s = 0.25$ at $d_e = 3.6$ μm, which gives:

$$f_s = 0.5e^{-0.63(d_e - 2.5)} \qquad \text{for } d_e > 2.5\ \mu\text{m}. \tag{E.10}$$

For practical application it is more useful to relate f_s to the aerodynamic diameter d_{ae}, i.e. the diameter of the unit density sphere, 1 g cm^{-3}, that has the same settling velocity as the particle. To do so, account has to be taken of both particle density, ρ, and shape. The drag on an irregular particle, according to Stokes' law, is given by Hinds (1982):

$$F_D = 3\pi\mu u d_e \chi \tag{E.11}$$

where μ = dynamic viscosity of air
u = particle velocity
χ = the dynamic shape factor, typical values of which lie in the range 1–2 (Hinds, 1982).

By equating the terminal settling velocity, u_g, expressed in terms of either the equivalent volume diameter, d_e, or the aerodynamic diameter, d_{ae}, it was shown in Annexe D that

$$d_e = d_{ae}\sqrt{\chi/\rho}. \tag{E.12}$$

Hence, in terms of the particle aerodynamic diameter, d_{ae}, the slow-cleared fraction f_s is given by

$$f_s = 0.5 \text{ for } d_{ae} \leq 2.5\sqrt{\rho/\chi}\ \mu\text{m} \tag{E.13}$$

$$f_s = 0.5e^{-0.63(d_{ae}\sqrt{\chi/\rho} - 2.5)} \quad \text{for } d_{ae} > 2.5\sqrt{\rho/\chi}\ \mu\text{m}. \tag{E.14}$$

In view of the uncertainties associated with the extent of slow clearance, it is assumed for modelling that these values of f_s apply to both BB and bb, and that $\Phi_u = 3$. (See Paragraph 181, Chapter 5 for aerosol default values used for relating f_s to d_{ae}.)

(E161) Stahlhofen (1989) reported the half-time of the slow phase observed in the bolus clearance studies to be 20 ± 10 d. On this basis a rounded value of 0.03 d^{-1} was chosen, which corresponds to a $t_{1/2}$ of 23 d. However, since measurements were only made for a few days after inhalation, this might only be representative of part of the retained material. Generally particle transport rates tend to decrease with time, so an overall rate is more likely to be lower than this value than higher. For the present, however, it is proposed that $\Phi_u = 3$.

(E162) *Retention in the airway wall.* As discussed in Section E.5.4, there is evidence for particle retention in the airway wall in the BB and bb regions from studies on several species, including humans. However, only for particles deposited in the rat trachea has the phenomenon been well quantified: about 0.7% of the material deposited is retained near the basement membrane of the epithelium, from which it clears to lymph nodes with $t_{1/2}$ of 88 d. These results form the basis of the reference values.

(E163) In the model this retention is represented by the sequestration compartments BB_{seq} and bb_{seq}, which receive 0.007 of the deposits in regions BB and bb, respectively. Since these fractions are based only on animal data, and these data were only for the trachea, it is proposed that $\Phi_u = 3$.

(E164) It is assumed that the sequestered particles are cleared to thoracic lymph nodes (LN_{TH}). The rounded value chosen for the clearance rate from BB_{seq} and bb_{seq} to LN_{TH} is 0.01 d^{-1} ($t_{1/2} \approx 70$ d). Since this is based on animal data only, it is proposed that $\Phi_u = 3$.

E.5.6.2. *Modifying factors*

(E165) There have been many studies of the effects of factors on LMC, much of the interest resulting from the possible involvement of impaired clearance in the development of lung diseases. Most of the studies fall into one of three categories: effects of lung disease, effects of pharmaceuticals, and effects of air pollutants. There is no information on factors affecting either the magnitude or duration of slow TB clearance, or of particle retention in the airway wall in humans.

(E166) Several recent reviews have focused on factors affecting LMC (Lippmann and Schlesinger, 1984; Pavia, 1984; Schlesinger, 1985, 1989; Wolff, 1986; Matthys *et al.*, 1987; Camner, 1988; Camner and Mossberg, 1988). Only a brief account is therefore given here, concentrating on estimating values of Φ_m, the number by which the clearance rate should be multiplied when a specific population group is considered. Only measurements on humans are included here. The reviews cited above also provide information from animal studies, for example on the effects of atmospheric pollutants at relatively high levels, or following chronic exposure.

(E167) While many factors have been shown qualitatively to alter LMC, it is difficult to quantify the effects, since LMC cannot be expressed easily by a single number. The simplest relevant parameter is tracheal mucociliary transport rate (TMTR), but as noted above (Section E.5.2.3) different measurement techniques give different values, all tend to measure the maximum, rather than the average rate, and changes in TMTR are not a reliable guide to changes in LMC overall. (See below.) Pavia (1984) considered that the discrepancies between the absolute values of TMTR by different techniques "do not invalidate the use of each for studying the effect of specific factors on mucous clearance rates." However, Yeates *et al.* (1981a) noted that "when higher transport rates were measured the predicted stimulation due to an adrenergic agonist was not observed."

(E168) Transient and permanent factors modifying TMTR from the literature are given in Tables E.14 and E.15, respectively. Here Φ_m is taken to be the ratio of the mucus velocity in the study group to that in the controls.

Table E.14. Transient factors modifying tracheal mucociliary transport rates

Modifying factor	Subjects[a]	Φ_m[b]	Reference
Acetylsalicylic acid (aspirin)	Normal (NS)	0.8	Gerrity *et al.* (1983)
β-adrenergic agent (Alupent)	Normal (NS)	1.7	Spektor *et al.* (1979)
β-adrenergic agent (terbutaline)	COLD	2	Santa Cruz *et al.* (1974)
	CF	2	Wood *et al.* (1975)
β-adrenergic agent (isoproterenol)	Normal (NS)	1.4	Foster *et al.* (1980)
	Asthma	1.4	Foster *et al.* (1982)
Adrenergic (aerosol fenoterol)	Normal (NS)	1.2	Sackner *et al.* (1979)
	Bronchitis	=	
Adrenergic (aerosol Th1165a)	Normal (NS)	2	Yeates *et al.* (1975)
Antigen bronchial provocation	Asthma	0.7	Mezey *et al.* (1978)
General anaesthesia: initially	Normal (NS)	0.4	Lichtiger *et al.* (1975)
after 90 min		0.0	
Lidocaine (2% local)	Normal (NS)	=	Friedman *et al.* (1977)
Histamine	Normal (NS)	1.7	Mussatto *et al.* (1988)
Metaproterenol sulphate	Normal (NS)	1.5	Yeates *et al.* (1979)
Parasympatholytic (atropine)	Normal (NS)	0.2	Yeates *et al.* (1975)
Atropine	Normal (NS) under anaesthetic	0.5	Annis *et al.* (1976)
Theophylline	Normal (NS)	=	Cotromanes *et al.* (1985)
Freon aerosol propellant	Normal (NS)	=	Sackner *et al.* (1979)
	Normal (NS)	=	Yeates *et al.* (1975)
	Bronchitis	=	Sackner *et al.* (1979)
Sodium chloride solution (aerosol)	Normal (NS)	1.2	Wood *et al.* (1977)
	CF	=	
Cough	Normal (NS)	=	Yeates *et al.* (1975)
Respiratory virus (influenza)	Normal (NS)	0.0	Gerrard *et al.* (1985)
Rhinovirus	Normal (NS)	=	Gerrard *et al.* (1985)
Cigarette smoking	Smokers	=	Yeates *et al.* (1975)
	Normal (NS)	=	
Oxygen (90–95%): 3 h	Normal	0.8	Sackner *et al.* (1975)
6 h		0.4	
Posture			
Erect/supine	Normal (NS)	=	Friedman *et al.* (1977)
Erect/supine	Normal	=	Ross *et al.* (1979)
Erect/25° head down	Normal (NS)	=	Wong *et al.* (1977)
Erect/25° head down	CF	+	Wong *et al.* (1977)
Sulphuric acid:	Normal (NS)	=	Leikauf *et al.* (1981, 1984)
1 h at 0.1, 0.3 or 1.0 mg m^{-3}	Asthma	±	Spektor *et al.* (1985)

[a] Disease, where given: CF = cystic fibrosis; COLD = chronic obstructive lung disease.
NS = nonsmokers (where stated).

[b] Where a number is given, this is the factor by which the clearance rate should be multiplied. The symbol = indicates no effect. The symbols + and − indicate unquantified increased and decreased clearance, respectively; ± indicates no significant change in group mean, but greater variation.

Table E.15. Permanent factors modifying tracheal mucociliary transport rates

Modifying factor	Φ_m[a]	Reference
Age (y) (± SD) (63 ± 5/23 ± 3)	0.6	Goodman *et al.* (1978)
Sex (women/men, healthy nonsmokers)	=	Yeates *et al.* (1975)
Asthma	0.5	Mezey *et al.* (1978)
	0.5	Foster *et al.* (1982)
	=	Garrard *et al.* (1989)
Asthma (mild)	=	Spektor *et al.* (1985)
Bronchiectasis	1.7	Baum *et al.* (1990)
Chronic obstructive lung diseases (bronchitis, asthma, emphysema)	0.1	Santa Cruz *et al.* (1974)
Chronic bronchitis	0.2	Goodman *et al.* (1977)
	0.1	Goodman *et al.* (1978)
	0.2	Sackner *et al.* (1979)
Ciliary dyskinesia	0.6	Baum *et al.* (1990)
Cystic fibrosis	0.1	Wood *et al.* (1975)
(5/20 patients)	0.0	Yeates *et al.* (1976)
(5/20)	–	
(10/20)	=	
(9/13)	0.0	Wong *et al.* (1977)
(4/13)	=	
Cigarette smoking	0.3	Goodman *et al.* (1977)
	0.4	Goodman *et al.* (1978)
	0.7	Chopra *et al.* (1979)
	=	Yeates *et al.* (1975)
	0.4	Toomes *et al.* (1981)

[a] Where a number is given, this is the factor by which the clearance rate should be multiplied. The symbol = indicates no effect. The symbols + and – indicate unquantified increased and decreased clearance, respectively.

(E169) However, changes in TMTR are not always reflected in similar changes in mucociliary clearance throughout the TB region, or even in the BB region. For example, Yeates *et al.* (1979) found that metaproterenol increased TMTR but not bronchial clearance. Conversely, Foster *et al.* (1982) found that beta-adrenergic aerosols (isoproterenol or isoetharine) increased mucous velocity in the main bronchus of healthy nonsmokers by much more (145%) than in the trachea (40%). Leikauf *et al.* (1981) found that exposure to H_2SO_4 reduced the bronchial clearance half-time, but not TMTR. Foster *et al.* (1987) found that, while exposure to 0.2 ppm ozone did not affect whole-lung mucociliary clearance (Table E.16A), it increased clearance from airways distal to the main bronchus. These differences in response to inhaled materials (pharmaceuticals or pollutants) may have arisen from differences in the pattern of deposition, and/or of sensitivity.

(E170) Transient and permanent factors modifying LMC from the literature are given in Tables E.16A–C and E.17A–C, respectively. Again the objective was to obtain values of Φ_m representing the ratio of the clearance rate in the study group to that in the controls. However, as noted above, because of the inhomogeneity of the region, and the nonuniform rate of clearance from it, the clearance kinetics cannot generally be described fully by a single number, and a variety of endpoints have been used by different workers (Section E.5.2.1). Most often, lung retention or "bronchial" retention as a fraction of initial deposition is given at one or more times, either for the whole lung, or for each "zone" (Section E.5.2.2). Since estimates are required of factors

Table E.16A. Transient factors modifying lung mucociliary clearance: Pollutants and diseases

Modifying factor	Subjects	Parameter[b]	Φ_m[c]	Reference
Carbon dust	Normal	CT(60)	1.5	Camner *et al.* (1973a)
Cigarette smoke	Smokers	$1/t_{1/2}$	+	Camner *et al.* (1971)
	Smokers	$1/t_{1/2}$	−	Pavia *et al.* (1971)
	Smokers	$1/T_{90}$	2	Albert *et al.* (1975)
	Normal (NS)[a]	$1/T_{90}$	2	
Abstinence from cigarettes				
1 wk	Smokers	$1/t_{1/2}$	−	Camner *et al.* (1971)
1 wk		CT(120)	=	Camner *et al.* (1973b)
3 mo		CT(120)	1.3	
Ozone				
2 h at 0.2 ppm	Normal (NS)	$1/T_{avg}$	=	Foster *et al.* (1987)
2 h at 0.4 ppm	Normal (NS)	$1/T_{avg}$	1.2	
Sulphur dioxide				
2 h at 5 ppm at rest	Normal (NS)	CT(120)	=	Wolff *et al.* (1975)
2 h at 5 ppm with exercise	Normal (NS)	CT(120)	1.1	Newhouse *et al.* (1978)
2.5 h at 5 ppm with exercise	Bronchitis	CT(120)	=	Wolff *et al.* (1984)
+ carbon at 10 mg m^{-3}	Bronchitis	CT(120)	=	
Sulphuric acid				
2 h at 1.0 mg m^{-3} with exercise	Normal (NS)	CT(120)	1.2	Newhouse *et al.* (1978)
1 h at 0.1 mg m^{-3}	Normal (NS)	$1/T_{50}$	1.6	Leikauf *et al.* (1981)
0.3 mg m^{-3}	Normal (NS)	$1/T_{50}$	±	
1.0 mg m^{-3}	Normal (NS)	$1/T_{50}$	0.7	
1 h at 0.1 mg m^{-3}	Normal (NS)	$1/T_{50}$	0.7	Leikauf *et al.* (1984)
0.3 mg m^{-3}	Normal (NS)	$1/T_{50}$	0.8	
1.0 mg m^{-3}	Normal (NS)	$1/T_{50}$	0.6	
1 h at 0.1 mg m^{-3}	Asthma	$1/T_{50}$	=	Spektor *et al.* (1985)
0.3 mg m^{-3}	Asthma	$1/T_{50}$	=	
1.0 mg m^{-3}	Asthma	$1/T_{50}$	0.7	
1 h at 0.1 mg m^{-3}	Normal (NS)	$1/T_{50}$	0.7	Spektor *et al.* (1989)
2 h at 0.1 mg m^{-3}	Normal (NS)	$1/T_{50}$	0.5	
Influenza				
1 wk after onset		CT(120)	0.2	Camner *et al.* (1973c)
2–3 mo later		CT(120)	=	
Mycoplasma pneumoniae				
2 wk after onset		CT(120)	0.3	Jarstrand *et al.* (1974)
3 wk–1 y later		CT(120)	0.7	
1 y later		CT(120)	0.8	Camner *et al.* (1978)
Urban air	Discordant twins	CT(120)	=	Camner and Philipson (1973)

[a] NS = nonsmokers.

[b] CT(τ) = Fraction of *total* lung deposit, cleared at time τ (min).

T_{avg} is the average retention time of particles cleared by bronchial mucociliary clearance. $t_{1/2}$ = clearance half-time (single exponential fit). T_{50} = time for 50% bronchial clearance. T_{90} = time for 90% bronchial clearance. Changes in these suggest effect on small airways since they clear most slowly and hence determine total clearance time.

[c] Where a number is given, this is the factor by which the parameter is multiplied. The symbol = indicates no effect. The symbols + and − indicate unquantified increased and decreased clearance, respectively. ± indicates no significant change in group mean, but greater variation.

Table E.16B. Transient factors modifying lung mucociliary clearance: Pharmacological agents

Modifying factor	Subjects[a]	Parameter[b]	Φ_m[c]	Reference
β-adrenergic agents				
Albuterol	Normal (NS)	CB(60)	2.4	Bennett *et al.* (1993)
		CB(120)	1.5	
		CB(180)	1.2	
Alupent	Normal (NS)	CB(120)	–	Spektor *et al.* (1979)
Epinephrine (aerosol)	Normal (NS)	$1/T_{50}$	4	Foster *et al.* (1976)
		$(1/T_{avg})$	2	
Fenoterol	COLD	CT(60)	1.6	Matthys *et al.* (1985)
	Bronchitis	$1/t_{1/2}$	3	Weich *et al.* (1988)
Isoetharine	Normal (NS)	CB(90)IZ	1.6	Foster *et al.* (1980)
		CB(80)PZ	1.6	
	Smokers	$1/T_{50}$	+	Foster *et al.* (1985)
		$(1/T_{50})$PZ	+	
Isoproterenol (aerosol)	Normal (NS)	$1/T_{50}$	4	Foster *et al.* (1976)
		$(1/T_{avg})$	2	
Isoproterenol (sublingual)	Normal (NS)	$1/T_{50}$	1.7	Foster *et al.* (1976)
		$(1/T_{avg})$	–	
Isoproterenol	Normal (NS)	CB(80)IZ	1.9	Foster *et al.* (1980)
		CB(80)PZ	1.3	
		CT(40)	1.5	Perry and Smaldone (1990)
	Asthma	CB(150)IZ	2.4	Foster *et al.* (1982)
Metaproterenol sulphate	Normal (NS)	CB(120)	–	Yeates *et al.* (1979)
Salbutamol	ICS	CT(0–120)	–	Rossman *et al.* (1980)
Terbutaline	Normal (NS)	CT(60)	1.5	Camner *et al.* (1976)
	Asthma	CT(60)	1.2	Mossberg *et al.* (1976a)
	Bronchitis	CT(60)	1.9	Mossberg *et al.* (1976b)
	Bronchitis	CT(0–360)	–	Pavia *et al.* (1980b)
	Asthma	CB(0–360)	–	Bateman *et al.* (1983a)
Tulobuterol	COLD	CT(60)	1.6	Matthys *et al.* (1985)
Methylxanthines				
Aminophylline (oral)	COLD	CB(360)	1.2	Sutton *et al.* (1981)
Theophylline	Normal	CT(60)	1.4	Matthys and Köhler (1980)
	Infertile men	CT(60)	1.6	
	Normal (NS)	CB(60)	–	Cotromanes *et al.* (1985)
	Normal	CT(60)	1.4	Matthys *et al.* (1985)
Cholinergic				
Bethanechol chloride	Normal (NS)	CT(60)	1.4	Camner *et al.* (1974)
Methacholine bromide	Normal	CT(120)	1.4	Svartengren *et al.* (1989)
	Asthma		–	
Anticholinergic				
Atropine (oral)	Normal (NS)	CT(0–300)	0.0	Foster *et al.* (1976)
Hyoscine	Normal	CT(300)	0.8	Pavia and Thomson (1971)
Ipratropium bromide	Normal	CT(0–360)	–	Francis *et al.* (1977)
	Bronchitis	CT(0–360)	–	Pavia *et al.* (1979, 1980b)
	Bronchitis	CT(60)	2	Matthys *et al.* (1985)
Methylscopolamine nitrate	Normal (NS)	CT(60)	–	Camner *et al.* (1974)
Oxitropium bromide	COLD	CT(0–60)	–	Matthys *et al.* (1985)
	Asthma	CB(0–360)	–	Pavia *et al.* (1989)
	Bronchitis	CB(0–360)	–	

Table E.16B. (*continued*)

Modifying factor	Subjects[a]	Parameter[b]	Φ_m[c]	Reference
Mucolytics/Expectorants				
Ambroxol	Bronchitis	CT(120)	=	Ericsson *et al.* (1987)
Bromhexine (oral)	Bronchitis	CT(360)	1.1	Thomson *et al.* (1974)
Bromhexine (intravenous)	Patients	CT(0–60)	=	Mossberg *et al.* (1981)
Guaiphenesin	Normal	CT(0–360)	=	Thomson *et al.* (1973b)
	Bronchitis	CT(180)	1.7	
	Bronchitis	CT(360)	=	
Iodopropylidene glycerol	Bronchitis	CB(0–360)	=	Pavia *et al.* (1985a)
Sodium chloride (hypertonic)	Bronchitis	CT(360)	1.4	Pavia *et al.* (1978)
Sodium chloride (iso- or hypertonic)	Bronchitis	CT(60)	=	Würtemberger *et al.* (1987)
		CT(60)CZ	1.3	
Sodium 2-mercaptoethane sulphonate	Bronchitis	CT(360)	=	Clarke *et al.* (1979)
Water	Normal (NS)	$1/T_{50}$	1.3	Foster *et al.* (1976)
		$(1/T_{avg})$	1.3	
Corticosteroids				
Prednisolone (oral)	Asthma	CB(180)IZ	1.2	Agnew *et al.* (1984b)
		CB(180)MZ	1.2	
		CB(180)PZ	1.6	
Miscellaneous				
Acetylsalicylic acid (aspirin)	Normal (NS)	CB(280)	0.9	Gerrity *et al.* (1983)
Alcohol	Normal (NS)	CB(0–280)	±	Venizelos *et al.* (1981)
Histamine	Normal (NS)	CB(60)	1.3	Mussatto *et al.* (1988)
	Asthma	CB(60)	1.5	Garrard *et al.* (1989)

[a] Disease, where given: COLD = chronic obstructive lung disease; ICS = immotile cilia syndrome.
NS = nonsmokers (where stated).

[b] CT(τ) = Fraction of *total* lung deposit, cleared at time τ (min).
CB(τ) = Fraction of bronchial mucociliary clearance complete at time τ (min), e.g.
$(1/T_{50})$ PZ = inverse of time for 50% peripheral-zone clearance.
CT(τ)CZ, CB(τ)IZ, CB(τ)MZ, CB(τ)PZ } as above but for central, inner, middle, and peripheral zone, respectively.
T_{avg} is the average retention time of particles cleared by bronchial mucociliary clearance. $t_{1/2}$ = clearance half-time (single exponential fit). T_{50} = time for 50% bronchial clearance. Changes in these suggest effect on small airways since they clear most slowly and hence determine total clearance time.

[c] Where a number is given, this is the factor by which the parameter is multiplied. The symbol = indicates no effect. The symbol + indicates unquantified increased clearance. ± indicates no significant change in group mean, but greater variation.

modifying *clearance*, where results were given in terms of retention they have been converted to clearance:

$$\mathrm{CT}(\tau) = 1 - (\text{total lung retention at time } \tau)$$

$$\mathrm{CB}(\tau) = 1 - (\text{bronchial retention at time } \tau).$$

Similarly the reciprocal of the characteristic retention time (T_{avg}, $t_{1/2}$, or T_{50}) is taken as a measure of clearance rate. In Tables E.16 and E.17, Φ_m is again taken to be the ratio of the clearance parameter in the study group to that in the controls.

Table E.16C. Transient factors modifying lung mucociliary clearance: Physiological

Modifying factor	Subjects[a]	Parameter[b]	Φ_m[c]	Reference
Chest physiotherapy	COLD	CT(90)IZ	5	Bateman *et al.* (1979a)
	COLD	CT(90)MZ	5	
	COLD	CT(90)PZ	4	
Circadian rhythm	Normal	CB(360)	=	Bateman *et al.* (1979b)
Cough	Normal	CT(0–40)	=	Camner *et al.* (1979)
	Patients	CT(0–40)	+	
	Bronchitis	CT(72)	5	Oldenburg *et al.* (1979)
	Bronchitis	CT(72)PZ	4	
	Normal (NS)	CT(60)	=	Puchelle *et al.* (1980)
	Bronchitis	CT(60)	+	
Exercise	Normal (NS)	CT(120)	1.2	Wolff *et al.* (1977)
	Normal	CB(360)	=	Bateman *et al.* (1979b)
	Bronchitis	CT(72)	1.7	Oldenburg *et al.* (1979)
	Bronchitis	CT(72)PZ	1.6	
Bronchoscopy	Patients	CT(0–120)	=	Lundgren *et al.* (1983)
Posture				
Supine	Normal	CB(360)	=	Bateman *et al.* (1979b)
	Bronchiectasis	$t_{1/2}$	+	Ross *et al.* (1979)
15° head down	Bronchitis	CT(72)	=	Oldenburg *et al.* (1979)
	Bronchitis	CT(72)PZ	=	
Sleep	Normal	CB(360)	0.4	Bateman *et al.* (1978a)
		CB(360)	0.2	Bateman *et al.* (1978b)
		CB(360)	0.5	Bateman *et al.* (1979b)
Vibrating pad therapy	Bronchitis	CT(0–300)	=	Pavia *et al.* (1976)

[a] Disease, where given: COLD = chronic obstructive lung disease.
NS = nonsmokers.

[b] CT(τ) = Fraction of *total* lung deposit, cleared at time τ (min).
CB(τ) = Fraction of bronchial mucociliary clearance complete at time τ (min), e.g.
CT(τ)IZ, CT(τ)MZ, CT(τ)PZ as above but for inner, middle, and peripheral zone, respectively.
$t_{1/2}$ = clearance half-time (single exponential fit). Changes in this suggest effect on small airways since they clear most slowly and hence determine total clearance time.

[c] Where a number is given, this is the factor by which the parameter is multiplied. The symbol = indicates no effect. The symbol + indicates unquantified increased clearance.

(E171) A particular problem that arises in evaluating effects on LMC is that some factors (e.g. smoking and certain diseases) will alter the pattern of deposition as well, which in turn affects clearance. Factors resulting in restricted airways may give rise to more central deposition and hence faster overall LMC, even if the clearance is actually impaired. This is more likely to arise when small particles (< 5 μm) are used, which would normally deposit peripherally. It has given rise to apparently conflicting results, especially where different particle sizes have been used, but that has been recognised for some time. Thus the faster LMC observed by Sanchis *et al.* (1973, 1974) and by Thomson *et al.* (1973a; Thomson and Pavia, 1973, 1974) in smokers and subjects with cystic fibrosis and chronic bronchitis was attributed to more central deposition. Coughing may also compensate for impaired mucociliary clearance in subjects with lung disease.

(E172) *Proposed modifying factors for modelling.* Values of Φ_m to be applied to the compartment model for the respiratory tract (Chapter 7, Table 17) are only proposed for

Table E.17A. Permanent factors modifying lung mucociliary clearance: Diseases

Modifying factor	Parameter[a]	Φ_m[b]	Reference
Asbestosis	$1/t_{1/2}$	=	Thomson and Short (1969)
Asthma (mild)	CB(360)	0.7	Bateman *et al.* (1979c)
	$1/T_{50}$	0.6	Spektor *et al.* (1985)
Asthma	CT(120)	=	Mossberg *et al.* (1976a)
	CB(360)	0.8	Bateman *et al.* (1983b)
	CB(180)IZ	0.7	Agnew *et al.* (1984a)
	CB(180)MZ	0.7	
	CB(180)PZ	0.7	
Asthma (discordant twins)	CT(120)	±	Svartengren *et al.* (1989)
Asthma (in remission)	CB(360)	=	Bateman *et al.* (1979c)
	CB(0–360)	–	Pavia *et al.* (1985b)
Bronchial carcinoma	CT(60)	0.3	Matthys *et al.* (1983)
	CT(60)IZ	0.3	
	CT(60)PZ	0.4	
Bronchiectasis	CT(0–360)	±	Lourenço *et al.* (1972)
	$t_{1/2}$	–	Ross *et al.* (1979)
	CT(120)	0.5	Svartengren *et al.* (1986)
Chronic bronchitis	CT(120)	0.5	Camner *et al.* (1973d)
	CT(360)	1.6	Thomson and Pavia (1974)
	CT(60–240)	2	Matthys *et al.* (1974)
	CT(60)	0.4	Bertrand and Puchelle (1977)
	CB(180)	–	Agnew *et al.* (1986a)
Chronic obstructive airway disease	CT(0–240)	–	Toigo *et al.* (1963)
	$1/t_{1/2}$	=	Thomson and Short (1969)
	CT(0–360)IZ	0.0	Short *et al.* (1979)
	CT(0–360)PZ	–	
	CB(120)	0.7	Isawa *et al.* (1984a)
Cystic fibrosis	CT(0–360)	+	Sanchis *et al.* (1973)
	CT(0–360)	+	Thomson *et al.* (1973a)
	CT(120)	–	Kollberg *et al.* (1978)
Diaphragmatic weakness	CB(0–360)	–	Mier *et al.* (1990)
Emphysema	$1/T_{50}$	–	Albert *et al.* (1969)
	$1/T_{90}$	–	
	CT(120)	=	Camner *et al.* (1973d)
	CT(120)	=	Mossberg *et al.* (1978)
Immotile-cilia syndrome	CT(120)	0.3	Rossman *et al.* (1980)
	CT(120)	0.1	Camner *et al.* (1983)
Immunoglobulin deficiency	CT(120)	0.4	Mossberg *et al.* (1982)
Kartagener's syndrome	CT(120)	0.0	Camner *et al.* (1975)
Sarcoidosis	$1/t_{1/2}$	=	Gongora *et al.* (1983)
Sjögren's syndrome	CB(360)	=	Fairfax *et al.* (1981)
Young's syndrome	CT(360)	0.7	Hendry *et al.* (1978)

[a] CT(τ) = Fraction of *total* lung deposit, cleared at time τ (min).
CB(τ) = Fraction of bronchial mucociliary clearance complete at time τ (min), e.g.
CT(τ)IZ, CT(τ)PZ
CB(τ)IZ, CB(τ)MZ, CB(τ)PZ } as above but for inner, middle, and peripheral zone, respectively.
$t_{1/2}$ = clearance half-time (single exponential fit). T_{50} = time for 50% bronchial clearance. T_{90} = time for 90%. Changes in these suggest effect on small airways since they clear most slowly and hence determine total clearance time.

[b] Where a number is given, this is the factor by which the parameter is multiplied. The symbol = indicates no effect. The symbols + and – indicate unquantified increased and decreased clearance, respectively. ± indicates no significant change in group mean, but greater variation.

Table E.17B. Permanent factors modifying lung mucociliary clearance: Miscellaneous

Modifying factor	Parameter[a]	Φ_m[b]	Reference
Age (y) (± SD) (64 ± 4/25 ± 4)	CT(60)	0.6	Puchelle *et al.* (1979)
65/25	CT(60)	0.7	Vastag *et al.* (1985)
Sex (women/men, healthy nonsmokers)	CB(60)	2	Gerrard *et al.* (1986)

[a] CT(τ) = Fraction of *total* lung deposit, cleared at time τ (min).
CB(τ) = Fraction of bronchial mucociliary clearance complete at time τ (min).

[b] This is the factor by which the parameter is multiplied.

Table E.17C. Permanent factors modifying lung mucociliary clearance: Cigarette smoking

Modifying factor	P-Y[a]	Parameter[b]	Φ_m[c]	Reference
Smokers	16	$1/T_{50}$ $1/T_{90}$	0.5 −	Albert *et al.* (1969)
Smokers without restrictive disease	40	CT(120, 300)	=	Pavia *et al.* (1970)
Smokers, asymptomatic	10	CB(120)	0.3	Lourenço *et al.* (1971)
Smokers		CT(0–360)	=	Thomson and Pavia (1973)
Smokers asymptomatic	> 3.7	CT(0–600)	+	Sanchis *et al.* (1974)
Smokers with chronic obstructive airway disease		CT(0–400)	+	
Smokers		CT(0–360)IZ CT(0–360)PZ	= −	Short *et al.* (1979)
Ex-smokers with chronic bronchitis	37	CT(60)	0.5	Puchelle *et al.* (1980)
Smokers, asymptomatic	21	CB(120)	=	Isawa *et al.* (1984b)
Smokers, asymptomatic	17	CB(180)IZ CB(180)PZ	0.6 =	Agnew *et al.* (1986b)
Smokers, asymptomatic	< 7.5	$1/T_{25}$ $1/T_{50}$ $1/T_{75}$	0.6 0.6 0.6	Foster *et al.* (1985)
Ex-smokers without chronic bronchitis	8	CT(60) CT(60)IZ CT(60)PZ	= = =	Vastag *et al.* (1985)
Ex-smokers with chronic bronchitis	35	CT(60) CT(60)IZ CT(60)PZ	0.7 0.5 =	Vastag *et al.* (1985)
Smokers without chronic bronchitis	9	CT(60) CT(60)IZ CT(60)PZ	0.8 0.8 =	Vastag *et al.* (1986)
Smokers with simple chronic bronchitis	21	CT(60) CT(60)IZ CT(60)PZ	0.5 0.6 0.6	Vastag *et al.* (1986)
Smokers with obstructive chronic bronchitis	41	CT(60) CT(60)IZ CT(60)PZ	0.4 0.4 0.5	Vastag *et al.* (1986)
Smokers (smoking-discordant twins)	25 10	CT(60) T_{50}, T_{95}	0.8 =	Camner and Philipson (1972) Bohning *et al.* (1975)

[a] Average cigarette consumption in pack-years (P-Y).

[b] CT(τ)IZ, CT(τ)PZ, CB(τ)IZ, CB(τ)PZ as above but for central, inner, intermediate, and peripheral zone, respectively.

T_{25}, T_{50} = time for 50% bronchial clearance. T_{75}, T_{90}, T_{95}, T_{25} = time for 90%, 95% bronchial clearance. Changes in these suggest effect on small airways since they clear most slowly and hence determine total clearance time.

[c] Where a number is given, this is the factor by which the parameter is multiplied. The symbol = indicates no effect. The symbols + and − indicate unquantified increased and decreased clearance, respectively.

important factors, and only those for which: (1) the effect is large ($\Phi_m > 1.2$ or $\Phi_m < 0.8$); (2) there is reasonably self-consistent human data; and (3) a reasonable assessment can be made on whether the BB and/or bb are affected. Generally it would be expected that a change in TMTR and bronchial clearance at 1 or 2 h after inhalation, or in T_{50}, or in inner zone would reflect alteration to clearance from the BB. A change in LMC at three or more hours after inhalation, or in T_{90}, or in peripheral zone would reflect alteration to clearance from the bb.

(E173) Proposed modifying factors are given in Table E.18. Because of the similarity in clearance mechanism, it is assumed, in the absence of information to the contrary, that a factor that applies to BB applies similarly to bb. It is also assumed that the agents considered do not alter the fraction of material entering the region that is subject to slow clearance or airway wall retention.

(E174) *Individual and physiological factors.* As noted above, there is considerable variation in both TMTR and LMC between individuals, even healthy nonsmokers, while in an individual they are relatively reproducible (Albert *et al.*, 1969). The variation seems to be partly genetic, since Camner *et al.* (1972) found LMC in pairs of monozygotic twins to be very similar.

(1) *Sex*: Yeates *et al.* (1975) found no difference in TMTR between men and women. Gerrard *et al.* (1986) found LMC to be significantly faster in female nonsmokers than in males, but this might well have been due to smaller lung dimensions. (Study

Table E.18. Proposed modifying factors for the compartment model to represent particle transport from the human respiratory tract

	Φ_m[a]	
Modifying factor	Bronchial region (BB) $m_{7,11}$ (BB_1 to ET_2)	Bronchiolar region (bb) $m_{4,7}$ (bb_1 to BB_1)
Age (after 60 y)	0.6	(0.6)[b]
Sleep	0.3	0.3
Asthma	0.7	0.7
Bronchial carcinoma	0.3	0.3
Chronic bronchitis	0.5	(0.5)
Cystic fibrosis	0.5	(0.5)
Immotile-cilia syndrome	0.1	(0.1)
Immunoglobulin deficiency	0.4	(0.4)
Influenza	0.2	(0.2)
Kartagener's syndrome	0.1	(0.1)
Mycoplasma pneumoniae	0.3	(0.3)
Atropine	0.1	0.1
β-adrenergic agent	2	2
Cigarette smoke (acute)	1	2
Cigarette smoking	0.5	1
Sulphuric acid	1	0.7

	Alveolar-interstitial region (AI)		
	a_1	$m_{2,4}$ (AI_2 to bb_1)	$m_{1,4}$ (AI_1 to bb_1)
Cigarette smoking	0.3	0.7	0.7

[a] Amount by which a parameter should be multiplied in order to calculate doses for a specific individual or group for which the modifying factor is recommended.

[b] Values in parentheses are adopted by analogy with BB.

groups frequently contain both men and women on the assumption that they have similar clearance, e.g. Pavia *et al.*, 1971.)

(2) *Age*: If the explanation above for faster LMC in women is correct, then it should also be faster in children. However, there are no measurements of TMTR or LMC in healthy children. (One study reported LMC in children without lung disease, but without equivalent measurements in adults [Hühnerbein *et al.*, 1984].) Both parameters have been found to decrease with age over about 60 y. Vastag *et al.* (1985) found in healthy nonsmokers a decrease in mucociliary clearance with age over 20 y:

$$\mathrm{CT}(60) = 0.53 - 0.0037 \times \text{age in y } (20 < \text{age} < 75). \qquad \text{(E.15)}$$

It is therefore proposed that for age over 60 y, $\Phi_m = 0.6$ for both bb and BB.

(3) *Sleep*: LMC is reduced. The factors of 0.2 and 0.4 from Bateman *et al.* (1978a,b) are based on comparison (sleep/awake) at equivalent times after inhalation. The factor of 0.5 from Bateman *et al.* (1979b) includes clearance between inhalation and the onset of sleep. The latter, however, showed that the effect was due to sleep itself, rather than posture or circadian rhythm. It is proposed that $\Phi_m = 0.3$ for both bb and BB.

(E175) *Pathological factors.*

(1) *Asthma*: TMTR and LMC for inner, intermediate, and peripheral zones at 3 h are all markedly reduced. It is proposed that $\Phi_m = 0.7$ for both bb and BB.
(2) *Bronchial carcinoma*: LMC in both inner and peripheral zones is reduced. It is proposed that $\Phi_m = 0.3$ for both BB and bb.
(3) *Chronic bronchitis*: TMTR and (in more recent studies) LMC up to 3 h are markedly reduced. It is proposed that $\Phi_m = 0.5$ for BB.
(4) *Cystic fibrosis*: Several authors have found TMTR to be zero in some patients and within the normal range for others. A decrease in LMC up to 3 h was also reported. It is proposed that $\Phi_m = 0.5$ for BB.
(5) *Immotile-cilia syndrome*: LMC at 2 h is reduced. It is proposed that $\Phi_m = 0.1$ for BB.
(6) *Immunoglobulin deficiency*: LMC at 2 h is reduced. It is proposed that $\Phi_m = 0.4$ for BB.
(7) *Influenza*: LMC at 2 h is reduced, but returns to normal after a few weeks. It is proposed that $\Phi_m = 0.2$ for BB.
(8) *Kartagener's syndrome*: LMC at 2 h is reduced. It is proposed that $\Phi_m = 0.1$ for BB.
(9) *Mycoplasma pneumonia*: LMC at 2 h is reduced. It may remain impaired up to a year later. It is proposed that during the illness $\Phi_m = 0.3$ for BB.

(E176) *Pharmacological agents.* Perry and Smaldone (1990) point out some of the additional difficulties in evaluating and comparing the effects of pharmaceuticals on mucociliary clearance. In particular if the agent is a bronchodilator and is taken before the test aerosol, it may alter the pattern of deposition and hence clearance. Pharmaceuticals are generally taken in combination, and their effect may depend on interactions, and the health status of the subject. Foster *et al.* (1976) found that, although oral atropine inhibited LMC, administration of isoproterenol after atropine resulted in the same increase in LMC as isoproterenol alone. Matthys *et al.* (1985) reported an additive effect on LMC between theophylline and beta-adrenergic agents, but not between anticholinergic agents and beta-adrenergic agents.

(1) *Beta-adrenergic agents (e.g. isoproterenol)*: TMTR and LMC increased in both large and small airways. (Perry and Smaldone [1990] used isoproterenol as a positive control.) It is proposed that $\Phi_m = 2$ for both bb and BB.

(2) *Atropine*: TMTR and LMC almost completely stopped. It is proposed that $\Phi_m = 0.1$ for both bb and BB.

(E177) *Pollutants.* The effects of inhaled irritants such as cigarette smoke and sulphuric acid can be complex. Acute exposures may cause a transient increase or decrease according to the concentration, and may affect clearance in some airways more than others, depending on the size distribution. Chronic exposure can result in permanent impairment of clearance, and also changes to airway dimensions and lung function, which in turn alter the pattern of deposition and subsequent clearance of the test aerosol.

(1) *Cigarette Smoke*: Conflicting results have been obtained for both acute and chronic effects of cigarette smoking. Pavia *et al.* (1971) reported a slowing of LMC with smoking a few cigarettes; Yeates *et al.* (1975) found no effect on TMTR, while Camner *et al.* (1971) and Albert *et al.* (1975) reported increased clearance. Camner *et al.* (1971) also found a reduction in clearance in smokers who abstained for a few days, supporting the view that smoke stimulated clearance. Albert *et al.* (1975) noted that the effect was on the small airways, which might account for the different findings. Mortensen *et al.* (1989) observed by bronchoscintigraphy that chain-smoking by healthy smokers increased mucociliary clearance in lobar bronchi, but did not affect clearance in the main bronchi or trachea. It is therefore proposed that $\Phi_m = 2$ for bb but not for BB.

(2) *Cigarette smoking*: Comparing chronic smokers and nonsmokers, Goodman *et al.* (1978), Chopra *et al.* (1979), and Toomes *et al.* (1981) all found a marked reduction in TMTR, but Yeates *et al.* (1975) did not. Some studies found little or no difference in LMC between smokers and nonsmokers (Thomson and Pavia, 1973; Isawa *et al.*, 1984b), but others found impaired clearance in smokers (Albert *et al.*, 1969; Lourenço *et al.*, 1971). The faster clearance observed by Sanchis *et al.* (1974) in smokers was probably due to more central deposition. Camner and Philipson (1972) found LMC to be slower in five out of ten smokers compared with nonsmoking monozygotic twin brothers, and similar in the other pairs. Bohning *et al.* (1975) found similar overall LMC in four such pairs, but noted indications that upper bronchial clearance was impaired in the smokers. Camner *et al.* (1973b) also found an improvement in clearance by smokers after stopping smoking for 3 months. Lourenço *et al.* (1971), using a gamma camera, observed that in nonsmokers clearance started immediately and rapidly in the central airways and progressed smoothly, while in smokers it was delayed, especially in the larger airways. Agnew *et al.* (1986b) found that, while total lung clearance was not significantly different, clearance from the inner zone was slower in smokers. Vastag *et al.* (1985, 1986) found that LMC (total and inner zone) decreased with cigarette consumption (measured in pack-years) in ex-smokers and current smokers, with or without chronic bronchitis, but some individuals were affected much more than others. It is, therefore, proposed that $\Phi_m = 0.5$ for BB but not bb.

(3) *Sulphuric acid*: Leikauf *et al.* (1981, 1984) determined the effect of inhaled sulphuric acid (1-h exposure at 0.1 mg m^{-3}, 0.3 mg m^{-3}, or 1 mg m^{-3}) on both TMTR and LMC using 7.6-μm and 4.2-μm-AMAD test aerosols. The sulphuric

acid and the 4.2-μm aerosol deposited predominantly in distal airways, while the 7.6-μm aerosol deposited predominantly in proximal airways. In neither case was TMTR altered. For the 4.2-μm aerosol there was depressed LMC at all levels: but for the 7.6-μm aerosol it was depressed at the highest level and increased at the lowest. The conclusion was that sulphuric acid stimulates mucociliary clearance at low levels and reduces it at higher levels. At 0.1 mg m^{-3}, deposition is enough to increase clearance in large airways and reduce it in small airways, while at 1 mg m^{-3}, it is enough to decrease clearance in all. It is, therefore, proposed that $\Phi_m = 0.7$ for bb but not BB.

E.6. The Alveolar-Interstitial Region

E.6.1. *Retention*

E.6.1.1. *Early phase (up to 7 d)*

(E178) In the current ICRP Lung Model (ICRP, 1979) it is assumed that 40% of the initial alveolar deposit (IAD) of a relatively insoluble material is cleared with $t_{1/2}$ of 1 d, and the rest with $t_{1/2}$ of 500 d. (The term pulmonary used in *ICRP Publication 30* is here treated as synonymous with alveolar.) However, recent human inhalation studies do not support the assumption of a significant rapid phase of particle transport from the AI region. Following deposition of small (d_{ae} 1-μm to 2-μm) particles, which would be expected to deposit mainly in the AI region, lung retention at 24 h often considerably exceeds 60% of the ILD. Lippmann (1970b) noted that if there is a rapid phase of pulmonary clearance, it accounts for much less than 20% IAD. Foord *et al.* (1977) similarly noted that their results were inconsistent with rapid clearance of 40% IAD. Stahlhofen *et al.* (1980) administered particles in a manner designed to maximise AI deposition and minimise TB deposition: 1-μm-d_{ae} particles inhaled as a bolus at the beginning of a breath. They found that 1% ILD cleared rapidly (an effect attributed to dissolution), while the rest followed a single exponential with $t_{1/2}$ of 85 d. Bailey *et al.* (1982) found 8% and 40% ILD, respectively, of 2-μm-d_{ae} and 6-μm-d_{ae} particles cleared within 6 d, but these fractions were less than the corresponding predicted TB deposits, and therefore no rapid phase of pulmonary clearance was observed.

(E179) The possibility that a significant fraction of material deposited in TB is not cleared in the rapid phase cannot be excluded (Section E.5.3). Generally, however, it would be expected that most of the material cleared in the slow phase would be associated with AI, because of greater initial deposition in AI than in TB, and because much of the material deposited in TB is cleared in the rapid phase. For simplicity, therefore, in the following discussion, material not cleared in the rapid phase is described as being in AI. Similarly, at long times after intake a significant fraction of the material described as being in the lungs may be in lung-associated lymphatic tissue (Section E.7).

E.6.1.2. *Intermediate phase (up to 300 d)*

(E180) Experimental studies of particle retention in the human lung lasting at least 50 d are summarised in Tables E.19 and E.20. Studies appear in Table E.20 if smokers and nonsmokers were identified, and if there were at least two subjects in each experimental group. Several recent studies extended to 300 d, but very few measurements have been made beyond 500 d (Bohning *et al.*, 1982; Bailey *et al.*, 1985a; Pearman *et al.*, 1989). A current study (Philipson *et al.*, 1992) is intended to follow

Table E.19. Human lung retention studies

Material	Size[a] (μm)	σ_g	Label	Subject numbers and habit[b]	Duration of measurements (d)	Retention half-time (d)	Reference
Polystyrene	5	1.1	^{51}Cr	7	20–160	150–300	Booker *et al.* (1967)
Polystyrene	5	1.1	^{51}Cr, ^{103}Pd	3	80	140–340	Newton *et al.* (1978)
Iron oxide	MMD 1.4–2.3	~ 1.7	^{59}Fe	4	Up to 100	~ 70	Albert and Arnett (1955); Albert *et al.* (1967)
Fe_2O_3	3.6	1.2	^{51}Cr	1 S	56	70	Albert *et al.* (1967)
Fe_2O_3	0.8	1.7	^{51}Cr	2	~ 60	62	Morrow *et al.* (1967a,b)
Fe_2O_3	CMD 0.1	1.2	^{51}Cr	2	60	270 ± 20	Waite and Ramsden (1971a)
Fe_2O_3	CMD 0.1		^{237}Pu	1	70	118	Waite and Ramsden (1971b)
	CMD 0.3			1		160	
Fe_2O_3	95% < 2.5		^{59}Fe	2	60	100–280	Le Bouffant *et al.* (1972); Le Bouffant and Henin (1974)
Fe_2O_3	90% < 1		^{59}Fe	2 NS	240	183, 560[c]	Le Bouffant and Henin (1974)
				1 S		117[c]	
MnO_2	MMD 0.9	1.75	^{54}Mn	6	Up to 120	62–68	Morrow *et al.* (1967a,b)

[a] MMD = Mass median diameter; CMD = Count median diameter.

[b] NS = nonsmokers; S = smokers (where stated).

[c] Between 10 and 52 d.

Table E.20. Human lung retention studies; retention evaluated at different times after exposure

Material	Diameter[a] (μm)	σ_g	Label	Habit[b]	Retention[c] (% initial alveolar deposit) $\bar{x} \pm$ SD (n) or x_1, x_2 (for $n < 3$)			Reference
					50 d	100 d	300 d	
Polystyrene	0.5		^{51}Cr	NS	86 ± 12 (3)			Jammet *et al.* (1978)
				S	93 ± 4 (6)			
Polystyrene	3.5	~ 1.6	^{85}Sr	NS	73 ± 6 (11)	61 ± 6 (11)	37 ± 5 (6)	Bohning *et al.* (1982)
				S	87 ± 11 (8)	83 ± 10 (7)	64 ± 19 (4)	
FAP	1	1.1	^{85}Sr	NS	85 ± 6 (12)	75 ± 8 (12)	50 ± 10 (12)	Bailey *et al.* (1985a)
	4	1.1	^{88}Y	NS	84 ± 6 (12)	74 ± 9 (12)	58 ± 11 (12)	
Teflon H-L[d]	4	1.1	^{51}Cr	NS	68 ± 1 (3)	58 ± 5 (3)	39 ± 18 (3)	Philipson *et al.* (1985)
L-L	4	1.1	^{51}Cr	NS	72 ± 6 (3)	65 ± 6 (3)	53 ± 16 (3)	
Fe_3O_4	MMAD 2.8	1.4	MPG[e]	NS	56 ± 6 (9)	34 ± 7 (9)	11 ± 4 (9)	Cohen *et al.* (1979a)
				S	76 ± 4 (3)	62 ± 5 (3)	49 ± 7 (3)	
Fe_3O_4	MMAD 1.1	1.4	MPG[e]	NS	59 ± 5 (13)	34 ± 6 (13)	16 ± 10 (6)	Freedman *et al.* (1988)
				S	73 ± 7 (12)	52 ± 9 (12)	30 ± 13 (7)	
				CF	69 ± 7 (8)	47 ± 9 (8)		
				COPD	64 ± 13 (4)	42 ± 16 (4)		
Co_3O_4	MGD 0.8	1.1	^{57}Co	NS	78, 69	71, 49	37, 22	Foster *et al.* (1989)
	MGD 1.7	1.1		NS	85, 77	81, 66	43, 33	
	Combined 0.8 and 1.7				77 ± 6 (4)	67 ± 13 (4)	34 ± 9 (4)	Pearman *et al.* (1989)
Fe_3O_4	d_{ae} 2.8	1.1	MPG[e]	NS	76 ± 8 (5)	58 ± 13 (5)	22 ± 17 (5)	Möller (1991); Stahlhofen and Möller (1991)

[a] MGD = Mean geometric diameter; MMAD = Mass median aerodynamic diameter.

[b] NS = nonsmokers; S = smokers; CF = patients with cystic fibrosis; COPD = patients with chronic obstructive pulmonary disease.

[c] Lung retention, excluding rapid phase.

[d] H-L = 'high-leaching'; L-L = 'low-leaching' (different heat treatment).

[e] Magnetopneumography, i.e. measurement of the remanent magnetic field produced by aligned particles after a strong magnetic field has been applied to the chest.

retention of ^{195}Au-labelled Teflon particles for about 3 y following inhalation by ten male subjects. Measurements over the first year have been consistent with the results of studies in Table E.20.

(E181) After the initial rapid clearance phase, lung retention of relatively insoluble particles measured over a period of several weeks can be adequately represented by a single exponential function (Table E.19). The associated half-time can conveniently be used to compare clearance in different groups (Gongora *et al.*, 1983) or to compare clearance of different materials. Generally longer retention half-times have been found for polystyrene and Teflon particles than for iron or manganese oxides, suggesting that dissolution of the oxides is faster (Table E.19) (Stahlhofen *et al.*, 1981).

(E182) It is, however, generally found that the retention half-time increases as the duration of measurements increases. When retention is followed for several months, a two-component exponential function is usually required, the components having half-lives of about 30 d (intermediate phase) and several hundred days (slow phase). Similar functions have been fitted to lung retention following accidental intakes (Watts, 1975; Section E.6.1.3). The proportion in the intermediate phase varies considerably: typically in experimental studies it is about 20–30% (Bohning *et al.*, 1982; Bailey *et al.*, 1985a; Philipson *et al.*, 1985). In some subjects, especially smokers, it is negligible, while for some occupational exposures it is the major component (Ramsden, 1976). Even when subjects have inhaled similar particles under controlled conditions, there is great variation in both the amplitudes and coefficients of the fitted functions. Some scatter is due to intersubject variation, but it is a feature of multiexponential curve fitting that, unless marked changes in slope occur, it may well be possible to vary the value of each parameter over a wide range, and by adjusting the other parameters appropriately make little change to the shape of the curve over a fixed interval. Thus while such a function provides a concise and accurate description of retention, the individual parameters may have little significance, and cannot be used directly to compare the results from different studies. In Table E.20, therefore, retention as a fraction of the IAD has been evaluated at three specific times from the functions reported.

(E183) Retention was very similar in studies in which nonsmokers inhaled FAP, Teflon, or polystyrene particles, which is consistent with the view that particle transport is independent of the material (Section E.3.3.2). Retention of Co_3O_4 was also very similar up to 100 d, but at 300 d was substantially lower, presumably reflecting the progressively increasing dissolution rate of Co_3O_4 (Bailey *et al.*, 1989). Clearance of Fe_3O_4 was faster throughout, probably because of more rapid dissolution in the lungs.

E.6.1.3. *Late Phase (> 300 d)*

(E184) Particle retention in the human respiratory tract has been reasonably well characterised in controlled experimental studies up to 300 d after intake, at least in healthy adult males. However, at this time about 50% of the estimated IAD remains, and there are insufficient data at later times to determine the subsequent pattern of retention. Measurements of thoracic retention of materials in the human respiratory tract following accidental intakes are therefore reviewed here. These fall into two main categories: *in vivo* measurements, usually of radioactive materials; and *postmortem* measurements of the amounts of material in the lungs, which in some cases have been compared with the estimated intakes.

(E185) There are several well-known general problems associated with interpreting measurements of thoracic retention of activity in terms of lung retention and clearance.

There may be considerable uncertainties about the time course of intake and the physicochemical nature of the material. The fact that an intake has occurred may not be recognised, and days or even years elapse before measurements begin. There may have been other identified or unidentified intakes before measurements started, and also afterwards if the subject is not removed from work with the material. There have, however, also been cases when exposure has occurred as a result of a known incident involving a single, well-defined material. Some extensive sets of measurements have been made during retirement after chronic exposure (e.g. Kalliomäki *et al.*, 1978, 1983; Crawford-Brown and Wilson, 1984), but to interpret them in terms of retention following an acute intake, assumptions must be made about the form of the retention curve.

(E186) In general the measurements were made for the purpose of assessing the workers' exposure and may therefore not be as intensive as desirable for modelling purposes. However, in other cases (notably exposures to ^{60}Co) measurements were continued when the intakes were clearly far below levels of concern, because the operational health physicists recognised the value of obtaining human data. There will be errors in the measurement process itself: statistical counting errors where the amount retained is close to the limit of detection; and, for low-energy photon emitters, notably plutonium isotopes, errors due to differences between the true distribution of the radionuclide *in vivo* and that assumed in the calibration, absorption in overlying tissue, etc. (Swinth *et al.*, 1988).

(E187) Generally, *in vivo* measurements of activity in the thorax are unable to distinguish between material in the lungs themselves, or in other thoracic organs, although attempts to do so have been made recently (Northcutt *et al.*, 1988; Pomroy and Noel, 1988). In particular, there has been considerable discussion about whether the very long-term thoracic retention of uranium observed by, for example, West *et al.* (1979) represents material retained in the lungs, lymph nodes, or skeleton (Scott and West, 1975; Keane and Polednak, 1983; Crawford-Brown and Wilson, 1984).

(E188) In a typical incident, only one or two people are exposed to the extent that requires or enables long-term follow-up measurements to be made. This adds to the difficulty in generalising the results, since experimental studies have shown considerable intersubject variation in retention, even following closely controlled administrations of the same material (Table E.20).

(E189) While many of the factors above lead to an overestimation of lung retention, all materials will dissolve to some extent in the lung, and it is rarely possible to take account of this to estimate lung retention in the absence of dissolution. This is a particular problem following intakes of uranium compounds, because of the extreme range of *in vivo* dissolution rates they exhibit.

(E190) Despite these problems, it is necessary to take account of such information because of the lack of human experimental data and the recognised interspecies differences in the rates of particle transport (Fig. E.6). Furthermore, a considerable number of such follow-up studies have been made, involving a range of materials.

(E191) In vivo *measurements of thoracic retention in humans following accidental inhalation.* Information on thoracic retention in humans following accidental inhalation, based on *in vivo* measurements of radionuclides, is summarised in Table E.21. Since retention up to 300 d after intake has been characterised in controlled experiments, only studies of accidental intakes in which retention was followed for at least 400 d have been included. Nevertheless this includes measurements on nearly 100 persons,

Table E.21. Human thoracic retention following accidental inhalation: Measurements of at least 400-d duration

Radionuclide/ material	Number of subjects (code)[a]	Measurement period (d)[b]		Retention half-times (d)		Retention	Comment	Reference
		t_0	t_t	$t_{1/2,1}$ (%)	$t_{1/2,2}$	$\frac{R(t_t)}{R(300)}$		
^{60}Co/metal or oxide							Intakes in previous:	Newton and Rundo (1971)
	1 (B)		3,300	—	1,800	0.32	2 y	
	1 (M)		4,015	—	6,200	0.66	3 wk	
	1 (S)		1,460	—	3,000	0.78	12 wk	
^{60}Co/oxide	1	0	1,400	—	900 at 3 y	0.26	Intake in previous 6 mo; 10% IAD left at 1,200 d	Gupton and Brown (1972)
^{60}Co	1	6	1,003	—	1,522	0.73	No further exposure	Raghavendran *et al.* (1978)
	1	103	1,250	—	17,613	0.96		
	1	7	985	68 (30)	854	0.57		
	1	6	411	—	539	0.87		
^{60}Co/oxide	2	0	1,500	—		0.63	Acute intakes[c]	Ramsden (1984)
^{144}Ce/nitrate?	1	1	420	—	570	0.86		Tyler and Lister (1973)
^{182}Ta/oxide	1		430	—	1,400	0.94	1% ILD retained at 7 d	Newton (1977)
U_3O_8 (enriched)	1	60	717	—	380	0.58[d]	Faecal > urinary excretion	Saxby *et al.* (1964)
^{137}Cs U_3O_8	1	6	864	—	113	0.03	Uranium not measured directly. Presumably, Cs leached from material	Rundo (1965)
^{95}Zr-Nb (enriched,					250	0.21		
^{103,106}Ru irradiated)					> 230	> 0.18		
^{141,144}Ce					> 2,800	> 0.87		
U_3O_x (enriched)[e]	1 (K1)	0	500	—	245	0.57	Faecal ≈ urinary excretion	Schultz (1966)
U_3O_x (enriched)/fume	1	0	1,250	70[e] (88)	390	0.11	Identified incident. Subject removed from U work	Scott and West (1967)
U/alloy (natural)	1	120	790	~ 80	1,800[f]	0.83	Few measurements	Ronen (1969)
U_3O_x?	1 (Y3)	0?	720	—	380	0.46	[g]	West and Scott (1966)

U_3O_8?	1 (Y1)	0?	1,660	—	550	0.18	[g]	West and Scott (1969)
U_3O_8?	1 (Y2)	0?	5,000	725 (75)	∞	0.32	[g]	West *et al.* (1979)
	1 (Y4)			644 (60)	∞	0.48		
	1 (Y5)			382 (60)	∞	0.53		
UO_2	1		500	—	511	—	Removed from chronic exposure	Pomroy and Noel (1981)
	1		480	—	1,655	—		
	1		580	—	691	—		
U/compounds	22	up to 4,700		120 (95)	2,400	0.06	Pooled data. Subjects retired after chronic exposure	Crawford-Brown and Wilson (1984)
U/"product"	1	6	471	—	310	0.68	Few measurements	Kvasnicka (1987)
UO_2	9	0?	5,000	274 (52)	∞	0.66	Max. of group	Price (1989)
				376 (74)	∞	0.38	Mean of group	
				242 (89)	∞	0.23	Min. of group	
^{238}Pu/Pu oxide	1	7	869	—	800	0.61	Faecal excretion ~ 8% of lung clearance	Newton *et al.* (1983)
^{239}Pu/Pu oxide	1 (Fig. 2a)	0	450	32 (81)	580	0.84	Possible prior intakes, Pu work continued	Ramsden (1976)
	1 (Fig. 2b)	0	1,650	17 (66)	650	0.23		
	1 (Fig. 2c)	0	1,000	25 (38)	230	0.12		
^{241}Am/Pu oxide	1 (A)	0	5,000	300 (85)[h]	∞	0.26	[i]	Ramsden *et al.* (1978); Ramsden (1984)
^{241}Am/Pu-U oxide	1	0	1,000	—	3,000	0.84	[j]	Foster (1991)
^{241}Am/Pu oxide	1 (HAN1)	0	3,700	—	6,000	0.68	[k]	Bihl *et al.* (1988a,b,c)
	1 (HAN2)	900	3,200	—	> 20,000	> 0.90	[l]	
	1 (HAN3)	?	?	—	> 10,000			
	1 (HAN4)	?	?	—	13,000			
	1 (HAN5)	?	?	—	6,000			
	1 (HAN6)	?	?	50 (20)	5,000			
	1 (HAN7)	?	?	—	30,000			
	1 (HAN8)	?	?	—	> 10,000			
	1 (HAN9)	?	?	—	> 20,000			
	1 (HAN10)	?	?	—	> 10,000			
^{241}Am/oxide	2[m]	150	1,600	—	900	0.37	Lung clearance almost entirely to blood	Fry (1976)

Continued overleaf

Table E.21. (*continued*)

Radionuclide/ material	Number of subjects (code)[a]	Measurement period (d)[b]		Retention half-times (d)		Retention $\frac{R(t_f)}{R(300)}$	Comment	Reference
		t_0	t_f	$t_{1/2,1}$ (%)	$t_{1/2,2}$			
^{241}Am/oxide	1[n] 1	2,200 2,200	5,100 5,100	— —	5,000 440		Adult Boy, 4 y old at intake	Cohen *et al.* (1979b)
^{241}Am/oxide?	1	700	4,400	—	9,000 (at 8–12 y)	0.50[o]	Lung ~ 10% of whole body	Toohey and Essling (1980)
^{241}Am/oxide	1	7	869	11 (78)	920	0.65	No evidence for "intermediate" (~ 30 d) component	Newton *et al.* (1983)

[a] Case identification code.

[b] Time after exposure measurements were made.

[c] A case of multiple low-level intakes of ^{60}Co over 10 y was also studied. At 3 y into retirement, retention was about twice that predicted by the ICRP 30 model.

[d] Based on 23.8 nCi at 304 d and 13.6 nCi at 717 d ($t_{1/2}$ = 380 d based on measurements up to 594 d only).

[e] Excluding first phase. Three-component fit was $0.40 \exp(-0.69t/7) + 0.53 \exp(-0.69t/70) + 0.07 \exp(-0.69t/390)$. Excretion was mainly urinary (~ 80%).

[f] Based on estimated lung contents of 61 mg at 280 d and 50 mg at 790 d.

[g] Of 49 workers restricted from uranium work because thorax or urine activity exceeded the Plant Action Value, 36 returned to 'nominal' values within 20 d; 8 with a biological half-time of about 100 d; 5 showed long-term retention.

[h] Excluding first phase ($t_{1/2}$ = 30 d); see Note b.

[i] Well-documented case of multiple exposures to high-fired plutonium oxide over a period of 2,300 d, with total 'retained lung content' of 2.7 kBq (73 nCi), described by $R(t) = 0.67 \exp(-0.69t/30) + 0.33 \exp(-0.69t/300)$ (Ramsden *et al.*, 1978). Measurements made during retirement, up to 5,000 d, showed no further clearance of remaining activity, which was about 0.15 kBq (4 nCi), or ~ 5% of the initial deposit (Ramsden, 1984). It has therefore been assumed here that thoracic retention is described by $R(t) = 0.67 \exp(-0.69t/30) + 0.28 \exp(-0.69t/300) + 0.05$.

[j] Half-time and retention based on the smoothed activity balance given in Table 2 of Foster (1991).

[k] Known incident involving high-fired oxide (Spitz and Robinson, 1981).

[l] No detectable plutonium in urine at any time.

[m] Five other cases in same incident had $t_{1/2}$ 500 to 2,000 d, but only a few measurements were made on each.

[n] Four other cases in same incident with lower level, and not followed long-term.

[o] Assuming $t_{1/2}$ between 300 d and 2 y was the same as between 2 y and 6 y, i.e. 3,200 d.

and about 40 of these have been followed for more than 10 y. Since a major objective in compiling these data was to obtain guidance on the likely fate of the 50% IAD that remains at 300 d after intake, thoracic retention $R(t_f)$ at t_f, the time of the final measurement, is expressed as a fraction of $R(300)$, retention at 300 d. This also facilitates including information in cases where the first measurement was made some time after intake, and avoids the effects of differences in early clearance due to factors such as aerosol size, breathing patterns, and soluble components.

(E192) In Fig. E.10 thoracic retention $R(t_f)$ at t_f, the time of the final measurement, as a fraction of $R(300)$, retention at 300 d, is plotted against t_f. Evidence for very long-term retention of a significant fraction (> 10%) of the material remaining in the thorax at 300 d has been seen for each of the elements (cobalt, uranium, plutonium, and americium) for which measurements have extended to 10 y after acute intake of the oxide.

(E193) It is recognised that this procedure may have resulted in selecting cases showing unusually long retention. In a group exposed under similar conditions, those

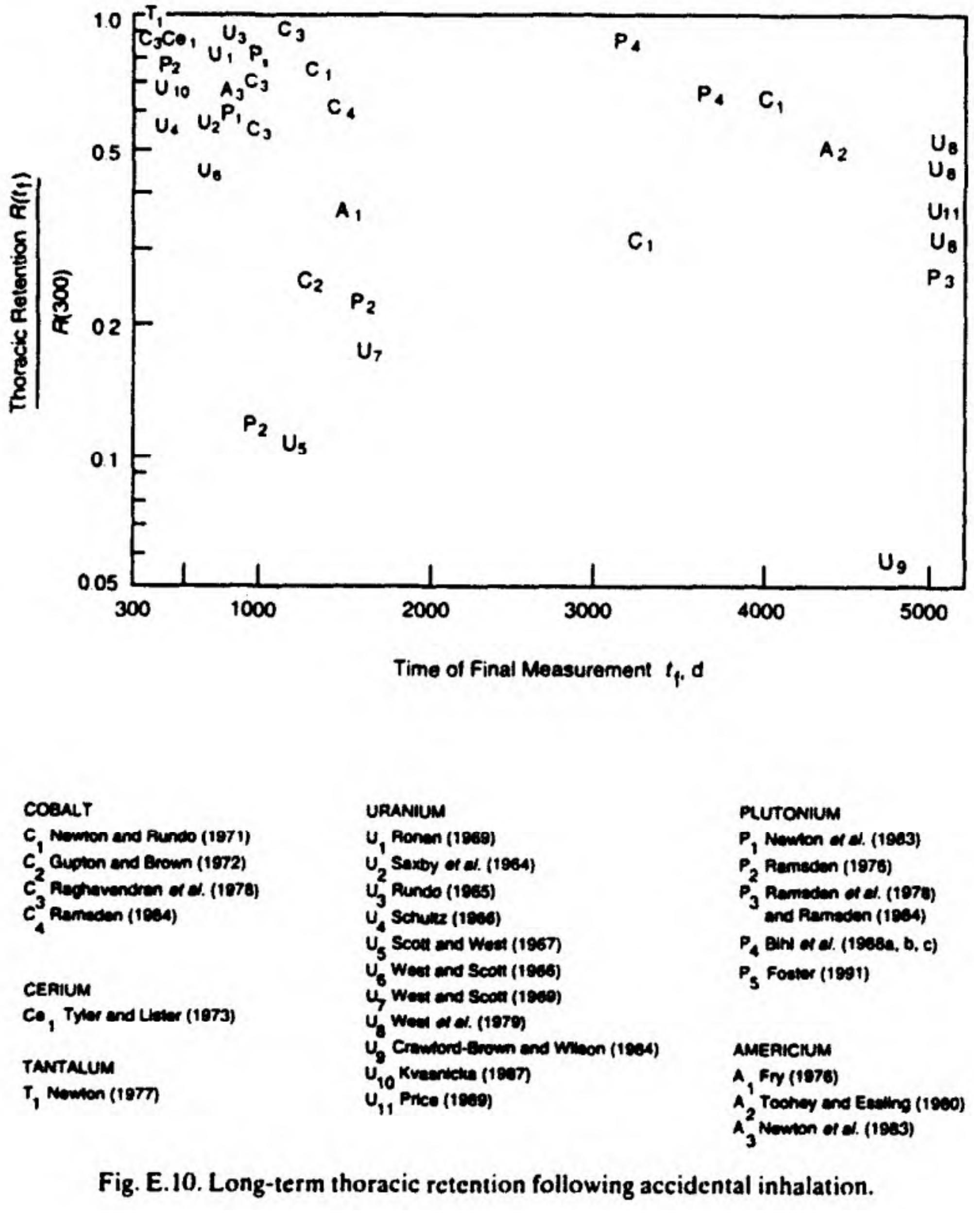

Fig. E.10. Long-term thoracic retention following accidental inhalation.

subjects with relatively slow lung clearance characteristics will remain measurable for longer, and their longer lung retention and hence potential dose will justify more intensive follow-up. Similarly, cases showing unusually long retention might well be considered more worthy of reporting than those showing expected or faster clearance. In addition, since many of the exposures took place in the 1950s and 1960s, it is likely that some of the subjects were cigarette smokers, and consequently may have slower lung clearance than nonsmokers (Section E.6.3.2).

(E194) Further evidence for a long-term component of thoracic retention of uranium comes from measurements on workers whose exposure has stopped through change of work or retirement (e.g. Pomroy and Noel, 1981; Crawford-Brown and Wilson, 1984). However, when the exposure period is long, assumptions must be made to infer the retention pattern following an acute intake, for example, to allow for clearance during the exposure period. Crawford-Brown and Wilson (1984) analysed thoracic retention of uranium in 22 subjects, who had a mean exposure to uranium compounds of 21 y. Measurements were made from retirement for up to 12.5 y later. A least-squares fit to the pooled data gave a half-time of 2400 d. Assuming constant intake over 21 y, and two-component retention with half-times of 120 d and 2400 d, they estimated that about 5% was associated with the latter.

(E195) *Comparison of intakes with lung content* In vivo. Kalliomäki *et al.* (1978, 1983, 1985) used magnetopneumography to measure the lung contents of magnetic dusts in groups of welders with similar exposures. By comparing the lung contents of workers exposed to mild steel welding fumes for 2 y, 9 y, or 18 y, and assuming a single exponential retention, they obtained a clearance rate constant of 0.1 y^{-1} (retention $t_{1/2}$ of 2500 d). A comparison of working with retired welders gave a clearance rate constant of 0.23 y^{-1} (retention $t_{1/2}$ of 1100 d). For stainless-steel welders they obtained a retention $t_{1/2}$ of 8.5 y (3100 d).

(E196) Schieferdecker *et al.* (1985) compared measured uranium thoracic contents, urinary, and faecal excretion over a 6-y period in 12 workers handling uranium oxides, with amounts predicted using intakes estimated from measured air concentrations and size distributions, and a model based on those used in *ICRP Publication 30*. Agreement was obtained using an AMAD of 8 μm and a pulmonary retention half-time of 110 d.

(E197) Thind (1987) compared measured uranium thoracic contents and urinary excretion in a group of 29 workers over a 5-y period, with amounts predicted using intakes estimated from measured air concentrations and size distributions, and the ICRP 30 model. On this basis the best agreement was obtained using an AMAD of 6 μm and a pulmonary retention half-time of 250 d.

(E198) *Comparison of intakes with lung content* Postmortem. Stöber *et al.* (1967) compared the lung contents *postmortem* with estimated dust exposures of two groups of coal miners, selected for having little or no pathological changes in their lungs: 49 who died more than a year after their last exposure, and 16 who died in a mining accident. Assuming a single exponential function for alveolar retention, they obtained a clearance half-time of 5 y (4×10^{-4} d^{-1}).

(E199) Fisenne and Welford (1986) found a significant increase with increasing age in the concentration of uranium in the lungs (including lymph nodes) of New York City residents. They observed that the increase was consistent with the measured uranium concentration in New York City air (0.4 ng m^{-3}), an inhalation rate of 20 m^3 d^{-1}, and negligible clearance from lymph nodes. Assuming 10% AI deposition, these figures give a rate of deposition in the AI of about 1 ng d^{-1}. The lung content (assuming a lung mass of 1 kg) increased from about 0.25 μg uranium at about age 25 (10^4 d) to about 0.9 μg uranium at about age 60 (2×10^4 d), i.e. a rate of 0.05 ng d^{-1}. This suggests that about 5% of the AI deposit goes to sites of very long-term retention, since compartments with half-lives less than about 10^3 d would have reached equilibrium by age 25 y.

(E200) Sunta *et al.* (1987) estimated the daily intake of thorium by inhalation in Bombay to be 0.02 μg, from a measured concentration of 1 ng m^{-3}, and an assumed daily intake of 20 m^3 air. Assuming 20% deposition in long-term retention sites and an equilibrium lung content, they obtained a retention half-time of 650 d.

(E201) McInroy *et al.* (1989) found in four whole-body autopsies, where intake was by inhalation about 30 y before death, an average of 45% of the whole-body content in the respiratory tract. They concluded that this indicated respiratory tract retention may be greater than proposed by the *ICRP Publication 30* model.

E.6.2. *Particle Clearance Rate to the GI Tract*

E.6.2.1. *Experimental studies (up to 300 d)*

(E202) In three of the studies listed in Table E.20 (Bailey *et al.*, 1985a; Philipson *et al.*, 1985; Foster *et al.*, 1989) the contribution to lung clearance made by dissolution was estimated from measurements of urinary excretion of the labels. From these it is possible to estimate the particle transport rate: $m(t)$ at time t after inhalation.

(E203) For FAP and Teflon, $m(t)$ was estimated as follows:

- a function was fitted to the decay-corrected measurements of lung retention in each subject, $R(t)$;
- the overall rate of clearance from the lung $\lambda(t)$ was calculated as a fraction of the contemporary lung content:

$$\lambda(t) = \frac{-\mathrm{d}R(t)/\mathrm{d}t}{R(t)} \tag{E.16}$$

- $m(t)$ was taken to be $\lambda(t) - s(t)$, where $s(t)$ is the estimated rate at which activity is absorbed from the particles into the blood, as a fraction of the contemporary lung content.

(E204) In the Co_3O_4 study, faecal excretion was also measured, and therefore $m(t)$ was evaluated from it directly (Bailey *et al.*, 1989):

$$F(t) = g_f m(t) + b_f s(t) \tag{E.17}$$

where $F(t)$ is the amount excreted in faeces per day as a fraction of $R(t)$; b_f and g_f are the fractions of cobalt excreted in faeces, respectively, following absorption of cobalt from lung into blood; and after Co_3O_4 particles enter the GI tract.

(E205) Average values of $m(t)$ are shown in Fig. E.11. For FAP and Teflon it was estimated that for the first 3 months particle transport was the dominant clearance mechanism. Subsequently dissolution made a significant contribution to clearance, and there is considerable uncertainty attached to the estimated value of $s(t)$, and hence that of $m(t)$. For Co_3O_4 it was estimated that absorption into blood was the dominant clearance mechanism after the first few days in all four subjects. Nevertheless the average clearance rates estimated for the three materials are reasonably consistent. The rate decreases with time from about 3×10^{-3} d^{-1} at 25 d after inhalation to 1×10^{-3} d^{-1} at 150 d, and decreases slowly thereafter.

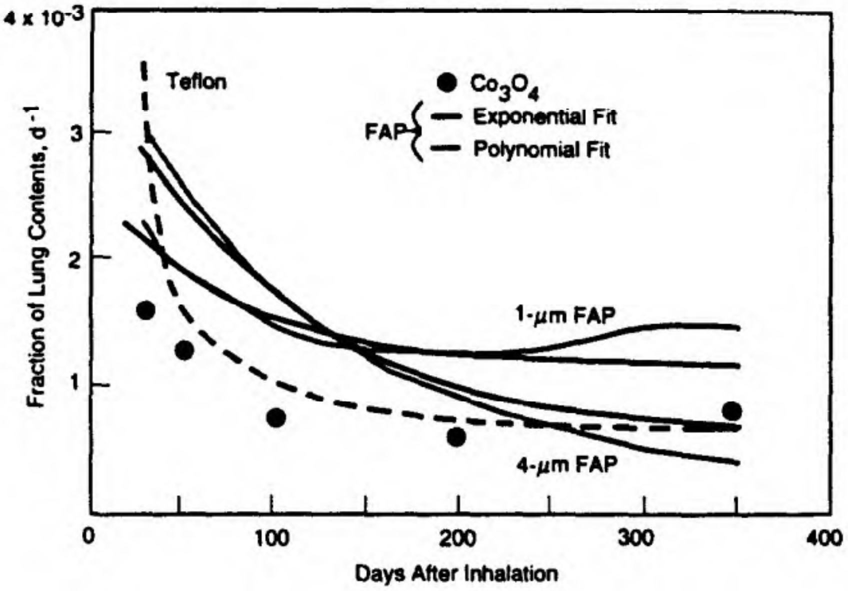

Fig. E.11. Rates of particle clearance from lungs to GI tract from human experimental studies.

(E206) Bailey *et al.* (1985a) and Philipson *et al.* (1985) fitted an exponential function (one-, or more often, two-component) to the lung retention measurements on each subject. Bailey (1989), however, considered that using an exponential model might well have influenced the estimated clearance rates, in particular, resulting in relatively constant rates beyond 150 d. He therefore fitted polynomial functions to the original data in the FAP study. Up to 200 d after inhalation the two functions gave very similar clearance rates. For the 1-μm particles at later times, the polynomials gave more variable results than the exponentials but with a similar average value (Fig. E.11). For the 4-μm particles at later times, they gave consistently lower values, indicating that $m(t)$ continues to decrease.

(E207) Since the estimated value of $m(t)$ for the 4-μm FAP involves a smaller correction for dissolution than that for the 1-μm FAP, and since the results are consistent with those from the studies using Teflon and Co_3O_4 particles (which involved smaller numbers of subjects), it is felt that it provides the best currently available estimate of $m(t)$. Thus by 350 d after inhalation the estimated average value of $m(t)$ has fallen to 5×10^{-4} d^{-1} ($t_{1/2}$ about 1400 d). However, it is not clear from these results whether $m(t)$ continues at a rate of about 10^{-3} d^{-1}, or continues to decrease. (See Sections E.6.2.2 and E.6.2.3 below.)

(E208) To provide an estimate of intersubject variation in $m(t)$, the lung clearance rate for each subject was evaluated at 200 d after inhalation (Table E.22). This time was chosen as being after the intermediate phase, but still well before the final measurement (between 270 and 500 d in most cases). The distribution of particle clearance rates is plotted in Fig. E.3, which shows that most of the results conform well to a log-normal distribution with a median value of 0.8×10^{-3} d^{-1}, and a $\sigma_g = 1.7$. Clearance rates estimated for seven subjects were lower than expected from this distribution.

E.6.2.2. *Late phase (> 300 d)*

(E209) West and Scott (1966, 1969) reported measurements of urinary and faecal excretion of uranium in five subjects who showed long-term thoracic retention, for times up to about 5 y after the subjects were removed from uranium work. Urinary and faecal

Table E.22. Intersubject variation in lung clearance rates at 200 d after inhalation[a]

Material (inhaled)	Subject	Lung clearance rate, $m(t)$ fraction of lung content ($\times 10^{-3}$ d^{-1})	Material	Subject	Lung clearance rate, $m(t)$ fraction of lung content ($\times 10^{-3}$ d^{-1})
FAP (4 μm)	A[b]	1.61	Teflon (H-L)[c]	1	0.
	B	0.84		2	0.82
	C	0.96		3	1.09
	D	1.23			
	E	0.70	Teflon (L-L)[c]	4	0.22
	F	0.63		5	2.31
	G	0.85		6	0.01
	H	0.69			
	I	1.12	Co_3O_4 (0.8 μm)	1	0.25
	J	0.26		2	1.2
	K	0.89			
	L	1.80	Co_3O_4 (1.7 μm)	3	0.17
				4	0.42

[a] Results for FAP from Bailey *et al.* (1985a); Teflon from Philipson *et al.* (1985); Co_3O_4 from Foster *et al.* (1989). Details of calculations for FAP and Teflon are given by Bailey (1989).

[b] Average from two investigations on subject A.

[c] H-L = 'high-leaching'; L-L = 'low-leaching'.

excretion were of similar magnitude in these cases. Since systemic uranium is largely excreted in urine, the faecal excretion rate $F(t)$ would be expected to approximate to the particle transport rate $m(t)$, as for cobalt oxide, discussed above. The values are summarised in Table E.23. To obtain an estimate of the faecal excretion rate at 1000 d, values of faecal excretion and thorax content between 750 d and 1250 d were pooled. Average values at 1000 d and 1500 d are about 4×10^{-4} d^{-1}, a little lower than estimated from the experimental data at 300 d after intake. A somewhat higher value is obtained at 2000 d, but is based on a relatively small number of measurements. Furthermore, it should be noted that continued *in vivo* measurements on three of these subjects indicated that lung clearance effectively ceased (Table E.21).

E.6.2.3. *Animal studies of long-term lung clearance*

(E210) Several long-term animal studies of lung clearance of particles have indicated that the fractional rate of clearance from the lungs to the GI tract decreases continuously over several years after intake.

(E211) Stuart *et al.* (1970) developed a model to describe the biokinetics of plutonium following inhalation of PuO_2, based on measurements on dogs up to 8.5 y (3100 d) after intake. Pulmonary retention was modelled with 85% IAD clearing with $t_{1/2}$ of 4 y, mainly to lymph nodes, but 9% to the GI tract, i.e. a clearance rate of 4×10^{-5} d^{-1}. The remaining 15% IAD cleared to GI tract with a $t_{1/2}$ of 50 d initially, doubling every year, i.e. a rate of $0.014 \exp(-0.69/365t)$ d^{-1}.

(E212) Métivier *et al.* (1977) found that, for PuO_2 inhaled by baboons, the lung retention $t_{1/2}$ increased with the duration of measurements up to 1000 d, and concluded that the particle excretion rate decreased continuously.

(E213) Snipes *et al.* (1983) modelled the biokinetics of ^{134}Cs following inhalation of labelled FAP based on measurements on dogs up to 850 d after intake. They estimated $m(t)$ to have the form $0.005 \exp(-0.03t) + 0.0001$ d^{-1}, i.e. an initial decrease, to a low but constant level.

Table E.23. Long-term faecal clearance of uranium following accidental inhalation (West and Scott, 1966, 1969). In parentheses is the number of measurements on which the value is based.

Time[a] (d)	1000			1500			2000		
Subject	Faecal excretion ($Bq\,d^{-1}$)	Thoracic content (Bq)	$F(t)$[b] ($\times 10^{-4}\,d^{-1}$)	Faecal excretion ($Bq\,d^{-1}$)	Thoracic content (Bq)	$F(t)$[b] ($\times 10^{-4}\,d^{-1}$)	Faecal excretion ($Bq\,d^{-1}$)	Thoracic content (Bq)	$F(t)$[b] ($\times 10^{-4}\,d^{-1}$)
Y1				0.10 (6)	250 (6)	4.1			
Y2	0.48 (11)	760 (12)	6.3	0.26 (11)	500 (11)	5.1	0.27 (8)	490 (9)	5.5
Y4	0.16 (10)	590 (14)	2.7	0.07 (15)	400 (13)	1.7	0.46 (2)	400 (4)	11.5
Y5	0.21 (10)	450 (10)	4.6	0.30 (5)	470 (10)	6.4			
Mean			4.5			4.3			8.5

[a] Time after subject was removed from uranium work. For 1000 d, the average of measurements between 750 and 1250 d was taken; for 1500 d values between 1250 and 1750 d; etc.

[b] $F(t)$ = faecal excretion rate, daily faecal excretion as a fraction of thoracic content.

(E214) Kreyling *et al.* (1988) studied retention and clearance of ^{57}Co for up to 850 d after inhalation of labelled FAP or Co_3O_4 by dogs. They estimated that for both materials $m(t)$ started at 5×10^{-4} d^{-1} and decreased exponentially with $t_{1/2}$ of 170 d. These results are notable in that the rate was based on measurements of faecal samples involving a procedure that separated ^{57}Co-FAP from nonparticulate ^{57}Co, and therefore gave a more direct measure of $m(t)$ than the other studies cited here.

E.6.3. *Conclusions for Modelling*

E.6.3.1. *Reference values and uncertainties*

(E215) Experimental studies (Table E.20) indicate that about 80% IAD remains at 50 d after intake, 70% at 100 d, and 50% at 300 d. Measurements of activity in the chest up to 5000 d after accidental inhalation (Fig. E.9), and of activity in the lungs at autopsy decades after exposure (Section E.7), show that some material is retained for a period on the order of 10,000 d.

(E216) Similarly, the experimental data indicate that for healthy nonsmokers the average clearance rate of particles from the lungs to the GI tract decreases with time from 3×10^{-3} d^{-1} at 25 d after inhalation to 8×10^{-4} d^{-1} at 200 d, and 5×10^{-4} d^{-1} at 350 d. The few data found on faecal excretion of relatively insoluble material at later times indicate a rate of 4×10^{-4} d^{-1} at 1000–1500 d.

(E217) These results suggest that AI retention needs to be represented by three compartments, which clear at rates of about 0.02 d^{-1} (i.e. $t_{1/2}$ about 30 d), 0.001 d^{-1}, and 0.0001 d^{-1} (AI_1, AI_2, and AI_3, respectively). The fraction of the AI deposit that goes to AI_1 ($a_1 = DE[AI_1]/DE_{AI}$) approximates the fraction of IAD cleared at 100 d, i.e. 0.3. (At this time AI_1 has almost completely cleared, but there is little clearance from either AI_2 or AI_3.) The fraction of the AI deposit that goes to AI_3 (a_3) is not easily quantified. Since only 50% IAD is retained at 300 d, a_3 is less than 0.5. Since there is measurable thoracic retention at 5000 d after intake in some subjects (Fig. E.10), a_3 is likely to be at least a few percent of the IAD. As a rounded value it is assumed that $a_3 = 0.1$, and, hence, by difference, that $a_2 = 0.6$. (The concept of a very long-term retention compartment in lung is not new. Thomas [1968], in modelling transport of relatively insoluble materials from lung to lymph nodes, assumed that 10% of material in the lungs at 10 d was retained with $t_{1/2}$ of 10,000 d, in order to prevent the lymph node/lung ratio becoming too large at later times.)

(E218) In considering uncertainty and modifying factors it is unrealistic to treat all the parameters as variables, partly because of lack of information, but also because considerable variation in the retention pattern can be achieved by altering either the amount in each compartment or the clearance rates. Among the considerations in deciding which parameters to make "variable", it was noted that Bohning *et al.* (1982) had observed that in smokers the "intermediate" phase (AI_1) was often absent, and the slow-phase $t_{1/2}$ increased with cigarette consumption expressed in pack-years. It is therefore proposed that a_1 is treated as one variable; assumed that a_3 remains 0.1; and hence that $a_2 = 0.9 - a_1$. The clearance rates from AI_2 and AI_3 ($m_{2,4}$ and $m_{3,4}$ in Table 17 of Chapter 7) are also treated as variables.

(E219) The value of a_1 is well defined since it approximates the fraction of IAD cleared at 100 d. The experiments with polystyrene, FAP, and Teflon give average retention in nonsmokers at 100 d between 60% and 75% IAD. Varying a_1 by ±20% results in retention at 100 d varying from 64% to 73% IAD (Table E.24). It is therefore proposed that $\Phi_u = 1.2$.

Table E.24. Comparison of observed and modelled alveolar-interstitial retention and clearance, and effects of varying parameters over ranges of uncertainty

Parameter		Values substituted in model						
		Default	Vary a_1		Vary $m_{2,4}$		Vary $m_{3,4}$	
$DE(AI_1)/DE_{AI}$ (a_1)[a]		0.3	0.24	0.36	0.3	0.3	0.3	0.3
$DE(AI_2)/DE_{AI}$		0.6	0.66	0.54	0.6	0.6	0.6	0.6
$DE(AI_3)/DE_{AI}$		0.1	0.1	0.1	0.1	0.1	0.1	0.1
$m_{1,4}$ (d^{-1})		0.02	0.02	0.02	0.02	0.02	0.02	0.02
$m_{2,4}$ (d^{-1})		0.001	0.001	0.001	0.0005	0.002	0.001	0.001
$m_{3,4}$ (d^{-1})		0.0001	0.0001	0.0001	0.0001	0.0001	0.000033	0.0003
Time (d)	Observed values	Modelled values						
		Retention (% IAD)						
50	80	78	82	75	80	75	78	78
100	68	68	73	64	71	63	68	68
300	50	54	59	50	61	43	54	54
5000	<30	6.5	6.5	6.4	11	6.1	8.9	2.6
		Clearance rate ($\times 10^{-4}$ d^{-1})						
25	30	49	40	58	45	56	49	49
200	8	10	9.9	11	6.1	18	10	11
350	5	8.4	8.5	8.3	4.5	16	8.3	8.9
1500	4	6.5	6.7	6.3	4.1	5.9	6.0	7.7

[a] The fraction of the AI deposit that goes to AI_1.

(E220) The clearance rate at 200–300 d after inhalation is mainly determined by clearance from AI_2. From Fig. E.8 this is likely to be in the range 4×10^{-4} to 1.5×10^{-3} d^{-1}, suggesting that $\Phi_u = 2$. The effect of varying $m_{2,4}$ by a factor of two is shown in Table E.24. The clearance rate at 200 d varies over a range similar to that observed: from 6×10^{-4} to 1.8×10^{-3} d^{-1}.

(E221) From Fig. E.10, retention at 5000 d can be up to 60% of that at 300 d, i.e. up to 30% IAD. In view of the great uncertainty in long-term lung retention, it is assumed that for $m_{3,4}$, $\Phi_u = 3$. The effect of varying $m_{3,4}$ by a factor of three is shown in Table E.24. Retention at 5000 d ranges from 3% to 9% IAD.

E.6.3.2. *Modifying factors*

(E222) *Cigarette smoking.* In all studies included in Table E.20 that compared smokers with nonsmokers, retention was greater in smokers. The difference was most marked in the MPG studies, suggesting that smoking may impair both particle transport and absorption into blood. Cigarette smoking was found to impair alveolar clearance of $^{239}PuO_2$ in rats (Filipy *et al.*, 1980, 1981a) provided there was exposure to smoke before and after inhalation of plutonium and also possibly in dogs, but on the basis of small numbers of animals (Filipy *et al.*, 1981b, 1982). Bohning *et al.* (1982) observed no "intermediate" phase in five out of eight current cigarette smokers, giving an average of 7% for a_1, compared with 27% in nonsmokers and 26% in ex-smokers. Hence Φ_m is taken to be 0.3 for a_1. They also observed longer slow-phase $t_{1/2}$ in smokers than nonsmokers. Clearance rates corresponding to the slow-phase half-times were calculated. The average in smokers was 1.6×10^{-3} d^{-1}, compared with 2.4×10^{-3} d^{-1} in nonsmokers. Hence Φ_m is taken to be 0.7 for $m_{2,4}$. Kathren *et al.* (1993) found that the concentrations of $^{239+240}Pu$ and ^{241}Am in lymph nodes, relative to their concentrations in lungs, were greater in nonsmokers than in smokers (see Section E.7). This is consistent with long-term lung clearance in smokers also being slower than in nonsmokers, and hence it is proposed that Φ_m is also taken to be 0.7 for $m_{3,4}$.

(E223) *Lung disease.* Bohning *et al.* (1982) also measured retention in six subjects with various forms of chronic obstructive lung disease. Results were quite variable, but two (one with bullous emphysema, the other chronic bronchitis and pulmonary fibrosis) had long slow-phase half-times. Roy *et al.* (1984) fitted a single exponential function to lung retention measured from 3 d to 28 d after inhalation and found a much longer $t_{1/2}$ in patients with silicosis (225 d) than in healthy subjects (81 d), suggesting a reduced intermediate phase (a_1). The retention $t_{1/2}$ measured in four silicotic subjects up to 90 d, was also long (500 d), suggesting that $m_{2,4}$ is also reduced.

E.7. The Lymph Nodes

(E224) Many *postmortem* measurements have been made of the concentrations of materials in human lungs and associated lymph nodes, here represented by [L] and [LN], respectively. The following review of such measurements is confined to studies on human tissues, on materials which would be expected to be relatively insoluble, and for which measurements on both lung and lymph nodes were reported.

(E225) Results are summarised in Tables E.25–E.30, where possible on the basis of concentration ratio [LN]/[L], since this is a useful parameter on which to compare results from exposures at different levels, and to compare observations with model predictions. Thomas (1968) reviewed data from inhalation experiments using relatively

Table E.25. Concentrations[a] of $^{239+240}$Pu in lungs and tracheobronchial lymph nodes (TBLN) of nonoccupationally exposed people

Year of death	Location	Measured			Predicted[c]			Reference
		Lung	TBLN	Ratio[b]	Lung	TBLN	Ratio	
1970	All USA	13.7 (32)	50 (33)	3.6	11.8	1500	120	McInroy *et al.* (1981)
1971	All USA	7.0 (73)	100 (59)	14.3	9.6	1300	140	McInroy *et al.* (1981)
1972	All USA	10.0 (79)	149 (53)	15.0	7.0	1200	170	McInroy *et al.* (1981)
1973	All USA	6.3 (56)	67 (35)	10.6	4.8	1100	220	McInroy *et al.* (1981)
1973–74	New York City	2.2 (52)	4.1 (23)[d]	1.9				Fisenne *et al.* (1980)
1974	All USA	5.2 (141)	74 (64)	14.2	4.4	980	220	McInroy *et al.* (1981)
1975	All USA	4.1 (210)	32 (65)	7.9	3.3	900	270	McInroy *et al.* (1981)
1976	All USA	3.7 (54)	26 (15)	7.1	3.0	840	280	McInroy *et al.* (1981)
1976–77	S. Finland	1.0 (29)	14 (19)[e]	14.0				Mussalo *et al.* (1980)
1977	All USA	5.9 (27)	31 (25)	5.3	1.9	780	420	McInroy *et al.* (1981)
1978					1.1	710	640	
1977–79	Colorado	6.3 (9)	25 (7)	4.0				Singh *et al.* (1983)
1978–79	Washington, DC	3.0 (10)	17 (10)	5.8				Singh *et al.* (1983)
1979					0.7	660	940	
1980					0.4	620	1550	
1980–81	Munich, FRG	1.0 (29)	2.1 (30)[f]	2.1				Bunzl and Kracke (1983)
1980–84	Great Britain[g]	2.2 (30)	12 (25)	5.5				Popplewell *et al.* (1985)

[a] Concentrations in mBq kg^{-1} wet weight. Values are medians except for southern Finland (mean). In parentheses are numbers of samples.

[b] (Median TBLN concentration)/(median lung concentration).

[c] Predicted values based on plutonium air concentrations in New York, and the ICRP (1972) lung model, assuming an AMAD of 0.4 μm, no intake after 1975, and Class Y behaviour (Bennett, 1974, 1976).

[d] Nine individual TBLN samples, 14 composites of 2–5 specimens each.

[e] Six composite TBLN samples from 19 specimens.

[f] One composite sample of 30 specimens.

[g] Excluding West Cumbria.

Table E.26. Concentrations[a] of ^{144}Ce in lungs and tracheobronchial lymph nodes (TBLN) of nonoccupationally exposed people

Year of death	Location	Lung	TBLN	Ratio	Reference
1960	Vienna	0.95 (3) {1.8}	23 (3) {1.7}	24 (3) {2.4}	Liebscher *et al.* (1961)

[a] Concentrations in Bq kg^{-1} wet weight. Values are geometric means. In parentheses are numbers of samples. Numbers in braces are geometric standard deviations.

insoluble materials (compounds of polonium, plutonium, thorium, and uranium), and found that when [LN]/[L] was plotted against the time, t, after the start of inhalation, on logarithmic scales, a consistent linear increasing trend was obtained, equivalent to:

$$[\mathrm{LN}]/[\mathrm{L}] = 0.0107t^{1.08} \qquad \text{for } 1 < t(\text{days}) < 3000. \tag{E.18}$$

This equation predicts values of [LN]/[L] of about 20 at 1000 d after the start of inhalation and 60 at 3000 d; it is, however, based mainly on results of dog studies, since very few human data were then available.

(E226) The presentation of results in the literature is, however, quite variable: individual values or central values for groups (median, arithmetic, or geometric mean) may be given, expressed as the amounts in lung and lymph nodes, the concentrations, or the concentration ratio.

(E227) In addition to the general problems relating to the interpretation of measurements following unplanned exposures, particularly uncertainty about the intake, there are specific problems associated with the measurement of lymph node contents. Since it may not be possible to analyse complete organs, concentrations are frequently determined. The concentration of material, even in adjacent nodes in the same individual, is extremely variable. (See, for example, Morrow and Casarett, 1961.) It may be so low that samples from a number of individuals are combined. Complete separation of lymph nodes from other tissues may not be achieved, and since the concentration in the nodes is generally higher than in the lungs, this tends to increase the measured lung concentration [L], and to reduce the measured lymph node concentration [LN] and the ratio [LN]/[L]. It is also recognised that much of the material in the lung sample may in fact be in lymphatic vessels within the lung tissue, but which cannot be separated from it by dissection. Thus, Cottier *et al.* (1987) found that aggregates of carbonaceous particles in lung sections from elderly subjects were predominantly located in lymphatic vessels, rather than in the alveolar parenchyma.

(E228) The information falls into four main categories: environmental exposure to nuclear weapons fallout, particularly plutonium; and environmental exposure to natural long-lived radionuclides, particularly thorium isotopes; occupational exposure to actinides, especially plutonium; and occupational exposure to mine dusts. Note that the units in Tables E.25–E.30 necessarily differ.

E.7.1. *Environmental Exposure*

E.7.1.1. *Nuclear weapons fallout*

(E229) Since inhalation is the main route of intake of plutonium from weapons fallout, and the air concentration was highest in the mid 1960s, activities in tissues

Table E.27. Concentrations[a] of naturally occurring radionuclides in lungs and tracheobronchial lymph nodes (TBLN) of nonoccupationally exposed people

Radionuclide or element	Location	Concentration		Ratio		Reference
		Lung	TBLN	[b]	[c]	
^{232}Th[d]	United Kingdom	40 (11)	800 (6)	20		Hamilton *et al.* (1972)
^{228}Th	Colorado	10 (19)	190 (14)	18.2		Ibrahim *et al.* (1983);
^{230}Th		31 (19)	410 (14)	13.1		Singh *et al.* (1983)
^{232}Th		21 (19)	290 (14)	13.5		
^{228}Th	Washington, DC	9 (10)	96 (10)	10.8		
^{230}Th		11 (10)	170 (10)	14.8		
^{232}Th		12 (10)	100 (10)	8.8		
$^{234+235+238}$U	Colorado	70 (1)	380 (1)	5.4		Wrenn *et al.* (1985)
^{232}Th	(80-A-39)	57 (1)	84 (1)	1.5		
^{230}Th		35 (1)	150 (1)	4.3		
$^{234+235+238}$U	Colorado (27–88)	24 (1)	61 (1)	2.5		
^{232}Th[d]	Bombay, India	22 (18)	216 (6)	9.9		Sunta *et al.* (1987)
U					5.2 (9) {4.3}	Kathren *et al.* (1993)

[a] Concentrations in mBq kg^{-1} wet weight. Values are medians or geometric means, except for United Kingdom (mean). In parentheses are numbers of samples. Numbers in braces are geometric standard deviations.

[b] (Median TBLN concentration)/(median lung concentration).

[c] Median value of (TBLN concentration/lung concentration).

[d] Assuming specific activity of 4.05 mBq μg^{-1}. Values were given in μg.

Table E.28. Concentrations[a] of radionuclides in lungs and tracheobronchial lymph nodes (TBLN) of occupationally exposed people

Radionuclide	Exposure	Concentration		Ratio	Reference
		Lung	TBLN		
$^{239+240}$Pu	Chronic inhalation	3.2 (9) {15}	5.6 (9) {67}	1.8 (9) {9.6}	Foreman *et al.* (1960), Langham *et al.* (1962)
$^{239+240}$Pu	Multiple PuO_2 inhalation over 9 y (Case 667)	3.5	23	6.7	Lagerquist *et al.* (1969)
$^{239+240}$Pu	US Transuranium Registry (USTR) donors	15 (13) {16}	20 (13) {13}	1.3 (13) {9.9}	Norwood *et al.* (1973)
$^{239+240}$Pu	Los Alamos employees with high potential Pu exposure (Table A-V)	2.4 (15) {15}	24 (15) {27}	10.0 (15) {3.5}	Campbell *et al.* (1973)
$^{239+240}$Pu	USTR donors	20 (8) {40}	190 (8) {20}	9.4 (8) {9.4}	Norwood and Newton (1975)
^{232}Th	33 y (L-2107)	25	73	2.9 (1)	Mausner (1982)
	3 y, 30 y before death (L-2932)	0.09	0.93	10.9 (1)	
$^{234+235+238}$U	U miller (83-A-79)	14	150	10.4	Singh *et al.* (1987)
^{232}Th		0.13	2.3	17.2	
$^{234+235+238}$U	U miller (83-A-125)	1.8	38	21.2	
^{232}Th		0.041	0.056	1.4	
$^{239+240}$Pu	USTR donors. Typically, chronic inhalation with most exposure many years before death	All		7.8 (54) {6.2}	Kathren *et al.* (1993)
$^{239+240}$Pu		Smokers		6.7 (41) {5.3}	
$^{239+240}$Pu		Nonsmokers		19.4 (13) {3.9}	
^{238}Pu		All		12.7 (29) {5.8}	
^{241}Am		All		11.8 (36) {3.4}	
^{241}Am		Smokers		8.7 (8) {3.3}	
^{241}Am		Nonsmokers		34.4 (28) {1.8}	

[a] Concentrations in Bq kg^{-1} wet weight. Values are geometric means or medians. In parentheses are numbers of samples. Numbers in braces are geometric standard deviations.

Table E.29. Concentrations[a] of uranium in lungs and tracheobronchial lymph nodes (TBLN) of occupationally exposed people

Material	Exposure	Concentration		Ratio	Reference
		Lung	TBLN		
UO_2, UF_4	5 y inhalation	50	120[b]	2.4 (1)	Butterworth (1959)
?	9 y (case 7)	1600	320	0.2 (1)	Meichen (1962)
	5 y (case 9)	50	100	2.0 (1)	
Mainly U_3O_8	10 y inhalation	1200	1800	1.5 (1)	Donoghue *et al.* (1972)
Oxide	Chronic inhalation	5600	400	0.1 (1)	Heid and Fuqua (1974)
U	Machinists and scientists	72 (6) {6.1}	178 (6) {5.3}	2.5 (6) {5.5}	Campbell *et al.* (1975)

[a] Concentrations in $\mu g\ kg^{-1}$ wet weight. Values are geometric means. In parentheses are numbers of samples. Numbers in braces are geometric standard deviations.

[b] 'Mediastinal' lymph nodes; concentrations were given in ppm.

Table E.30. Dust concentrations[a] in lungs and hilar lymph nodes (HLN) of coal miners

Material	Location	Concentration (mean)		Ratio [LN]/[L] (geometric mean)	Reference
		Lung	HLN		
Total dust[b]	West Virginia	70 (145)		0.88 (63) {2.2}	Carlberg *et al.* (1971)
Coal		44 (145)		0.92 (63) {2.0}	
Free silica		2 (145)		3.6 (41) {2.6}	
Total dust	Great Britain	88 (49)	114 (31)		Chapman and Ruckley (1985)
Coal[c]		51 (31)	54 (31)		
Quartz		7 (31)	22 (31)		
Kaolin + mica		26 (31)	34 (31)		

[a] Concentrations in $g\ kg^{-1}$ dried tissue weight. In parentheses are the numbers of samples. Numbers in braces are geometric standard deviations.

[b] Lymph node/lung concentration ratios were also given by Carlberg *et al.* (1971) for 11 individual trace elements. Geometric means ranged from 0.78 (Fe) to 1.63 (V), and only for Ni (0.79) and V were significantly different from 1.0.

[c] Mean composition of coal, quartz, and kaolin + mica given as 57.8%, 7.4%, and 29.8% in whole lungs and 47.4%, 19.2%, and 30.2% in lymph nodes. These percentages were applied here to the total dust concentrations.

depend on the date of sampling. Results in Table E.25 are therefore presented by year of death. Most are given as median concentrations in lung $[L]_{50}$ and lymph nodes $[LN]_{50}$. McInroy *et al.* (1979) considered the median to provide the best estimate of central tendency for plutonium concentrations in tissues, because it is insensitive to extreme values, the shape of the distribution, and the detection limit. The median concentration ratio $([LN]/[L])_{50}$ is not normally readily available from the published data, and may in practice be difficult to determine when some measurements are below the limit of detection. However, a reasonable estimate can be obtained from the ratio of $[LN]_{50}$ to $[L]_{50}$. Such data tend to be approximately log-normally distributed, and therefore the median approximates the geometric mean. The geometric mean ratio is given by:

$$\begin{aligned}\left(\frac{[LN]}{[L]}\right)_g &= \left(\frac{[LN_1]}{[L_1]} \times \frac{[LN_2]}{[L_2]} \cdots \times \frac{[LN_n]}{[L_n]}\right)^{1/n} \\ &= \left(\frac{[LN_1] \times [LN_2] \ldots \times [LN_n]}{[L_1] \times [L_2] \ldots \times [L_n]}\right)^{1/n} = \frac{[LN]_g}{[L]_g}.\end{aligned} \tag{E.19}$$

Hence $([LN]/[L])_{50} \approx [LN]_{50}/[L]_{50}$. For example, the geometric mean concentration of $^{239+240}$Pu in 30 lungs measured by Popplewell *et al.* (1985) was 2.0 mBq kg^{-1} and the median 2.2 mBq kg^{-1}. For 25 of these, the concentrations in tracheobronchial lymph nodes (TBLN) were also reported. These had a geometric mean of 15 mBq kg^{-1} and a median of 12 mBq kg^{-1}. The concentration ratio ([LN]/[L]) had a geometric mean of 8.9 and a median of 6.3, which is not far from the estimate (5.5) obtained by taking the ratio of the median concentrations in TBLN and lungs.

(E230) Since most of the intake of fallout plutonium occurred over a relatively short period (now over 25 y ago), it is feasible to compare the observed levels with those expected on the basis of the current and revised lung models. The predicted values in Table E.25 were based on the calculations of Bennett (1974, 1976), who used measured and inferred plutonium air concentrations for New York, and the current version of the ICRP lung model (ICRP, 1972), assuming Class Y behaviour, an AMAD of 0.4 μm, and no intake after 1977. The concentration depends on latitude, and so should have been similar in Great Britain and Germany. Mussalo *et al.* (1980), however, noted that the plutonium air concentration in Finland in 1967 was only about 30% of that in New York. The model predicts the lung concentration [L] well up to about 1976 but at later times appears to underestimate it. However, the lymph node concentration [LN], and the concentration ratio [LN]/[L], are consistently much lower than predicted.

E.7.1.2. *Other environmental intakes*

(E231) If sufficient data were available on naturally occurring insoluble materials (Table E.27), it would best be treated as a function of age, since exposure is from birth. Ibrahim *et al.* (1983) measured the concentration of isotopes of thorium in samples from two populations, one of which lived near mine tailings. Some were the same samples that they analysed for plutonium (Singh *et al.*, 1983), which are included in Table E.25. They noted that the ratio of thorium concentration in lymph nodes to lung was significantly greater than that of fallout plutonium, and concluded that the latter is more soluble than natural thorium. However, in view of the persistence of the plutonium concentrations summarised in Table E.25, the dissolution rate of fallout plutonium can hardly be much less than assumed for a Class Y material.

E.7.2. *Occupational Exposures*

E.7.2.1. *Radioactive materials*

(E232) Most data (Tables E.28 and E.29) are for plutonium and uranium. Uranium results presented in terms of mass, rather than activity, are given in Table E.29. In some reports, exposure histories are given, but a detailed analysis is beyond the scope of this review. Generally the exposure was mainly from chronic or multiple inhalation, and often many years elapsed between exposure and death.

E.7.2.2. *Dust in the lungs of coal miners*

(E233) There have been a number of major studies of the dust content of coal miners' lungs, in relation to the diseases associated with the occupation. One may presume that the subjects were chronically exposed to relatively high levels of airborne dust, and lung clearance may have been affected by the large amounts deposited. The results (Table E.30), however, consistently show similar dust concentrations in lung and lymph nodes, except in the case of quartz, for which the lymph node concentration is typically three times that in the lungs.

(E234) The results summarised in Table E.30 are consistent with the observations of Stöber *et al.* (1967). In discussing two groups of coal miners, 49 who died more than a year after their last exposure, and 16 who died in a mining accident, they noted that retention in lymph nodes "never exceeded 8% of the lung retention". Assuming lung and lymph nodes masses of 1 kg and 0.015 kg, respectively, this implies a concentration ratio [LN]/[L] always less than 5.

E.7.3. *Summary of* Postmortem *Measurements of Material in Lymph Nodes*

(E235) Although there are well-known difficulties in interpreting these results, mainly because of uncertainties about the time and composition of the intakes, there is now a considerable body of data on retention of inhaled materials in human lymph nodes. The data relate to a variety of materials and to both high and low levels of exposure. However, material is consistently found in both lungs and lymph nodes, even many years after exposure has ceased. The concentration in lymph nodes is generally higher than in the lungs. The concentration ratio is very variable, but amongst groups with similar exposures median values are usually between 1 and 20. (The ratio [LN]/[L] is generally lower for coal miners, but it would not be surprising if their very high exposure levels resulted in impairment of clearance from the lungs.) Since the mass of the TBLN (typically 0.015 kg) is so much smaller than that of the lungs (1 kg), the concentration ratio would have to exceed 60 for the amount of material in lymph nodes to exceed that in the lungs. While ratios in some individuals have reached such values, they are exceptional, and a ratio of about 10 would seem to be a reasonable representative value.

E.7.4. *Particle Transport from Lymph Nodes*

(E236) The presence of significant amounts of material in the lung-associated lymph nodes of people many years after exposure (Section E.7.2), and the accumulation of material in lymph nodes observed in animal inhalation studies, indicate that the particle transport rate from lymph nodes to blood must be extremely low. In dogs and baboons that died 750–1500 d after inhalation of $^{239}PuO_2$, the lymph nodes contained 10–50% of the ILD (Bair *et al.*, 1980). Bair (1974) observed that at 10 y after inhalation of $^{239}PuO_2$ by dogs, the lymph nodes contained about 50% ILD and that the rate of accumulation still exceeded the rate of elimination. Similarly, in a more recent study, which included lower exposure levels, the lymph nodes of dogs that died at 3000–5000 d after inhalation of $^{239}PuO_2$ contained 10–80% ILD (Park *et al.*, 1986).

(E237) Particles with diameters between a few nanometres and a few micrometres that enter the bloodstream would be expected to deposit predominantly in liver and spleen and be retained there (Berg, 1951; Kreyling *et al.*, 1986). The absence of marked accumulation of activity in these organs has been interpreted by a number of authors as further evidence for the low rate of particle penetration of lymph nodes. (Similarly, it indicates that there is no significant direct movement of particles in this size range from the respiratory tract itself to the bloodstream.) Hahn *et al.* (1952), Bryant *et al.* (1953), and Meneely *et al.* (1953) drew this conclusion from measurements following intratracheal instillation into dogs of radiolabelled gold or silver colloids. Bair (1974) noted that there was no direct evidence for clearance of plutonium particles from thoracic lymph nodes, but particles were occasionally observed in liver or spleen. Gearhart *et al.* (1980) studied by autoradiography the microscopic distribution of plutonium in the liver of dogs up to 1400 d after inhalation of monodisperse $^{238}PuO_2$ (AMAD 1.5 μm, hence the geometric diameter was about 0.5 μm, assuming a density of 10 g cm^{-3}). Some particles were found, but only in dogs exposed to high initial lung burdens. Snipes *et al.* (1983) noted that in dogs, rats, and mice followed for 850 d after inhalation of FAP: "No particle-associated activity was noted elsewhere in the animals which would account for particles passing through or around the LALNs [lung-associated lymph nodes]." Kreyling *et al.* (1988) followed dogs up to 1000 d after inhalation of ^{57}Co-labelled FAP or cobalt oxide, and concluded that particle penetration of lymph nodes must be small, based on both retention in the lymph nodes and low ^{57}Co levels in liver and spleen.

(E238) The presence of fibrous particles in organs other than the respiratory tract and GI tract has been more widely reported, and it seems possible that fibres penetrate the lymph nodes more readily than particles of compact shape. Oberdörster *et al.* (1988) found that 24 h after instillation of ^{59}Fe-labelled amosite fibres into the peripheral lung of dogs, about 3% of the instilled activity was in thoracic lymph nodes, and 0.1% of the instilled activity appeared in postnodal lymph in the 4 h before sacrifice. Fibres were also identified in the postnodal lymph. Both autopsy studies of exposed workers, and animal experiments, have shown that fibres can migrate from the respiratory tract and be widely spread through the body (Godwin and Jagatic, 1970; Bignon *et al.*, 1979; Sebastien *et al.*, 1979). Elevated concentrations of asbestos fibres have been found in the urine of exposed workers (Finn and Hallenbeck, 1985). Priest (1990) suggested that particle movement from the respiratory tract to other organs, notably liver, may be a general phenomenon, on the basis of cited observations of coal dust in the liver of miners, and of siliceous diatom skeletons in extrapulmonary tissues of humans. He suggested that this might account for the higher liver-to-skeleton ratio of plutonium following exposure to fallout (mainly inhalation of oxide), compared with that following intravenous injection.

(E239) Generally, however, it appears that only a small fraction of particles deposited in lymph nodes penetrate, although the fraction may be greater when the lymph nodes are heavily loaded or damaged (Oberdörster, 1988). The behaviour of particulate material entering the blood would be different from that of dissociated material, and, in view of the small fraction of material involved, the additional complexity this would introduce to the dosimetric models is considered unjustified. For modelling purposes it is therefore assumed that there is no direct movement of particles from lymph nodes to bloodstream, although, as stated elsewhere, absorption into blood (i.e. dissolution and uptake) is assumed to occur at the same rate as in the respiratory tract itself.

E.7.5. *Conclusions for Modelling*

E.7.5.1. *Reference values and uncertainties*

(E240) Analyses of tissues taken at autopsies, following exposures many years prior to death, have shown typical concentrations in LN_{TH} about ten times that in the lungs (Section E.7.3). However, in the one study that distinguished smokers from nonsmokers (Kathren *et al.*, 1993), the ratio was about 10 in smokers, but 20 in nonsmokers. Since the mass of LN_{TH} (0.015 kg) is so much less than that of the lungs (1.0 kg), this concentration ratio of 20 indicates that the amount in lungs is about three times that in lymph nodes. The transport rate from AI to LN_{TH} in the compartment model was therefore chosen to give this ratio at 10,000 d after inhalation. For simplicity, it is modelled only by transport from AI_3, and a rate of 0.00002 d^{-1} is needed to provide the required amount in LN_{TH}. Since it is based on a large amount of human data, it is proposed that $\Phi_u = 2$.

E.7.5.2. *Modifying factors*

(E241) No modifying factors are recommended. Kathren *et al.* (1993) did find lower values of [LN]/[L] for both plutonium and americium in smokers than in nonsmokers (Table E.28). While this could be due to reduced clearance to lymph nodes, it might result from increased AI retention, which is already taken into account (Section E.6.3.2).

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ANNEXE F. REFERENCE VALUES FOR REGIONAL DEPOSITION

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Table F.1. Fractional deposition in regions of the respiratory tract for reference workers as a function of aerosol size

AMTD (μm)	ET_1	ET_2	$BB_{fast+seq}$	BB_{slow}	$bb_{fast+seq}$	bb_{slow}	AI	Total
Normal nose breather (breathing rate = 1.2 $m^3 h^{-1}$)								
0.0006	4.5×10^{-1}	4.4×10^{-1}	3.0×10^{-2}	3.0×10^{-2}	2.0×10^{-2}	2.0×10^{-2}	2.9×10^{-4}	9.9×10^{-1}
0.001	4.0×10^{-1}	4.0×10^{-1}	4.0×10^{-2}	4.0×10^{-2}	4.8×10^{-2}	4.8×10^{-2}	3.7×10^{-3}	9.9×10^{-1}
0.002	3.0×10^{-1}	3.2×10^{-1}	4.4×10^{-2}	4.4×10^{-2}	1.1×10^{-1}	1.1×10^{-1}	4.3×10^{-2}	9.6×10^{-1}
0.005	1.6×10^{-1}	1.8×10^{-1}	2.8×10^{-2}	2.8×10^{-2}	1.3×10^{-1}	1.3×10^{-1}	2.7×10^{-1}	9.2×10^{-1}
0.01	8.7×10^{-2}	9.8×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	9.5×10^{-2}	9.5×10^{-2}	4.7×10^{-1}	8.8×10^{-1}
0.02	5.3×10^{-2}	5.9×10^{-2}	8.8×10^{-3}	8.8×10^{-3}	6.3×10^{-2}	6.3×10^{-2}	4.9×10^{-1}	7.4×10^{-1}
0.05	3.2×10^{-2}	3.4×10^{-2}	5.1×10^{-3}	5.1×10^{-3}	3.6×10^{-2}	3.6×10^{-2}	3.1×10^{-1}	4.6×10^{-1}
0.1	3.2×10^{-2}	3.2×10^{-2}	3.7×10^{-3}	3.7×10^{-3}	2.4×10^{-2}	2.4×10^{-2}	2.1×10^{-1}	3.3×10^{-1}
0.2	5.5×10^{-2}	6.1×10^{-2}	3.3×10^{-3}	3.3×10^{-3}	1.5×10^{-2}	1.5×10^{-2}	1.5×10^{-1}	3.0×10^{-1}
0.5	8.9×10^{-2}	1.1×10^{-1}	4.0×10^{-3}	3.9×10^{-3}	1.1×10^{-2}	1.1×10^{-2}	1.2×10^{-1}	3.5×10^{-1}
0.7	1.2×10^{-1}	1.5×10^{-1}	5.1×10^{-3}	4.8×10^{-3}	9.4×10^{-3}	9.2×10^{-3}	1.1×10^{-1}	4.2×10^{-1}
1	1.7×10^{-1}	2.1×10^{-1}	6.6×10^{-3}	5.8×10^{-3}	8.4×10^{-3}	8.1×10^{-3}	1.1×10^{-1}	5.1×10^{-1}
2	2.5×10^{-1}	3.2×10^{-1}	9.9×10^{-3}	7.4×10^{-3}	8.0×10^{-3}	6.8×10^{-3}	9.2×10^{-2}	7.0×10^{-1}
3	3.0×10^{-1}	3.7×10^{-1}	1.1×10^{-2}	7.3×10^{-3}	7.7×10^{-3}	6.0×10^{-3}	7.7×10^{-2}	7.8×10^{-1}
5	**3.4×10^{-1}**	**4.0×10^{-1}**	**1.2×10^{-2}**	**5.9×10^{-3}**	**6.6×10^{-3}**	**4.4×10^{-3}**	**5.3×10^{-2}**	**8.2×10^{-1}**
7	3.5×10^{-1}	4.0×10^{-1}	1.1×10^{-2}	4.6×10^{-3}	5.5×10^{-3}	3.2×10^{-3}	3.8×10^{-2}	8.1×10^{-1}
10	3.5×10^{-1}	3.8×10^{-1}	9.5×10^{-3}	3.1×10^{-3}	4.2×10^{-3}	2.1×10^{-3}	2.4×10^{-2}	7.7×10^{-1}
15	3.3×10^{-1}	3.6×10^{-1}	7.2×10^{-3}	1.8×10^{-3}	2.7×10^{-3}	1.1×10^{-3}	1.2×10^{-2}	7.1×10^{-1}
20	3.2×10^{-1}	3.3×10^{-1}	5.5×10^{-3}	1.1×10^{-3}	1.8×10^{-3}	6.6×10^{-4}	7.2×10^{-3}	6.7×10^{-1}
Habitual mouth breather (breathing rate = 1.2 $m^3 h^{-1}$)								
0.0006	2.0×10^{-1}	5.8×10^{-1}	6.0×10^{-2}	6.0×10^{-2}	4.0×10^{-2}	4.0×10^{-2}	6.1×10^{-4}	9.9×10^{-1}
0.001	1.8×10^{-1}	4.9×10^{-1}	6.6×10^{-2}	6.6×10^{-2}	8.1×10^{-2}	8.1×10^{-2}	6.2×10^{-3}	9.8×10^{-1}
0.002	1.4×10^{-1}	3.5×10^{-1}	5.8×10^{-2}	5.8×10^{-2}	1.4×10^{-1}	1.4×10^{-1}	5.8×10^{-2}	9.5×10^{-1}
0.005	7.5×10^{-2}	1.8×10^{-1}	3.1×10^{-2}	3.1×10^{-2}	1.5×10^{-1}	1.5×10^{-1}	3.0×10^{-1}	9.1×10^{-1}
0.01	4.2×10^{-2}	9.9×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.0×10^{-1}	1.0×10^{-1}	5.0×10^{-1}	8.7×10^{-1}
0.02	2.6×10^{-2}	6.0×10^{-2}	9.1×10^{-3}	9.1×10^{-3}	6.5×10^{-2}	6.5×10^{-2}	5.0×10^{-1}	7.3×10^{-1}
0.05	1.5×10^{-2}	3.4×10^{-2}	5.2×10^{-3}	5.2×10^{-3}	3.7×10^{-2}	3.7×10^{-2}	3.2×10^{-1}	4.5×10^{-1}
0.1	1.2×10^{-2}	2.4×10^{-2}	3.8×10^{-3}	3.8×10^{-3}	2.4×10^{-2}	2.4×10^{-2}	2.1×10^{-1}	3.0×10^{-1}
0.2	1.5×10^{-2}	2.5×10^{-2}	4.0×10^{-3}	3.9×10^{-3}	1.6×10^{-2}	1.6×10^{-2}	1.5×10^{-1}	2.3×10^{-1}
0.5	2.4×10^{-2}	3.7×10^{-2}	6.6×10^{-3}	5.9×10^{-3}	1.3×10^{-2}	1.2×10^{-2}	1.4×10^{-1}	2.4×10^{-1}
0.7	3.3×10^{-2}	5.5×10^{-2}	1.1×10^{-2}	8.6×10^{-3}	1.3×10^{-2}	1.2×10^{-2}	1.4×10^{-1}	2.8×10^{-1}
1	4.7×10^{-2}	8.3×10^{-2}	1.7×10^{-2}	1.2×10^{-2}	1.4×10^{-2}	1.2×10^{-2}	1.6×10^{-1}	3.4×10^{-1}
2	8.2×10^{-2}	1.7×10^{-1}	3.9×10^{-2}	2.0×10^{-2}	2.0×10^{-2}	1.4×10^{-2}	1.7×10^{-1}	5.2×10^{-1}
3	1.0×10^{-1}	2.4×10^{-1}	5.4×10^{-2}	2.3×10^{-2}	2.4×10^{-2}	1.4×10^{-2}	1.7×10^{-1}	6.2×10^{-1}
5	**1.2×10^{-1}**	**3.2×10^{-1}**	**6.8×10^{-2}**	**2.1×10^{-2}**	**2.6×10^{-2}**	**1.2×10^{-2}**	**1.3×10^{-1}**	**7.1×10^{-1}**
7	1.3×10^{-1}	3.7×10^{-1}	7.1×10^{-2}	1.8×10^{-2}	2.4×10^{-2}	9.9×10^{-3}	1.1×10^{-1}	7.3×10^{-1}
10	1.4×10^{-1}	4.1×10^{-1}	6.6×10^{-2}	1.3×10^{-2}	1.9×10^{-2}	7.0×10^{-3}	7.3×10^{-2}	7.2×10^{-1}
15	1.4×10^{-1}	4.3×10^{-1}	5.4×10^{-2}	8.3×10^{-3}	1.4×10^{-2}	4.1×10^{-3}	4.2×10^{-2}	6.9×10^{-1}
20	1.3×10^{-1}	4.3×10^{-1}	4.3×10^{-2}	5.3×10^{-3}	9.5×10^{-3}	2.5×10^{-3}	2.6×10^{-2}	6.5×10^{-1}

Table F.2. Fractional deposition in regions of the respiratory tract for heavy work as a function of aerosol size

AMTD (μm)	ET_1	ET_2	$BB_{fast+seq}$	BB_{slow}	$bb_{fast+seq}$	bb_{slow}	AI	Total
Normal nasal augmenter (breathing rate = 1.7 $m^3\,h^{-1}$)								
0.0006	4.0×10^{-1}	4.7×10^{-1}	3.4×10^{-2}	3.4×10^{-2}	3.0×10^{-2}	3.0×10^{-2}	1.2×10^{-3}	9.9×10^{-1}
0.001	3.5×10^{-1}	4.1×10^{-1}	4.2×10^{-2}	4.2×10^{-2}	6.3×10^{-2}	6.3×10^{-2}	8.3×10^{-3}	9.8×10^{-1}
0.002	2.6×10^{-1}	3.2×10^{-1}	4.1×10^{-2}	4.1×10^{-2}	1.2×10^{-1}	1.2×10^{-1}	6.5×10^{-2}	9.6×10^{-1}
0.005	1.4×10^{-1}	1.7×10^{-1}	2.4×10^{-2}	2.4×10^{-2}	1.3×10^{-1}	1.3×10^{-1}	3.2×10^{-1}	9.2×10^{-1}
0.01	7.6×10^{-2}	9.6×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	8.6×10^{-2}	8.6×10^{-2}	5.1×10^{-1}	8.8×10^{-1}
0.02	4.7×10^{-2}	5.8×10^{-2}	7.6×10^{-3}	7.6×10^{-3}	5.7×10^{-2}	5.7×10^{-2}	5.0×10^{-1}	7.4×10^{-1}
0.05	2.8×10^{-2}	3.3×10^{-2}	4.4×10^{-3}	4.4×10^{-3}	3.2×10^{-2}	3.2×10^{-2}	3.1×10^{-1}	4.5×10^{-1}
0.1	2.9×10^{-2}	3.2×10^{-2}	3.3×10^{-3}	3.3×10^{-3}	2.1×10^{-2}	2.1×10^{-2}	2.0×10^{-1}	3.1×10^{-1}
0.2	5.2×10^{-2}	6.0×10^{-2}	3.7×10^{-3}	3.7×10^{-3}	1.3×10^{-2}	1.3×10^{-2}	1.4×10^{-1}	2.9×10^{-1}
0.5	8.5×10^{-2}	1.1×10^{-1}	5.6×10^{-3}	5.4×10^{-3}	9.9×10^{-3}	9.8×10^{-3}	1.2×10^{-1}	3.4×10^{-1}
0.7	1.2×10^{-1}	1.5×10^{-1}	8.0×10^{-3}	7.3×10^{-3}	8.6×10^{-3}	8.4×10^{-3}	1.1×10^{-1}	4.1×10^{-1}
1	1.6×10^{-1}	2.1×10^{-1}	1.2×10^{-2}	9.7×10^{-3}	8.1×10^{-3}	7.6×10^{-3}	1.0×10^{-1}	5.0×10^{-1}
2	2.4×10^{-1}	3.2×10^{-1}	2.0×10^{-2}	1.4×10^{-2}	8.4×10^{-3}	7.0×10^{-3}	8.9×10^{-2}	6.9×10^{-1}
3	2.8×10^{-1}	3.7×10^{-1}	2.4×10^{-2}	1.4×10^{-2}	8.4×10^{-3}	6.4×10^{-3}	7.4×10^{-2}	7.7×10^{-1}
5	**3.1×10^{-1}**	**4.0×10^{-1}**	**2.6×10^{-2}**	**1.2×10^{-2}**	**7.4×10^{-3}**	**4.9×10^{-3}**	**5.1×10^{-2}**	**8.2×10^{-1}**
7	3.2×10^{-1}	4.1×10^{-1}	2.5×10^{-2}	9.6×10^{-3}	6.2×10^{-3}	3.7×10^{-3}	3.6×10^{-2}	8.1×10^{-1}
10	3.1×10^{-1}	4.0×10^{-1}	2.2×10^{-2}	6.8×10^{-3}	4.6×10^{-3}	2.5×10^{-3}	2.2×10^{-2}	7.7×10^{-1}
15	3.0×10^{-1}	3.8×10^{-1}	1.6×10^{-2}	3.9×10^{-3}	2.8×10^{-3}	1.3×10^{-3}	1.1×10^{-2}	7.1×10^{-1}
20	2.9×10^{-1}	3.6×10^{-1}	1.2×10^{-2}	2.4×10^{-3}	1.9×10^{-3}	7.8×10^{-4}	6.5×10^{-3}	6.7×10^{-1}
Habitual mouth breather (breathing rate = 1.7 $m^3\,h^{-1}$)								
0.0006	1.7×10^{-1}	5.9×10^{-1}	6.1×10^{-2}	6.1×10^{-2}	5.1×10^{-2}	5.1×10^{-2}	1.6×10^{-3}	9.9×10^{-1}
0.001	1.6×10^{-1}	4.9×10^{-1}	6.4×10^{-2}	6.4×10^{-2}	9.4×10^{-2}	9.4×10^{-2}	1.1×10^{-2}	9.8×10^{-1}
0.002	1.2×10^{-1}	3.5×10^{-1}	5.3×10^{-2}	5.3×10^{-2}	1.5×10^{-1}	1.5×10^{-1}	8.0×10^{-2}	9.5×10^{-1}
0.005	6.3×10^{-2}	1.7×10^{-1}	2.7×10^{-2}	2.7×10^{-2}	1.4×10^{-1}	1.4×10^{-1}	3.5×10^{-1}	9.2×10^{-1}
0.01	3.6×10^{-2}	9.6×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	9.1×10^{-2}	9.1×10^{-2}	5.4×10^{-1}	8.8×10^{-1}
0.02	2.2×10^{-2}	5.8×10^{-2}	7.8×10^{-3}	7.8×10^{-3}	5.9×10^{-2}	5.9×10^{-2}	5.1×10^{-1}	7.3×10^{-1}
0.05	1.3×10^{-2}	3.4×10^{-2}	4.5×10^{-3}	4.5×10^{-3}	3.3×10^{-2}	3.3×10^{-2}	3.2×10^{-1}	4.4×10^{-1}
0.1	1.1×10^{-2}	2.4×10^{-2}	3.4×10^{-3}	3.4×10^{-3}	2.1×10^{-2}	2.1×10^{-2}	2.1×10^{-1}	2.9×10^{-1}
0.2	1.4×10^{-2}	2.5×10^{-2}	4.5×10^{-3}	4.4×10^{-3}	1.4×10^{-2}	1.4×10^{-2}	1.5×10^{-1}	2.2×10^{-1}
0.5	2.2×10^{-2}	3.8×10^{-2}	8.4×10^{-3}	7.5×10^{-3}	1.1×10^{-2}	1.1×10^{-2}	1.4×10^{-1}	2.4×10^{-1}
0.7	3.2×10^{-2}	5.7×10^{-2}	1.4×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.4×10^{-1}	2.7×10^{-1}
1	4.4×10^{-2}	8.7×10^{-2}	2.3×10^{-2}	1.7×10^{-2}	1.3×10^{-2}	1.1×10^{-2}	1.5×10^{-1}	3.4×10^{-1}
2	7.5×10^{-2}	1.8×10^{-1}	4.9×10^{-2}	2.7×10^{-2}	1.9×10^{-2}	1.4×10^{-2}	1.6×10^{-1}	5.2×10^{-1}
3	9.3×10^{-2}	2.5×10^{-1}	6.6×10^{-2}	3.0×10^{-2}	2.3×10^{-2}	1.4×10^{-2}	1.5×10^{-1}	6.3×10^{-1}
5	**1.1×10^{-1}**	**3.4×10^{-1}**	**8.1×10^{-2}**	**2.8×10^{-2}**	**2.4×10^{-2}**	**1.2×10^{-2}**	**1.2×10^{-1}**	**7.1×10^{-1}**
7	1.2×10^{-1}	3.9×10^{-1}	8.2×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	9.8×10^{-3}	9.4×10^{-2}	7.4×10^{-1}
10	1.2×10^{-1}	4.3×10^{-1}	7.6×10^{-2}	1.7×10^{-2}	1.7×10^{-2}	6.9×10^{-3}	6.4×10^{-2}	7.3×10^{-1}
15	1.2×10^{-1}	4.5×10^{-1}	6.0×10^{-2}	1.0×10^{-3}	1.2×10^{-2}	4.0×10^{-3}	3.6×10^{-2}	6.9×10^{-1}
20	1.2×10^{-1}	4.5×10^{-1}	4.7×10^{-2}	6.7×10^{-3}	8.1×10^{-3}	2.4×10^{-3}	2.2×10^{-2}	6.6×10^{-1}

Table F.3. Fractional deposition in regions of the respiratory tract for sleeping subjects (normal nose breathers) as a function of aerosol size

AMTD (μm)	ET_1	ET_2	$BB_{fast+seq}$	BB_{slow}	$bb_{fast+seq}$	bb_{slow}	AI	Total
Adult male (breathing rate = 0.45 $m^3\,h^{-1}$)								
0.0006	4.6×10^{-1}	4.6×10^{-1}	3.0×10^{-2}	3.0×10^{-2}	6.1×10^{-3}	6.1×10^{-3}	1.3×10^{-6}	9.9×10^{-1}
0.001	4.2×10^{-1}	4.2×10^{-1}	4.8×10^{-2}	4.8×10^{-2}	2.3×10^{-2}	2.3×10^{-2}	9.9×10^{-5}	9.8×10^{-1}
0.002	3.2×10^{-1}	3.4×10^{-1}	6.2×10^{-2}	6.2×10^{-2}	7.9×10^{-2}	7.9×10^{-2}	6.3×10^{-3}	9.5×10^{-1}
0.005	1.7×10^{-1}	1.9×10^{-1}	4.5×10^{-2}	4.5×10^{-2}	1.5×10^{-1}	1.5×10^{-1}	1.3×10^{-1}	8.8×10^{-1}
0.01	9.7×10^{-2}	1.1×10^{-1}	2.5×10^{-2}	2.5×10^{-2}	1.3×10^{-1}	1.3×10^{-1}	3.2×10^{-1}	8.3×10^{-1}
0.02	5.7×10^{-2}	6.4×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	8.8×10^{-2}	8.8×10^{-2}	4.0×10^{-1}	7.3×10^{-1}
0.05	3.4×10^{-2}	3.6×10^{-2}	8.5×10^{-3}	8.5×10^{-3}	5.3×10^{-2}	5.3×10^{-2}	2.9×10^{-1}	4.8×10^{-1}
0.1	2.6×10^{-2}	2.6×10^{-2}	5.9×10^{-3}	5.9×10^{-3}	3.5×10^{-2}	3.5×10^{-2}	2.0×10^{-1}	3.3×10^{-1}
0.2	3.1×10^{-2}	3.1×10^{-2}	4.2×10^{-3}	4.2×10^{-3}	2.3×10^{-2}	2.3×10^{-2}	1.5×10^{-1}	2.7×10^{-1}
0.5	4.7×10^{-2}	5.1×10^{-2}	3.7×10^{-3}	3.6×10^{-3}	1.8×10^{-2}	1.8×10^{-2}	1.4×10^{-1}	2.8×10^{-1}
0.7	6.6×10^{-2}	7.6×10^{-2}	3.8×10^{-3}	3.5×10^{-3}	1.7×10^{-2}	1.6×10^{-2}	1.4×10^{-1}	3.2×10^{-1}
1	9.5×10^{-2}	1.1×10^{-1}	4.5×10^{-3}	3.7×10^{-3}	1.6×10^{-2}	1.5×10^{-2}	1.4×10^{-1}	3.9×10^{-1}
2	1.7×10^{-1}	2.1×10^{-1}	7.4×10^{-3}	4.4×10^{-3}	1.8×10^{-2}	1.5×10^{-2}	1.5×10^{-1}	5.7×10^{-1}
3	2.2×10^{-1}	2.7×10^{-1}	9.5×10^{-3}	4.5×10^{-3}	1.9×10^{-2}	1.3×10^{-2}	1.4×10^{-1}	6.7×10^{-1}
5	**2.7×10^{-1}**	**3.2×10^{-1}**	**1.2×10^{-2}**	**4.0×10^{-3}**	**1.8×10^{-2}**	**1.0×10^{-2}**	**1.1×10^{-1}**	**7.4×10^{-1}**
7	2.9×10^{-1}	3.4×10^{-1}	1.2×10^{-2}	3.2×10^{-3}	1.6×10^{-2}	7.8×10^{-3}	8.2×10^{-2}	7.5×10^{-1}
10	3.0×10^{-1}	3.5×10^{-1}	1.2×10^{-2}	2.3×10^{-3}	1.3×10^{-2}	5.3×10^{-3}	5.6×10^{-2}	7.4×10^{-1}
15	3.0×10^{-1}	3.4×10^{-1}	9.9×10^{-3}	1.4×10^{-3}	9.2×10^{-3}	2.9×10^{-3}	3.2×10^{-2}	7.0×10^{-1}
20	3.0×10^{-1}	3.2×10^{-1}	8.2×10^{-3}	8.9×10^{-4}	6.6×10^{-3}	1.7×10^{-3}	2.0×10^{-2}	6.6×10^{-1}
Adult female (breathing rate = 0.32 $m^3\,h^{-1}$)								
0.0006	4.7×10^{-1}	4.6×10^{-1}	2.9×10^{-2}	2.9×10^{-2}	4.0×10^{-3}	4.0×10^{-3}	1.1×10^{-7}	9.9×10^{-1}
0.001	4.2×10^{-1}	4.2×10^{-1}	4.9×10^{-2}	4.9×10^{-2}	1.7×10^{-2}	1.7×10^{-2}	1.9×10^{-5}	9.8×10^{-1}
0.002	3.3×10^{-1}	3.5×10^{-1}	6.8×10^{-2}	6.8×10^{-2}	6.9×10^{-2}	6.9×10^{-2}	2.6×10^{-3}	9.5×10^{-1}
0.005	1.8×10^{-1}	2.0×10^{-1}	5.1×10^{-2}	5.1×10^{-2}	1.5×10^{-1}	1.5×10^{-1}	8.7×10^{-2}	8.8×10^{-1}
0.01	1.0×10^{-1}	1.1×10^{-1}	2.9×10^{-2}	2.9×10^{-2}	1.4×10^{-1}	1.4×10^{-1}	2.6×10^{-1}	8.1×10^{-1}
0.02	5.9×10^{-2}	6.5×10^{-2}	1.7×10^{-2}	1.7×10^{-2}	1.0×10^{-1}	1.0×10^{-1}	3.5×10^{-1}	7.1×10^{-1}
0.05	3.4×10^{-2}	3.7×10^{-2}	9.8×10^{-3}	9.8×10^{-3}	6.1×10^{-2}	6.1×10^{-2}	2.6×10^{-1}	4.7×10^{-1}
0.1	2.6×10^{-2}	2.6×10^{-2}	6.8×10^{-3}	6.8×10^{-3}	4.1×10^{-2}	4.1×10^{-2}	1.8×10^{-1}	3.3×10^{-1}
0.2	2.9×10^{-2}	2.9×10^{-2}	4.8×10^{-3}	4.7×10^{-3}	2.7×10^{-2}	2.7×10^{-2}	1.4×10^{-1}	2.6×10^{-1}
0.5	4.3×10^{-2}	4.6×10^{-2}	4.0×10^{-3}	3.9×10^{-3}	2.2×10^{-2}	2.2×10^{-2}	1.3×10^{-1}	2.7×10^{-1}
0.7	6.1×10^{-2}	6.9×10^{-2}	3.9×10^{-3}	3.6×10^{-3}	2.0×10^{-2}	2.0×10^{-2}	1.3×10^{-1}	3.1×10^{-1}
1	8.8×10^{-2}	1.0×10^{-1}	4.3×10^{-3}	3.6×10^{-3}	2.0×10^{-2}	1.9×10^{-2}	1.4×10^{-1}	3.8×10^{-1}
2	1.6×10^{-1}	1.9×10^{-1}	6.7×10^{-3}	4.0×10^{-3}	2.3×10^{-2}	1.8×10^{-2}	1.5×10^{-1}	5.5×10^{-1}
3	2.1×10^{-1}	2.5×10^{-1}	8.7×10^{-3}	4.0×10^{-3}	2.4×10^{-2}	1.7×10^{-2}	1.4×10^{-1}	6.5×10^{-1}
5	**2.6×10^{-1}**	**3.1×10^{-1}**	**1.1×10^{-2}**	**3.5×10^{-3}**	**2.3×10^{-2}**	**1.3×10^{-2}**	**1.1×10^{-1}**	**7.2×10^{-1}**
7	2.8×10^{-1}	3.3×10^{-1}	1.1×10^{-2}	2.9×10^{-3}	2.0×10^{-2}	9.7×10^{-3}	8.3×10^{-2}	7.4×10^{-1}
10	3.0×10^{-1}	3.4×10^{-1}	1.1×10^{-2}	2.1×10^{-3}	1.7×10^{-2}	6.5×10^{-3}	5.7×10^{-2}	7.3×10^{-1}
15	3.0×10^{-1}	3.3×10^{-1}	9.6×10^{-3}	1.3×10^{-3}	1.2×10^{-2}	3.6×10^{-3}	3.3×10^{-2}	6.9×10^{-1}
20	2.9×10^{-1}	3.2×10^{-1}	8.1×10^{-3}	8.0×10^{-4}	8.3×10^{-3}	2.2×10^{-3}	2.0×10^{-2}	6.6×10^{-1}

Male 15 y old (breathing rate = 0.42 m³ h⁻¹)								
0.0006	4.6×10^{-1}	4.6×10^{-1}	3.0×10^{-2}	3.0×10^{-2}	5.7×10^{-3}	5.7×10^{-3}	1.2×10^{-6}	9.9×10^{-1}
0.001	4.2×10^{-1}	4.2×10^{-1}	4.8×10^{-2}	4.8×10^{-2}	2.1×10^{-2}	2.1×10^{-2}	9.6×10^{-5}	9.8×10^{-1}
0.002	3.2×10^{-1}	3.4×10^{-1}	6.3×10^{-2}	6.3×10^{-2}	7.6×10^{-2}	7.6×10^{-2}	6.0×10^{-3}	9.5×10^{-1}
0.005	1.7×10^{-1}	2.0×10^{-1}	4.5×10^{-2}	4.5×10^{-2}	1.5×10^{-1}	1.5×10^{-1}	1.2×10^{-1}	8.7×10^{-1}
0.01	9.8×10^{-2}	1.1×10^{-1}	2.6×10^{-2}	2.6×10^{-2}	1.2×10^{-1}	1.2×10^{-1}	3.0×10^{-1}	8.1×10^{-1}
0.02	5.8×10^{-2}	6.5×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	8.6×10^{-2}	8.6×10^{-2}	3.8×10^{-1}	7.0×10^{-1}
0.05	3.4×10^{-2}	3.7×10^{-2}	8.7×10^{-3}	8.7×10^{-3}	5.2×10^{-2}	5.2×10^{-2}	2.6×10^{-1}	4.6×10^{-1}
0.1	2.6×10^{-2}	2.7×10^{-2}	6.0×10^{-3}	6.0×10^{-3}	3.4×10^{-2}	3.4×10^{-2}	1.8×10^{-1}	3.2×10^{-1}
0.2	3.2×10^{-2}	3.2×10^{-2}	4.3×10^{-3}	4.3×10^{-3}	2.3×10^{-2}	2.3×10^{-2}	1.4×10^{-1}	2.6×10^{-1}
0.5	4.8×10^{-2}	5.3×10^{-2}	3.7×10^{-3}	3.6×10^{-3}	1.8×10^{-2}	1.7×10^{-2}	1.3×10^{-1}	2.7×10^{-1}
0.7	6.9×10^{-2}	7.9×10^{-2}	3.8×10^{-3}	3.5×10^{-3}	1.6×10^{-2}	1.5×10^{-2}	1.3×10^{-1}	3.1×10^{-1}
1	9.8×10^{-2}	1.2×10^{-1}	4.5×10^{-3}	3.7×10^{-3}	1.5×10^{-2}	1.4×10^{-2}	1.3×10^{-1}	3.9×10^{-1}
2	1.7×10^{-1}	2.1×10^{-1}	7.3×10^{-3}	4.4×10^{-3}	1.7×10^{-2}	1.4×10^{-2}	1.4×10^{-1}	5.7×10^{-1}
3	2.2×10^{-1}	2.7×10^{-1}	9.3×10^{-3}	4.5×10^{-3}	1.8×10^{-2}	1.2×10^{-2}	1.3×10^{-1}	6.6×10^{-1}
5	**2.7×10^{-1}**	**3.3×10^{-1}**	**1.1×10^{-2}**	**3.9×10^{-3}**	**1.7×10^{-2}**	**9.6×10^{-3}**	**9.8×10^{-2}**	**7.4×10^{-1}**
7	2.9×10^{-1}	3.5×10^{-1}	1.2×10^{-2}	3.2×10^{-3}	1.5×10^{-2}	7.3×10^{-3}	7.4×10^{-2}	7.5×10^{-1}
10	3.1×10^{-1}	3.5×10^{-1}	1.1×10^{-2}	2.3×10^{-3}	1.2×10^{-2}	4.9×10^{-3}	5.1×10^{-2}	7.4×10^{-1}
15	3.1×10^{-1}	3.4×10^{-1}	9.5×10^{-3}	1.4×10^{-3}	8.5×10^{-3}	2.7×10^{-3}	2.9×10^{-2}	7.0×10^{-1}
20	3.0×10^{-1}	3.2×10^{-1}	7.9×10^{-3}	8.7×10^{-4}	6.0×10^{-3}	1.6×10^{-3}	1.8×10^{-2}	6.6×10^{-1}
Female 15 y old (breathing rate = 0.35 m³ h⁻¹)								
0.0006	4.7×10^{-1}	4.6×10^{-1}	2.9×10^{-2}	2.9×10^{-2}	4.5×10^{-3}	4.5×10^{-3}	4.9×10^{-7}	9.9×10^{-1}
0.001	4.2×10^{-1}	4.2×10^{-1}	4.9×10^{-2}	4.9×10^{-2}	1.8×10^{-2}	1.8×10^{-2}	5.1×10^{-5}	9.8×10^{-1}
0.002	3.3×10^{-1}	3.4×10^{-1}	6.6×10^{-2}	6.6×10^{-2}	7.1×10^{-2}	7.1×10^{-2}	4.3×10^{-3}	9.5×10^{-1}
0.005	1.8×10^{-1}	2.0×10^{-1}	4.8×10^{-2}	4.8×10^{-2}	1.5×10^{-1}	1.5×10^{-1}	1.1×10^{-1}	8.7×10^{-1}
0.01	9.9×10^{-2}	1.1×10^{-1}	2.8×10^{-2}	2.8×10^{-2}	1.3×10^{-1}	1.3×10^{-1}	2.8×10^{-1}	8.0×10^{-1}
0.02	5.9×10^{-2}	6.5×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	9.0×10^{-2}	9.0×10^{-2}	3.6×10^{-1}	7.0×10^{-1}
0.05	3.4×10^{-2}	3.7×10^{-2}	9.4×10^{-3}	9.4×10^{-3}	5.4×10^{-2}	5.4×10^{-2}	2.6×10^{-1}	4.6×10^{-1}
0.1	2.6×10^{-2}	2.7×10^{-2}	6.5×10^{-3}	6.5×10^{-3}	3.6×10^{-2}	3.6×10^{-2}	1.8×10^{-1}	3.2×10^{-1}
0.2	3.1×10^{-2}	3.2×10^{-2}	4.6×10^{-3}	4.6×10^{-3}	2.4×10^{-2}	2.4×10^{-2}	1.4×10^{-1}	2.6×10^{-1}
0.5	4.7×10^{-2}	5.1×10^{-2}	3.9×10^{-3}	3.8×10^{-3}	1.9×10^{-2}	1.8×10^{-2}	1.3×10^{-1}	2.7×10^{-1}
0.7	6.7×10^{-2}	7.6×10^{-2}	3.9×10^{-3}	3.6×10^{-3}	1.7×10^{-2}	1.6×10^{-2}	1.3×10^{-1}	3.1×10^{-1}
1	9.5×10^{-2}	1.1×10^{-1}	4.4×10^{-3}	3.7×10^{-3}	1.6×10^{-2}	1.5×10^{-2}	1.3×10^{-1}	3.8×10^{-1}
2	1.7×10^{-1}	2.1×10^{-1}	6.9×10^{-3}	4.2×10^{-3}	1.8×10^{-2}	1.4×10^{-2}	1.4×10^{-1}	5.6×10^{-1}
3	2.2×10^{-1}	2.7×10^{-1}	8.9×10^{-3}	4.3×10^{-3}	1.9×10^{-2}	1.3×10^{-2}	1.3×10^{-1}	6.6×10^{-1}
5	**2.7×10^{-1}**	**3.2×10^{-1}**	**1.1×10^{-2}**	**3.7×10^{-3}**	**1.8×10^{-2}**	**1.0×10^{-2}**	**9.9×10^{-2}**	**7.3×10^{-1}**
7	2.9×10^{-1}	3.4×10^{-1}	1.1×10^{-2}	3.0×10^{-3}	1.6×10^{-2}	7.6×10^{-3}	7.6×10^{-2}	7.5×10^{-1}
10	3.0×10^{-1}	3.5×10^{-1}	1.1×10^{-2}	2.2×10^{-3}	1.3×10^{-2}	5.1×10^{-3}	5.2×10^{-2}	7.3×10^{-1}
15	3.0×10^{-1}	3.4×10^{-1}	9.3×10^{-3}	1.3×10^{-3}	9.1×10^{-3}	2.8×10^{-3}	3.0×10^{-2}	6.9×10^{-1}
20	3.0×10^{-1}	3.2×10^{-1}	7.7×10^{-3}	8.3×10^{-4}	6.5×10^{-3}	1.7×10^{-3}	1.8×10^{-2}	6.6×10^{-1}

Continued overleaf

Table F.3.—(*continued*)

AMTD (μm)	ET$_1$	ET$_2$	BB$_{\text{fast+seq}}$	BB$_{\text{slow}}$	bb$_{\text{fast+seq}}$	bb$_{\text{slow}}$	AI	Total
Child 10 y old (breathing rate = 0.31 m^3 h^{-1})								
0.0006	4.7×10^{-1}	4.6×10^{-1}	3.0×10^{-2}	3.0×10^{-2}	4.5×10^{-3}	4.5×10^{-3}	5.4×10^{-7}	9.9×10^{-1}
0.001	4.2×10^{-1}	4.2×10^{-1}	5.0×10^{-2}	5.0×10^{-2}	1.8×10^{-2}	1.8×10^{-2}	5.6×10^{-5}	9.8×10^{-1}
0.002	3.3×10^{-1}	3.4×10^{-1}	6.8×10^{-2}	6.8×10^{-2}	7.1×10^{-2}	7.1×10^{-2}	4.6×10^{-3}	9.5×10^{-1}
0.005	1.8×10^{-1}	2.0×10^{-1}	5.0×10^{-2}	5.0×10^{-2}	1.5×10^{-1}	1.5×10^{-1}	1.1×10^{-1}	8.8×10^{-1}
0.01	9.9×10^{-2}	1.1×10^{-1}	2.9×10^{-2}	2.9×10^{-2}	1.3×10^{-1}	1.3×10^{-1}	2.9×10^{-1}	8.1×10^{-1}
0.02	5.8×10^{-2}	6.5×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	9.0×10^{-2}	9.0×10^{-2}	3.8×10^{-1}	7.1×10^{-1}
0.05	3.4×10^{-2}	3.7×10^{-2}	9.6×10^{-3}	9.6×10^{-3}	5.4×10^{-2}	5.4×10^{-2}	2.7×10^{-1}	4.7×10^{-1}
0.1	2.7×10^{-2}	2.8×10^{-2}	6.7×10^{-3}	6.7×10^{-3}	3.6×10^{-2}	3.6×10^{-2}	1.9×10^{-1}	3.3×10^{-1}
0.2	3.6×10^{-2}	3.8×10^{-2}	4.7×10^{-3}	4.7×10^{-3}	2.4×10^{-2}	2.4×10^{-2}	1.4×10^{-1}	2.7×10^{-1}
0.5	5.7×10^{-2}	6.4×10^{-2}	4.1×10^{-3}	4.0×10^{-3}	1.8×10^{-2}	1.8×10^{-2}	1.3×10^{-1}	2.9×10^{-1}
0.7	8.0×10^{-2}	9.4×10^{-2}	4.1×10^{-3}	3.8×10^{-3}	1.5×10^{-2}	1.5×10^{-2}	1.3×10^{-1}	3.4×10^{-1}
1	1.1×10^{-1}	1.4×10^{-1}	4.6×10^{-3}	4.0×10^{-3}	1.4×10^{-2}	1.3×10^{-2}	1.3×10^{-1}	4.2×10^{-1}
2	1.9×10^{-1}	2.4×10^{-1}	7.0×10^{-3}	4.5×10^{-3}	1.4×10^{-2}	1.2×10^{-2}	1.3×10^{-1}	6.0×10^{-1}
3	2.4×10^{-1}	3.0×10^{-1}	8.6×10^{-3}	4.5×10^{-3}	1.4×10^{-2}	1.0×10^{-2}	1.2×10^{-1}	6.9×10^{-1}
5	**2.9×10^{-1}**	**3.5×10^{-1}**	**1.0×10^{-2}**	**3.8×10^{-3}**	**1.3×10^{-2}**	**7.7×10^{-3}**	**8.7×10^{-2}**	**7.6×10^{-1}**
7	3.1×10^{-1}	3.6×10^{-1}	1.0×10^{-2}	3.1×10^{-3}	1.1×10^{-2}	5.7×10^{-3}	6.5×10^{-2}	7.7×10^{-1}
10	3.2×10^{-1}	3.6×10^{-1}	9.6×10^{-3}	2.2×10^{-3}	9.0×10^{-3}	3.8×10^{-3}	4.3×10^{-2}	7.5×10^{-1}
15	3.1×10^{-1}	3.4×10^{-1}	8.0×10^{-3}	1.3×10^{-3}	6.1×10^{-3}	2.1×10^{-3}	2.4×10^{-2}	7.0×10^{-1}
20	3.1×10^{-1}	3.3×10^{-1}	6.5×10^{-3}	8.1×10^{-4}	4.3×10^{-3}	1.2×10^{-3}	1.5×10^{-2}	6.6×10^{-1}
Child 5 y old (breathing rate = 0.24 m^3 h^{-1})								
0.0006	4.7×10^{-1}	4.6×10^{-1}	3.1×10^{-2}	3.1×10^{-2}	3.7×10^{-3}	3.7×10^{-3}	3.6×10^{-7}	9.9×10^{-1}
0.001	4.2×10^{-1}	4.2×10^{-1}	5.2×10^{-2}	5.2×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	4.2×10^{-5}	9.8×10^{-1}
0.002	3.3×10^{-1}	3.5×10^{-1}	7.2×10^{-2}	7.2×10^{-2}	6.7×10^{-2}	6.7×10^{-2}	3.9×10^{-3}	9.6×10^{-1}
0.005	1.8×10^{-1}	2.0×10^{-1}	5.4×10^{-2}	5.4×10^{-2}	1.5×10^{-1}	1.5×10^{-1}	1.0×10^{-1}	8.8×10^{-1}
0.01	9.9×10^{-2}	1.1×10^{-1}	3.1×10^{-2}	3.1×10^{-2}	1.3×10^{-1}	1.3×10^{-1}	2.8×10^{-1}	8.1×10^{-1}
0.02	5.8×10^{-2}	6.4×10^{-2}	1.8×10^{-2}	1.8×10^{-2}	9.0×10^{-2}	9.0×10^{-2}	3.8×10^{-1}	7.1×10^{-1}
0.05	3.4×10^{-2}	3.6×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	5.4×10^{-2}	5.4×10^{-2}	2.8×10^{-1}	4.8×10^{-1}
0.1	2.9×10^{-2}	3.0×10^{-2}	7.2×10^{-3}	7.2×10^{-3}	3.6×10^{-2}	3.6×10^{-2}	2.0×10^{-1}	3.4×10^{-1}
0.2	4.4×10^{-2}	4.7×10^{-2}	5.2×10^{-3}	5.1×10^{-3}	2.3×10^{-2}	2.3×10^{-2}	1.5×10^{-1}	3.0×10^{-1}
0.5	7.1×10^{-2}	8.2×10^{-2}	4.4×10^{-3}	4.3×10^{-3}	1.7×10^{-2}	1.7×10^{-2}	1.3×10^{-1}	3.2×10^{-1}
0.7	9.9×10^{-2}	1.2×10^{-1}	4.4×10^{-3}	4.2×10^{-3}	1.4×10^{-2}	1.4×10^{-2}	1.2×10^{-1}	3.8×10^{-1}
1	1.4×10^{-1}	1.7×10^{-1}	4.8×10^{-3}	4.3×10^{-3}	1.2×10^{-2}	1.2×10^{-2}	1.2×10^{-1}	4.6×10^{-1}
2	2.2×10^{-1}	2.8×10^{-1}	6.7×10^{-3}	4.7×10^{-3}	1.1×10^{-2}	9.2×10^{-3}	1.1×10^{-1}	6.4×10^{-1}
3	2.7×10^{-1}	3.3×10^{-1}	8.0×10^{-3}	4.5×10^{-3}	1.0×10^{-2}	7.8×10^{-3}	9.4×10^{-2}	7.3×10^{-1}
5	**3.2×10^{-1}**	**3.8×10^{-1}**	**8.9×10^{-3}**	**3.7×10^{-3}**	**8.8×10^{-3}**	**5.6×10^{-3}**	**6.8×10^{-2}**	**7.9×10^{-1}**
7	3.3×10^{-1}	3.8×10^{-1}	8.7×10^{-3}	2.9×10^{-3}	7.4×10^{-3}	4.1×10^{-3}	4.9×10^{-2}	7.9×10^{-1}
10	3.3×10^{-1}	3.7×10^{-1}	8.0×10^{-3}	2.1×10^{-3}	5.7×10^{-3}	2.6×10^{-3}	3.2×10^{-2}	7.6×10^{-1}
15	3.3×10^{-1}	3.5×10^{-1}	6.4×10^{-3}	1.2×10^{-3}	3.8×10^{-3}	1.4×10^{-3}	1.7×10^{-2}	7.1×10^{-1}
20	3.1×10^{-1}	3.3×10^{-1}	5.1×10^{-3}	7.4×10^{-4}	2.6×10^{-3}	8.3×10^{-4}	1.0×10^{-2}	6.7×10^{-1}

Infant 1 y old (breathing rate = 0.15 $m^3 h^{-1}$)								
0.0006	4.7×10^{-1}	4.6×10^{-1}	3.2×10^{-2}	3.2×10^{-2}	2.1×10^{-3}	2.1×10^{-3}	7.5×10^{-8}	9.9×10^{-1}
0.001	4.3×10^{-1}	4.3×10^{-1}	5.7×10^{-2}	5.7×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.5×10^{-5}	9.9×10^{-1}
0.002	3.3×10^{-1}	3.5×10^{-1}	8.4×10^{-2}	8.4×10^{-2}	5.7×10^{-2}	5.7×10^{-2}	2.2×10^{-3}	9.6×10^{-1}
0.005	1.8×10^{-1}	2.0×10^{-1}	6.7×10^{-2}	6.7×10^{-2}	1.4×10^{-1}	1.4×10^{-1}	8.2×10^{-2}	8.8×10^{-1}
0.01	1.0×10^{-1}	1.1×10^{-1}	3.9×10^{-2}	3.9×10^{-2}	1.3×10^{-1}	1.3×10^{-1}	2.5×10^{-1}	8.1×10^{-1}
0.02	5.7×10^{-2}	6.4×10^{-2}	2.2×10^{-2}	2.2×10^{-2}	9.2×10^{-2}	9.2×10^{-2}	3.7×10^{-1}	7.2×10^{-1}
0.05	3.4×10^{-2}	3.6×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	5.6×10^{-2}	5.6×10^{-2}	3.0×10^{-1}	5.1×10^{-1}
0.1	3.4×10^{-2}	3.5×10^{-2}	8.8×10^{-3}	8.8×10^{-3}	3.7×10^{-2}	3.7×10^{-2}	2.2×10^{-1}	3.8×10^{-1}
0.2	5.9×10^{-2}	6.8×10^{-2}	6.3×10^{-3}	6.2×10^{-3}	2.4×10^{-2}	2.4×10^{-2}	1.6×10^{-1}	3.5×10^{-1}
0.5	9.7×10^{-2}	1.2×10^{-1}	5.2×10^{-3}	5.2×10^{-3}	1.7×10^{-2}	1.7×10^{-2}	1.3×10^{-1}	3.9×10^{-1}
0.7	1.3×10^{-1}	1.7×10^{-1}	5.0×10^{-3}	4.8×10^{-3}	1.4×10^{-2}	1.4×10^{-2}	1.2×10^{-1}	4.5×10^{-1}
1	1.8×10^{-1}	2.3×10^{-1}	5.1×10^{-3}	4.7×10^{-3}	1.1×10^{-2}	1.1×10^{-2}	1.1×10^{-1}	5.4×10^{-1}
2	2.7×10^{-1}	3.4×10^{-1}	6.1×10^{-3}	4.6×10^{-3}	7.7×10^{-3}	7.0×10^{-3}	8.3×10^{-2}	7.2×10^{-1}
3	3.1×10^{-1}	3.8×10^{-1}	6.7×10^{-3}	4.3×10^{-3}	6.5×10^{-3}	5.4×10^{-3}	6.7×10^{-2}	7.9×10^{-1}
5	$\mathbf{3.5 \times 10^{-1}}$	$\mathbf{4.1 \times 10^{-1}}$	$\mathbf{6.9 \times 10^{-3}}$	$\mathbf{3.4 \times 10^{-3}}$	$\mathbf{5.0 \times 10^{-3}}$	$\mathbf{3.5 \times 10^{-3}}$	$\mathbf{4.4 \times 10^{-2}}$	$\mathbf{8.2 \times 10^{-1}}$
7	3.6×10^{-1}	4.1×10^{-1}	6.5×10^{-3}	2.6×10^{-3}	4.0×10^{-3}	2.5×10^{-3}	3.0×10^{-2}	8.1×10^{-1}
10	3.5×10^{-1}	3.9×10^{-1}	5.7×10^{-3}	1.7×10^{-3}	2.9×10^{-3}	1.5×10^{-3}	1.9×10^{-2}	7.7×10^{-1}
15	3.4×10^{-1}	3.6×10^{-1}	4.4×10^{-3}	9.8×10^{-4}	1.8×10^{-3}	7.9×10^{-4}	9.5×10^{-3}	7.1×10^{-1}
20	3.2×10^{-1}	3.4×10^{-1}	3.4×10^{-3}	6.0×10^{-4}	1.2×10^{-3}	4.5×10^{-4}	5.4×10^{-3}	6.7×10^{-1}
Infant 3 mo old (breathing rate = 0.090 $m^3 h^{-1}$)								
0.0006	4.7×10^{-1}	4.6×10^{-1}	3.0×10^{-2}	3.0×10^{-2}	7.4×10^{-4}	7.4×10^{-4}	1.8×10^{-9}	$1.0 \times 10^{+0}$
0.001	4.3×10^{-1}	4.3×10^{-1}	5.8×10^{-2}	5.8×10^{-2}	5.8×10^{-3}	5.8×10^{-3}	1.2×10^{-6}	9.9×10^{-1}
0.002	3.4×10^{-1}	3.5×10^{-1}	9.6×10^{-2}	9.6×10^{-2}	4.0×10^{-2}	4.0×10^{-2}	5.7×10^{-4}	9.6×10^{-1}
0.005	1.8×10^{-1}	2.1×10^{-1}	8.4×10^{-2}	8.4×10^{-2}	1.4×10^{-1}	1.4×10^{-1}	4.6×10^{-2}	8.8×10^{-1}
0.01	1.0×10^{-1}	1.2×10^{-1}	5.1×10^{-2}	5.1×10^{-2}	1.4×10^{-1}	1.4×10^{-1}	1.8×10^{-1}	7.8×10^{-1}
0.02	5.9×10^{-2}	6.6×10^{-2}	2.9×10^{-2}	2.9×10^{-2}	1.0×10^{-1}	1.0×10^{-1}	2.9×10^{-1}	6.8×10^{-1}
0.05	3.4×10^{-2}	3.7×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	6.4×10^{-2}	6.4×10^{-2}	2.5×10^{-1}	4.9×10^{-1}
0.1	3.5×10^{-2}	3.7×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	4.3×10^{-2}	4.3×10^{-2}	1.9×10^{-1}	3.7×10^{-1}
0.2	6.2×10^{-2}	7.1×10^{-2}	8.0×10^{-3}	8.0×10^{-3}	2.8×10^{-2}	2.8×10^{-2}	1.4×10^{-1}	3.4×10^{-1}
0.5	1.0×10^{-1}	1.2×10^{-1}	6.3×10^{-3}	6.3×10^{-3}	2.0×10^{-2}	2.0×10^{-2}	1.1×10^{-1}	3.9×10^{-1}
0.7	1.4×10^{-1}	1.7×10^{-1}	5.7×10^{-3}	5.5×10^{-3}	1.6×10^{-2}	1.6×10^{-2}	9.8×10^{-2}	4.5×10^{-1}
1	1.8×10^{-1}	2.4×10^{-1}	5.4×10^{-3}	5.0×10^{-3}	1.2×10^{-2}	1.2×10^{-2}	8.7×10^{-2}	5.4×10^{-1}
2	2.7×10^{-1}	3.5×10^{-1}	5.7×10^{-3}	4.4×10^{-3}	8.3×10^{-3}	7.7×10^{-3}	6.7×10^{-2}	7.2×10^{-1}
3	3.2×10^{-1}	3.9×10^{-1}	6.1×10^{-3}	4.0×10^{-3}	6.7×10^{-3}	5.7×10^{-3}	5.3×10^{-2}	7.9×10^{-1}
5	$\mathbf{3.5 \times 10^{-1}}$	$\mathbf{4.1 \times 10^{-1}}$	$\mathbf{6.1 \times 10^{-3}}$	$\mathbf{3.0 \times 10^{-3}}$	$\mathbf{5.0 \times 10^{-3}}$	$\mathbf{3.6 \times 10^{-3}}$	$\mathbf{3.5 \times 10^{-2}}$	$\mathbf{8.2 \times 10^{-1}}$
7	3.6×10^{-1}	4.1×10^{-1}	5.7×10^{-3}	2.3×10^{-3}	3.9×10^{-3}	2.5×10^{-3}	2.4×10^{-2}	8.1×10^{-1}
10	3.6×10^{-1}	3.9×10^{-1}	5.0×10^{-3}	1.5×10^{-3}	2.8×10^{-3}	1.5×10^{-3}	1.5×10^{-2}	7.7×10^{-1}
15	3.4×10^{-1}	3.6×10^{-1}	3.9×10^{-3}	8.6×10^{-4}	1.7×10^{-3}	7.7×10^{-4}	7.5×10^{-3}	7.1×10^{-1}
20	3.2×10^{-1}	3.4×10^{-1}	3.0×10^{-3}	5.2×10^{-4}	1.1×10^{-3}	4.4×10^{-4}	4.3×10^{-3}	6.7×10^{-1}

Table F.4. Fractional deposition in regions of the respiratory tract for resting (sitting) subjects (normal nose breathers) as a function of aerosol size

AMTD (μm)	ET_1	ET_2	$BB_{fast+seq}$	BB_{slow}	$bb_{fast+seq}$	bb_{slow}	AI	Total
			Adult male (breathing rate = 0.54 $m^3 h^{-1}$)					
0.0006	4.6×10^{-1}	4.5×10^{-1}	3.1×10^{-2}	3.1×10^{-2}	7.8×10^{-3}	7.8×10^{-3}	3.8×10^{-6}	9.9×10^{-1}
0.001	4.2×10^{-1}	4.2×10^{-1}	4.8×10^{-2}	4.8×10^{-2}	2.7×10^{-2}	2.7×10^{-2}	2.1×10^{-4}	9.8×10^{-1}
0.002	3.2×10^{-1}	3.4×10^{-1}	6.0×10^{-2}	6.0×10^{-2}	8.7×10^{-2}	8.7×10^{-2}	9.4×10^{-3}	9.6×10^{-1}
0.005	1.7×10^{-1}	1.9×10^{-1}	4.1×10^{-2}	4.1×10^{-2}	1.5×10^{-1}	1.5×10^{-1}	1.5×10^{-1}	9.0×10^{-1}
0.01	9.5×10^{-2}	1.1×10^{-1}	2.3×10^{-2}	2.3×10^{-2}	1.2×10^{-1}	1.2×10^{-1}	3.6×10^{-1}	8.5×10^{-1}
0.02	5.6×10^{-2}	6.2×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	8.4×10^{-2}	8.4×10^{-2}	4.4×10^{-1}	7.5×10^{-1}
0.05	3.3×10^{-2}	3.5×10^{-2}	7.8×10^{-3}	7.8×10^{-3}	5.0×10^{-2}	5.0×10^{-2}	3.1×10^{-1}	4.9×10^{-1}
0.1	2.6×10^{-2}	2.6×10^{-2}	5.4×10^{-3}	5.4×10^{-3}	3.3×10^{-2}	3.3×10^{-2}	2.2×10^{-1}	3.5×10^{-1}
0.2	3.3×10^{-2}	3.4×10^{-2}	3.9×10^{-3}	3.9×10^{-3}	2.2×10^{-2}	2.2×10^{-2}	1.6×10^{-1}	2.8×10^{-1}
0.5	5.2×10^{-2}	5.7×10^{-2}	3.6×10^{-3}	3.5×10^{-3}	1.7×10^{-2}	1.7×10^{-2}	1.5×10^{-1}	3.0×10^{-1}
0.7	7.4×10^{-2}	8.6×10^{-2}	3.9×10^{-3}	3.6×10^{-3}	1.5×10^{-2}	1.5×10^{-2}	1.5×10^{-1}	3.4×10^{-1}
1	1.0×10^{-1}	1.3×10^{-1}	4.7×10^{-3}	3.9×10^{-3}	1.4×10^{-2}	1.4×10^{-2}	1.5×10^{-1}	4.2×10^{-1}
2	1.8×10^{-1}	2.3×10^{-1}	7.8×10^{-3}	4.9×10^{-3}	1.6×10^{-2}	1.3×10^{-2}	1.5×10^{-1}	6.0×10^{-1}
3	2.3×10^{-1}	2.8×10^{-1}	1.0×10^{-2}	5.0×10^{-3}	1.6×10^{-2}	1.1×10^{-2}	1.4×10^{-1}	6.9×10^{-1}
5	**2.8×10^{-1}**	**3.4×10^{-1}**	**1.2×10^{-2}**	**4.3×10^{-3}**	**1.5×10^{-2}**	**8.7×10^{-3}**	**1.0×10^{-1}**	**7.6×10^{-1}**
7	3.0×10^{-1}	3.5×10^{-1}	1.2×10^{-2}	3.5×10^{-3}	1.3×10^{-2}	6.6×10^{-3}	7.8×10^{-2}	7.7×10^{-1}
10	3.1×10^{-1}	3.5×10^{-1}	1.2×10^{-2}	2.5×10^{-3}	1.1×10^{-2}	4.4×10^{-3}	5.2×10^{-2}	7.5×10^{-1}
15	3.1×10^{-1}	3.4×10^{-1}	9.6×10^{-3}	1.5×10^{-3}	7.2×10^{-3}	2.4×10^{-3}	2.9×10^{-2}	7.0×10^{-1}
20	3.0×10^{-1}	3.3×10^{-1}	7.8×10^{-3}	9.5×10^{-4}	5.1×10^{-3}	1.4×10^{-3}	1.8×10^{-2}	6.6×10^{-1}
			Adult female (breathing rate = 0.39 $m^3 h^{-1}$)					
0.0006	4.6×10^{-1}	4.6×10^{-1}	3.0×10^{-2}	3.0×10^{-2}	5.4×10^{-3}	5.4×10^{-3}	4.7×10^{-7}	9.9×10^{-1}
0.001	4.2×10^{-1}	4.2×10^{-1}	4.8×10^{-2}	4.8×10^{-2}	2.1×10^{-2}	2.1×10^{-2}	5.0×10^{-5}	9.8×10^{-1}
0.002	3.2×10^{-1}	3.4×10^{-1}	6.4×10^{-2}	6.4×10^{-2}	7.6×10^{-2}	7.6×10^{-2}	4.3×10^{-3}	9.5×10^{-1}
0.005	1.7×10^{-1}	2.0×10^{-1}	4.6×10^{-2}	4.6×10^{-2}	1.5×10^{-1}	1.5×10^{-1}	1.1×10^{-1}	8.8×10^{-1}
0.01	9.8×10^{-2}	1.1×10^{-1}	2.6×10^{-2}	2.6×10^{-2}	1.3×10^{-1}	1.3×10^{-1}	2.8×10^{-1}	8.1×10^{-1}
0.02	5.8×10^{-2}	6.5×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	9.4×10^{-2}	9.4×10^{-2}	3.6×10^{-1}	7.0×10^{-1}
0.05	3.4×10^{-2}	3.7×10^{-2}	8.9×10^{-3}	8.9×10^{-3}	5.7×10^{-2}	5.7×10^{-2}	2.6×10^{-1}	4.6×10^{-1}
0.1	2.6×10^{-2}	2.7×10^{-2}	6.2×10^{-3}	6.2×10^{-3}	3.8×10^{-2}	3.8×10^{-2}	1.8×10^{-1}	3.2×10^{-1}
0.2	3.2×10^{-2}	3.3×10^{-2}	4.4×10^{-3}	4.4×10^{-3}	2.5×10^{-2}	2.5×10^{-2}	1.3×10^{-1}	2.6×10^{-1}
0.5	4.9×10^{-2}	5.4×10^{-2}	3.8×10^{-3}	3.7×10^{-3}	2.0×10^{-2}	1.9×10^{-2}	1.2×10^{-1}	2.7×10^{-1}
0.7	7.0×10^{-2}	8.0×10^{-2}	3.9×10^{-3}	3.6×10^{-3}	1.8×10^{-2}	1.7×10^{-2}	1.2×10^{-1}	3.2×10^{-1}
1	1.0×10^{-1}	1.2×10^{-1}	4.5×10^{-3}	3.8×10^{-3}	1.7×10^{-2}	1.6×10^{-2}	1.3×10^{-1}	3.9×10^{-1}
2	1.8×10^{-1}	2.2×10^{-1}	7.2×10^{-3}	4.4×10^{-3}	1.8×10^{-2}	1.5×10^{-2}	1.3×10^{-1}	5.7×10^{-1}
3	2.2×10^{-1}	2.7×10^{-1}	9.2×10^{-3}	4.5×10^{-3}	1.9×10^{-2}	1.4×10^{-2}	1.2×10^{-1}	6.6×10^{-1}
5	**2.7×10^{-1}**	**3.3×10^{-1}**	**1.1×10^{-2}**	**3.9×10^{-3}**	**1.8×10^{-2}**	**1.0×10^{-2}**	**9.4×10^{-2}**	**7.4×10^{-1}**
7	3.0×10^{-1}	3.5×10^{-1}	1.2×10^{-2}	3.2×10^{-3}	1.6×10^{-2}	7.8×10^{-3}	7.1×10^{-2}	7.5×10^{-1}
10	3.1×10^{-1}	3.5×10^{-1}	1.1×10^{-2}	2.3×10^{-3}	1.3×10^{-2}	5.2×10^{-3}	4.9×10^{-2}	7.4×10^{-1}
15	3.1×10^{-1}	3.4×10^{-1}	9.3×10^{-3}	1.4×10^{-3}	8.7×10^{-3}	2.8×10^{-3}	2.8×10^{-2}	7.0×10^{-1}
20	3.0×10^{-1}	3.2×10^{-1}	7.7×10^{-3}	8.6×10^{-4}	6.1×10^{-3}	1.7×10^{-3}	1.7×10^{-2}	6.6×10^{-1}

Male 15 y old (breathing rate = 0.48 m^3 h^{-1})								
0.0006	4.6×10^{-1}	4.6×10^{-1}	3.0×10^{-2}	3.0×10^{-2}	6.8×10^{-3}	6.8×10^{-3}	2.8×10^{-6}	9.9×10^{-1}
0.001	4.2×10^{-1}	4.2×10^{-1}	4.7×10^{-2}	4.7×10^{-2}	2.4×10^{-2}	2.4×10^{-2}	1.7×10^{-4}	9.8×10^{-1}
0.002	3.2×10^{-1}	3.4×10^{-1}	6.0×10^{-2}	6.0×10^{-2}	8.1×10^{-2}	8.1×10^{-2}	8.2×10^{-3}	9.5×10^{-1}
0.005	1.7×10^{-1}	1.9×10^{-1}	4.2×10^{-2}	4.2×10^{-2}	1.5×10^{-1}	1.5×10^{-1}	1.4×10^{-1}	8.8×10^{-1}
0.01	9.6×10^{-2}	1.1×10^{-1}	2.4×10^{-2}	2.4×10^{-2}	1.2×10^{-1}	1.2×10^{-1}	3.2×10^{-1}	8.1×10^{-1}
0.02	5.7×10^{-2}	6.4×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	8.3×10^{-2}	8.3×10^{-2}	3.9×10^{-1}	7.0×10^{-1}
0.05	3.4×10^{-2}	3.6×10^{-2}	8.2×10^{-3}	8.2×10^{-3}	4.9×10^{-2}	4.9×10^{-2}	2.7×10^{-1}	4.5×10^{-1}
0.1	2.7×10^{-2}	2.7×10^{-2}	5.6×10^{-3}	5.6×10^{-3}	3.3×10^{-2}	3.3×10^{-2}	1.9×10^{-1}	3.2×10^{-1}
0.2	3.4×10^{-2}	3.5×10^{-2}	4.1×10^{-3}	4.0×10^{-3}	2.1×10^{-2}	2.1×10^{-2}	1.4×10^{-1}	2.6×10^{-1}
0.5	5.3×10^{-2}	5.8×10^{-2}	3.6×10^{-3}	3.5×10^{-3}	1.6×10^{-2}	1.6×10^{-2}	1.2×10^{-1}	2.8×10^{-1}
0.7	7.5×10^{-2}	8.7×10^{-2}	3.9×10^{-3}	3.6×10^{-3}	1.5×10^{-2}	1.4×10^{-2}	1.2×10^{-1}	3.2×10^{-1}
1	1.1×10^{-1}	1.3×10^{-1}	4.7×10^{-3}	3.9×10^{-3}	1.4×10^{-2}	1.3×10^{-2}	1.3×10^{-1}	4.0×10^{-1}
2	1.8×10^{-1}	2.3×10^{-1}	7.6×10^{-3}	4.7×10^{-3}	1.5×10^{-2}	1.2×10^{-2}	1.3×10^{-1}	5.8×10^{-1}
3	2.3×10^{-1}	2.9×10^{-1}	9.6×10^{-3}	4.8×10^{-3}	1.6×10^{-2}	1.1×10^{-2}	1.2×10^{-1}	6.8×10^{-1}
5	**2.8×10^{-1}**	**3.4×10^{-1}**	**1.1×10^{-2}**	**4.2×10^{-3}**	**1.5×10^{-2}**	**8.5×10^{-3}**	**9.1×10^{-2}**	**7.5×10^{-1}**
7	3.0×10^{-1}	3.5×10^{-1}	1.2×10^{-2}	3.4×10^{-3}	1.3×10^{-2}	6.4×10^{-3}	6.9×10^{-2}	7.6×10^{-1}
10	3.1×10^{-1}	3.6×10^{-1}	1.1×10^{-2}	2.4×10^{-3}	1.0×10^{-2}	4.3×10^{-3}	4.6×10^{-2}	7.4×10^{-1}
15	3.1×10^{-1}	3.4×10^{-1}	9.3×10^{-3}	1.4×10^{-3}	7.1×10^{-3}	2.3×10^{-3}	2.6×10^{-2}	7.0×10^{-1}
20	3.0×10^{-1}	3.3×10^{-1}	7.6×10^{-3}	9.1×10^{-4}	5.0×10^{-3}	1.4×10^{-3}	1.6×10^{-2}	6.6×10^{-1}
Female 15 y old (breathing rate = 0.40 m^3 h^{-1})								
0.0006	4.6×10^{-1}	4.6×10^{-1}	3.0×10^{-2}	3.0×10^{-2}	5.5×10^{-3}	5.5×10^{-3}	1.2×10^{-6}	9.9×10^{-1}
0.001	4.2×10^{-1}	4.2×10^{-1}	4.8×10^{-2}	4.8×10^{-2}	2.1×10^{-2}	2.1×10^{-2}	9.3×10^{-5}	9.8×10^{-1}
0.002	3.2×10^{-1}	3.4×10^{-1}	6.3×10^{-2}	6.3×10^{-2}	7.5×10^{-2}	7.5×10^{-2}	5.9×10^{-3}	9.5×10^{-1}
0.005	1.7×10^{-1}	2.0×10^{-1}	4.5×10^{-2}	4.5×10^{-2}	1.4×10^{-1}	1.4×10^{-1}	1.2×10^{-1}	8.6×10^{-1}
0.01	9.8×10^{-2}	1.1×10^{-1}	2.6×10^{-2}	2.6×10^{-2}	1.2×10^{-1}	1.2×10^{-1}	3.0×10^{-1}	8.0×10^{-1}
0.02	5.8×10^{-2}	6.5×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	8.6×10^{-2}	8.6×10^{-2}	3.6×10^{-1}	6.8×10^{-1}
0.05	3.4×10^{-2}	3.7×10^{-2}	8.8×10^{-3}	8.8×10^{-3}	5.1×10^{-2}	5.1×10^{-2}	2.5×10^{-1}	4.4×10^{-1}
0.1	2.7×10^{-2}	2.7×10^{-2}	6.1×10^{-3}	6.1×10^{-3}	3.4×10^{-2}	3.4×10^{-2}	1.7×10^{-1}	3.1×10^{-1}
0.2	3.3×10^{-2}	3.4×10^{-2}	4.3×10^{-3}	4.3×10^{-3}	2.2×10^{-2}	2.2×10^{-2}	1.3×10^{-1}	2.5×10^{-1}
0.5	5.1×10^{-2}	5.7×10^{-2}	3.8×10^{-3}	3.7×10^{-3}	1.7×10^{-2}	1.7×10^{-2}	1.2×10^{-1}	2.7×10^{-1}
0.7	7.3×10^{-2}	8.4×10^{-2}	3.9×10^{-3}	3.6×10^{-3}	1.5×10^{-2}	1.5×10^{-2}	1.2×10^{-1}	3.1×10^{-1}
1	1.0×10^{-1}	1.2×10^{-1}	4.5×10^{-3}	3.8×10^{-3}	1.5×10^{-2}	1.4×10^{-2}	1.2×10^{-1}	3.9×10^{-1}
2	1.8×10^{-1}	2.2×10^{-1}	7.2×10^{-3}	4.5×10^{-3}	1.6×10^{-2}	1.3×10^{-2}	1.2×10^{-1}	5.7×10^{-1}
3	2.3×10^{-1}	2.8×10^{-1}	9.2×10^{-3}	4.6×10^{-3}	1.6×10^{-2}	1.1×10^{-2}	1.1×10^{-1}	6.7×10^{-1}
5	**2.8×10^{-1}**	**3.4×10^{-1}**	**1.1×10^{-2}**	**4.0×10^{-3}**	**1.5×10^{-2}**	**8.8×10^{-3}**	**8.8×10^{-2}**	**7.4×10^{-1}**
7	3.0×10^{-1}	3.5×10^{-1}	1.1×10^{-2}	3.2×10^{-3}	1.4×10^{-2}	6.7×10^{-3}	6.7×10^{-2}	7.5×10^{-1}
10	3.1×10^{-1}	3.5×10^{-1}	1.1×10^{-2}	2.3×10^{-3}	1.1×10^{-2}	4.5×10^{-3}	4.5×10^{-2}	7.4×10^{-1}
15	3.1×10^{-1}	3.4×10^{-1}	9.0×10^{-3}	1.4×10^{-3}	7.5×10^{-3}	2.5×10^{-3}	2.6×10^{-2}	7.0×10^{-1}
20	3.0×10^{-1}	3.3×10^{-1}	7.4×10^{-3}	8.6×10^{-4}	5.3×10^{-3}	1.5×10^{-3}	1.6×10^{-2}	6.6×10^{-1}

Continued overleaf

Table F.4.—(*continued*)

AMTD (μm)	ET_1	ET_2	$BB_{fast+seq}$	BB_{slow}	$bb_{fast+seq}$	bb_{slow}	AI	Total
Child 10 y old (breathing rate = 0.38 m^3 h^{-1})								
0.0006	4.6×10^{-1}	4.6×10^{-1}	3.1×10^{-2}	3.1×10^{-2}	6.1×10^{-3}	6.1×10^{-3}	2.0×10^{-7}	9.9×10^{-1}
0.001	4.2×10^{-1}	4.2×10^{-1}	4.9×10^{-2}	4.9×10^{-2}	2.3×10^{-2}	2.3×10^{-2}	1.3×10^{-4}	9.8×10^{-1}
0.002	3.2×10^{-1}	3.4×10^{-1}	6.4×10^{-2}	6.4×10^{-2}	7.9×10^{-2}	7.9×10^{-2}	7.3×10^{-3}	9.5×10^{-1}
0.005	1.7×10^{-1}	1.9×10^{-1}	4.5×10^{-2}	4.5×10^{-2}	1.5×10^{-1}	1.5×10^{-1}	1.3×10^{-1}	8.8×10^{-1}
0.01	9.6×10^{-2}	1.1×10^{-1}	2.6×10^{-2}	2.6×10^{-2}	1.2×10^{-1}	1.2×10^{-1}	3.2×10^{-1}	8.2×10^{-1}
0.02	5.7×10^{-2}	6.4×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	8.5×10^{-2}	8.5×10^{-2}	4.0×10^{-1}	7.2×10^{-1}
0.05	3.4×10^{-2}	3.6×10^{-2}	8.7×10^{-3}	8.7×10^{-3}	5.0×10^{-2}	5.0×10^{-2}	2.8×10^{-1}	4.7×10^{-1}
0.1	2.8×10^{-2}	2.9×10^{-2}	6.0×10^{-3}	6.0×10^{-3}	3.3×10^{-2}	3.3×10^{-2}	1.9×10^{-1}	3.3×10^{-1}
0.2	4.0×10^{-2}	4.2×10^{-2}	4.4×10^{-3}	4.4×10^{-3}	2.2×10^{-2}	2.2×10^{-2}	1.4×10^{-1}	2.8×10^{-1}
0.5	6.4×10^{-2}	7.3×10^{-2}	3.9×10^{-3}	3.8×10^{-3}	1.6×10^{-2}	1.6×10^{-2}	1.3×10^{-1}	3.0×10^{-1}
0.7	9.1×10^{-2}	1.1×10^{-1}	4.1×10^{-3}	3.9×10^{-3}	1.4×10^{-2}	1.3×10^{-2}	1.2×10^{-1}	3.6×10^{-1}
1	1.3×10^{-1}	1.6×10^{-1}	4.9×10^{-3}	4.2×10^{-3}	1.2×10^{-2}	1.2×10^{-2}	1.2×10^{-1}	4.4×10^{-1}
2	2.1×10^{-1}	2.6×10^{-1}	7.4×10^{-3}	4.9×10^{-3}	1.2×10^{-2}	9.9×10^{-3}	1.2×10^{-1}	6.3×10^{-1}
3	2.6×10^{-1}	3.2×10^{-1}	9.0×10^{-3}	4.9×10^{-3}	1.2×10^{-2}	8.6×10^{-3}	1.0×10^{-1}	7.2×10^{-1}
5	$\mathbf{3.1\times10^{-1}}$	$\mathbf{3.6\times10^{-1}}$	$\mathbf{1.0\times10^{-2}}$	$\mathbf{4.2\times10^{-3}}$	$\mathbf{1.0\times10^{-2}}$	$\mathbf{6.4\times10^{-3}}$	$\mathbf{7.6\times10^{-2}}$	$\mathbf{7.8\times10^{-1}}$
7	3.2×10^{-1}	3.7×10^{-1}	1.0×10^{-2}	3.3×10^{-3}	8.9×10^{-3}	4.7×10^{-3}	5.6×10^{-2}	7.8×10^{-1}
10	3.3×10^{-1}	3.7×10^{-1}	9.4×10^{-3}	2.3×10^{-3}	7.0×10^{-3}	3.1×10^{-3}	3.7×10^{-2}	7.6×10^{-1}
15	3.2×10^{-1}	3.5×10^{-1}	7.6×10^{-3}	1.4×10^{-3}	4.7×10^{-3}	1.7×10^{-3}	2.0×10^{-2}	7.1×10^{-1}
20	3.1×10^{-1}	3.3×10^{-1}	6.1×10^{-3}	8.5×10^{-4}	3.2×10^{-3}	9.9×10^{-4}	1.2×10^{-2}	6.6×10^{-1}
Child 5 y old (breathing rate = 0.32 m^3 h^{-1})								
0.0006	4.6×10^{-1}	4.6×10^{-1}	3.2×10^{-2}	3.2×10^{-2}	5.8×10^{-3}	5.8×10^{-3}	2.3×10^{-6}	9.9×10^{-1}
0.001	4.2×10^{-1}	4.2×10^{-1}	5.2×10^{-2}	5.2×10^{-2}	2.2×10^{-2}	2.2×10^{-2}	1.5×10^{-4}	9.8×10^{-1}
0.002	3.2×10^{-1}	3.4×10^{-1}	6.7×10^{-2}	6.7×10^{-2}	7.9×10^{-2}	7.8×10^{-2}	8.0×10^{-3}	9.6×10^{-1}
0.005	1.7×10^{-1}	1.9×10^{-1}	4.8×10^{-2}	4.8×10^{-2}	1.5×10^{-1}	1.5×10^{-1}	1.4×10^{-1}	8.9×10^{-1}
0.01	9.6×10^{-2}	1.1×10^{-1}	2.7×10^{-2}	2.7×10^{-2}	1.2×10^{-1}	1.2×10^{-1}	3.3×10^{-1}	8.3×10^{-1}
0.02	5.6×10^{-2}	6.3×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	8.3×10^{-2}	8.3×10^{-2}	4.2×10^{-1}	7.4×10^{-1}
0.05	3.3×10^{-2}	3.6×10^{-2}	9.1×10^{-3}	9.1×10^{-3}	4.9×10^{-2}	4.9×10^{-2}	3.1×10^{-1}	4.9×10^{-1}
0.1	3.1×10^{-2}	3.2×10^{-2}	6.3×10^{-3}	6.3×10^{-3}	3.3×10^{-2}	3.3×10^{-2}	2.1×10^{-1}	3.6×10^{-1}
0.2	5.1×10^{-2}	5.7×10^{-2}	4.6×10^{-3}	4.6×10^{-3}	2.1×10^{-2}	2.1×10^{-2}	1.6×10^{-1}	3.1×10^{-1}
0.5	8.3×10^{-2}	9.9×10^{-2}	4.3×10^{-3}	4.2×10^{-3}	1.5×10^{-2}	1.5×10^{-2}	1.3×10^{-1}	3.5×10^{-1}
0.7	1.2×10^{-1}	1.4×10^{-1}	4.5×10^{-3}	4.2×10^{-3}	1.2×10^{-2}	1.2×10^{-2}	1.2×10^{-1}	4.2×10^{-1}
1	1.6×10^{-1}	2.0×10^{-1}	5.1×10^{-3}	4.6×10^{-3}	1.0×10^{-2}	1.0×10^{-2}	1.2×10^{-1}	5.0×10^{-1}
2	2.5×10^{-1}	3.1×10^{-1}	7.2×10^{-3}	5.2×10^{-3}	8.6×10^{-3}	7.5×10^{-3}	1.0×10^{-1}	6.9×10^{-1}
3	2.9×10^{-1}	3.6×10^{-1}	8.3×10^{-3}	5.0×10^{-3}	7.8×10^{-3}	6.2×10^{-3}	8.4×10^{-2}	7.7×10^{-1}
5	$\mathbf{3.3\times10^{-1}}$	$\mathbf{3.9\times10^{-1}}$	$\mathbf{8.9\times10^{-3}}$	$\mathbf{4.1\times10^{-3}}$	$\mathbf{6.5\times10^{-3}}$	$\mathbf{4.3\times10^{-3}}$	$\mathbf{5.8\times10^{-2}}$	$\mathbf{8.1\times10^{-1}}$
7	3.5×10^{-1}	4.0×10^{-1}	8.5×10^{-3}	3.2×10^{-3}	5.4×10^{-3}	3.1×10^{-3}	4.1×10^{-2}	8.0×10^{-1}
10	3.5×10^{-1}	3.8×10^{-1}	7.5×10^{-3}	2.2×10^{-3}	4.1×10^{-3}	2.0×10^{-3}	2.6×10^{-2}	7.7×10^{-1}
15	3.3×10^{-1}	3.6×10^{-1}	5.9×10^{-3}	1.2×10^{-3}	2.6×10^{-3}	1.1×10^{-3}	1.3×10^{-2}	7.1×10^{-1}
20	3.2×10^{-1}	3.3×10^{-1}	4.6×10^{-3}	7.6×10^{-4}	1.8×10^{-3}	6.2×10^{-4}	7.8×10^{-3}	6.7×10^{-1}

Infant 1 y old (breathing rate = 0.22 $m^3 h^{-1}$)

0.0006	4.6×10^{-1}	4.6×10^{-1}	3.4×10^{-2}	3.4×10^{-2}	4.1×10^{-3}	4.1×10^{-3}	9.9×10^{-7}	$1.0 \times 10^{+0}$
0.001	4.2×10^{-1}	4.2×10^{-1}	5.7×10^{-2}	5.7×10^{-2}	1.8×10^{-2}	1.8×10^{-2}	8.4×10^{-5}	9.9×10^{-1}
0.002	3.2×10^{-1}	3.4×10^{-1}	7.8×10^{-2}	7.8×10^{-2}	7.2×10^{-2}	7.2×10^{-2}	5.8×10^{-3}	9.7×10^{-1}
0.005	1.7×10^{-1}	1.9×10^{-1}	5.8×10^{-2}	5.8×10^{-2}	1.5×10^{-1}	1.5×10^{-1}	1.2×10^{-1}	9.0×10^{-1}
0.01	9.6×10^{-2}	1.1×10^{-1}	3.3×10^{-2}	3.3×10^{-2}	1.3×10^{-1}	1.3×10^{-1}	3.2×10^{-1}	8.4×10^{-1}
0.02	5.5×10^{-2}	6.1×10^{-2}	1.8×10^{-2}	1.8×10^{-2}	8.4×10^{-2}	8.4×10^{-2}	4.4×10^{-1}	7.6×10^{-1}
0.05	3.3×10^{-2}	3.5×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	5.0×10^{-2}	5.0×10^{-2}	3.5×10^{-1}	5.4×10^{-1}
0.1	3.9×10^{-2}	4.1×10^{-2}	7.3×10^{-3}	7.3×10^{-3}	3.3×10^{-2}	3.3×10^{-2}	2.5×10^{-1}	4.1×10^{-1}
0.2	7.3×10^{-2}	8.6×10^{-2}	5.4×10^{-3}	5.4×10^{-3}	2.1×10^{-2}	2.1×10^{-2}	1.8×10^{-1}	3.9×10^{-1}
0.5	1.2×10^{-1}	1.5×10^{-1}	4.9×10^{-3}	4.8×10^{-3}	1.5×10^{-2}	1.5×10^{-2}	1.4×10^{-1}	4.5×10^{-1}
0.7	1.6×10^{-1}	2.0×10^{-1}	4.9×10^{-3}	4.8×10^{-3}	1.1×10^{-2}	1.1×10^{-2}	1.2×10^{-1}	5.2×10^{-1}
1	2.1×10^{-1}	2.7×10^{-1}	5.3×10^{-3}	4.9×10^{-3}	8.7×10^{-3}	8.6×10^{-3}	1.1×10^{-1}	6.1×10^{-1}
2	3.0×10^{-1}	3.7×10^{-1}	6.4×10^{-3}	5.1×10^{-3}	5.7×10^{-3}	5.2×10^{-3}	7.7×10^{-2}	7.7×10^{-1}
3	3.4×10^{-1}	4.1×10^{-1}	6.8×10^{-3}	4.7×10^{-3}	4.5×10^{-3}	3.9×10^{-3}	5.9×10^{-2}	8.3×10^{-1}
5	$\mathbf{3.7 \times 10^{-1}}$	$\mathbf{4.3 \times 10^{-1}}$	$\mathbf{6.7 \times 10^{-3}}$	$\mathbf{3.6 \times 10^{-3}}$	$\mathbf{3.3 \times 10^{-3}}$	$\mathbf{2.4 \times 10^{-3}}$	$\mathbf{3.6 \times 10^{-2}}$	$\mathbf{8.5 \times 10^{-1}}$
7	3.7×10^{-1}	4.2×10^{-1}	6.1×10^{-3}	2.7×10^{-3}	2.5×10^{-3}	1.7×10^{-3}	2.4×10^{-2}	8.3×10^{-1}
10	3.6×10^{-1}	3.9×10^{-1}	5.1×10^{-3}	1.8×10^{-3}	1.8×10^{-3}	1.0×10^{-3}	1.4×10^{-2}	7.8×10^{-1}
15	3.4×10^{-1}	3.6×10^{-1}	3.8×10^{-3}	9.9×10^{-4}	1.1×10^{-3}	5.2×10^{-4}	7.0×10^{-3}	7.2×10^{-1}
20	3.3×10^{-1}	3.4×10^{-1}	2.8×10^{-3}	5.9×10^{-4}	6.9×10^{-4}	3.0×10^{-4}	3.9×10^{-3}	6.7×10^{-1}

Table F.5. Fractional deposition in regions of the respiratory tract for subjects (normal nose breathers) engaged in light exercise as a function of aerosol size

AMTD (μm)	ET_1	ET_2	$BB_{fast+seq}$	BB_{slow}	$bb_{fast+seq}$	bb_{slow}	AI	Total
			Adult male (breathing rate = $1.50\ m^3\ h^{-1}$)					
0.0006	4.5×10^{-1}	4.4×10^{-1}	3.0×10^{-2}	3.0×10^{-2}	2.2×10^{-2}	2.2×10^{-2}	3.4×10^{-4}	9.9×10^{-1}
0.001	4.0×10^{-1}	4.0×10^{-1}	3.9×10^{-2}	3.9×10^{-2}	5.2×10^{-2}	5.2×10^{-2}	4.2×10^{-3}	9.9×10^{-1}
0.002	3.0×10^{-1}	3.2×10^{-1}	4.2×10^{-2}	4.2×10^{-2}	1.1×10^{-1}	1.1×10^{-1}	4.8×10^{-2}	9.7×10^{-1}
0.005	1.5×10^{-1}	1.7×10^{-1}	2.5×10^{-2}	2.5×10^{-2}	1.3×10^{-1}	1.3×10^{-1}	2.9×10^{-1}	9.2×10^{-1}
0.01	8.6×10^{-2}	9.7×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	9.0×10^{-2}	9.0×10^{-2}	4.9×10^{-1}	8.8×10^{-1}
0.02	5.3×10^{-2}	5.9×10^{-2}	8.1×10^{-3}	8.1×10^{-3}	6.0×10^{-2}	6.0×10^{-2}	5.0×10^{-1}	7.4×10^{-1}
0.05	3.2×10^{-2}	3.4×10^{-2}	4.7×10^{-3}	4.7×10^{-3}	3.4×10^{-2}	3.4×10^{-2}	3.1×10^{-1}	4.5×10^{-1}
0.1	3.3×10^{-2}	3.3×10^{-2}	3.4×10^{-3}	3.4×10^{-3}	2.2×10^{-2}	2.2×10^{-2}	2.1×10^{-1}	3.2×10^{-1}
0.2	5.8×10^{-2}	6.6×10^{-2}	3.2×10^{-3}	3.2×10^{-3}	1.4×10^{-2}	1.4×10^{-2}	1.4×10^{-1}	3.0×10^{-1}
0.5	9.5×10^{-2}	1.2×10^{-1}	4.1×10^{-3}	4.0×10^{-3}	1.0×10^{-2}	1.0×10^{-2}	1.2×10^{-1}	3.6×10^{-1}
0.7	1.3×10^{-1}	1.7×10^{-1}	5.3×10^{-3}	5.0×10^{-3}	8.5×10^{-3}	8.4×10^{-3}	1.1×10^{-1}	4.3×10^{-1}
1	1.8×10^{-1}	2.3×10^{-1}	6.9×10^{-3}	6.2×10^{-3}	7.5×10^{-3}	7.2×10^{-3}	9.9×10^{-2}	5.3×10^{-1}
2	2.7×10^{-1}	3.4×10^{-1}	1.0×10^{-2}	7.8×10^{-3}	6.7×10^{-3}	5.9×10^{-3}	8.3×10^{-2}	7.2×10^{-1}
3	3.1×10^{-1}	3.8×10^{-1}	1.2×10^{-2}	7.7×10^{-3}	6.3×10^{-3}	5.1×10^{-3}	6.7×10^{-2}	7.9×10^{-1}
5	**3.5×10^{-1}**	**4.1×10^{-1}**	**1.2×10^{-2}**	**6.2×10^{-3}**	**5.3×10^{-3}**	**3.7×10^{-3}**	**4.5×10^{-2}**	**8.3×10^{-1}**
7	3.6×10^{-1}	4.1×10^{-1}	1.1×10^{-2}	4.7×10^{-3}	4.3×10^{-3}	2.7×10^{-3}	3.1×10^{-2}	8.2×10^{-1}
10	3.5×10^{-1}	3.9×10^{-1}	9.2×10^{-3}	3.2×10^{-3}	3.1×10^{-3}	1.7×10^{-3}	1.9×10^{-2}	7.8×10^{-1}
15	3.4×10^{-1}	3.6×10^{-1}	6.8×10^{-3}	1.8×10^{-3}	1.9×10^{-3}	9.1×10^{-4}	9.6×10^{-3}	7.2×10^{-1}
20	3.2×10^{-1}	3.4×10^{-1}	5.1×10^{-3}	1.1×10^{-3}	1.3×10^{-3}	5.3×10^{-4}	5.4×10^{-3}	6.7×10^{-1}
			Adult female (breathing rate = $1.25\ m^3\ h^{-1}$)					
0.0006	4.5×10^{-1}	4.4×10^{-1}	3.0×10^{-2}	3.0×10^{-2}	2.0×10^{-2}	2.0×10^{-2}	1.7×10^{-4}	9.9×10^{-1}
0.001	4.0×10^{-1}	4.0×10^{-1}	4.1×10^{-2}	4.1×10^{-2}	4.9×10^{-2}	4.9×10^{-2}	2.7×10^{-3}	9.9×10^{-1}
0.002	3.0×10^{-1}	3.2×10^{-1}	4.4×10^{-2}	4.4×10^{-2}	1.1×10^{-1}	1.1×10^{-1}	3.8×10^{-2}	9.7×10^{-1}
0.005	1.5×10^{-1}	1.7×10^{-1}	2.7×10^{-2}	2.7×10^{-2}	1.4×10^{-1}	1.4×10^{-1}	2.6×10^{-1}	9.2×10^{-1}
0.01	8.7×10^{-2}	9.8×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	9.8×10^{-2}	9.8×10^{-2}	4.7×10^{-1}	8.8×10^{-1}
0.02	5.3×10^{-2}	5.9×10^{-2}	8.7×10^{-3}	8.7×10^{-3}	6.5×10^{-2}	6.5×10^{-2}	4.8×10^{-1}	7.4×10^{-1}
0.05	3.2×10^{-2}	3.4×10^{-2}	5.0×10^{-3}	5.0×10^{-3}	3.8×10^{-2}	3.8×10^{-2}	3.1×10^{-1}	4.6×10^{-1}
0.1	3.3×10^{-2}	3.4×10^{-2}	3.6×10^{-3}	3.6×10^{-3}	2.4×10^{-2}	2.4×10^{-2}	2.0×10^{-1}	3.3×10^{-1}
0.2	5.9×10^{-2}	6.7×10^{-2}	3.3×10^{-3}	3.3×10^{-3}	1.5×10^{-2}	1.5×10^{-2}	1.4×10^{-1}	3.1×10^{-1}
0.5	9.7×10^{-2}	1.2×10^{-1}	4.1×10^{-3}	4.0×10^{-3}	1.1×10^{-2}	1.1×10^{-2}	1.2×10^{-1}	3.6×10^{-1}
0.7	1.3×10^{-1}	1.7×10^{-1}	5.2×10^{-3}	4.9×10^{-3}	9.1×10^{-3}	9.0×10^{-3}	1.1×10^{-1}	4.4×10^{-1}
1	1.8×10^{-1}	2.3×10^{-1}	6.7×10^{-3}	6.0×10^{-3}	7.8×10^{-3}	7.6×10^{-3}	9.9×10^{-2}	5.3×10^{-1}
2	2.7×10^{-1}	3.4×10^{-1}	9.8×10^{-3}	7.5×10^{-3}	6.7×10^{-3}	5.9×10^{-3}	8.2×10^{-2}	7.2×10^{-1}
3	3.1×10^{-1}	3.9×10^{-1}	1.1×10^{-2}	7.3×10^{-3}	6.1×10^{-3}	5.0×10^{-3}	6.7×10^{-2}	8.0×10^{-1}
5	**3.5×10^{-1}**	**4.1×10^{-1}**	**1.1×10^{-2}**	**5.9×10^{-3}**	**5.0×10^{-3}**	**3.5×10^{-3}**	**4.4×10^{-2}**	**8.3×10^{-1}**
7	3.6×10^{-1}	4.1×10^{-1}	1.0×10^{-2}	4.5×10^{-3}	4.0×10^{-3}	2.6×10^{-3}	3.1×10^{-2}	8.2×10^{-1}
10	3.5×10^{-1}	3.9×10^{-1}	8.7×10^{-3}	3.1×10^{-3}	2.9×10^{-3}	1.6×10^{-3}	1.9×10^{-2}	7.8×10^{-1}
15	3.4×10^{-1}	3.6×10^{-1}	6.5×10^{-3}	1.7×10^{-3}	1.8×10^{-3}	8.6×10^{-4}	9.4×10^{-3}	7.2×10^{-1}
20	3.2×10^{-1}	3.4×10^{-1}	4.9×10^{-3}	1.0×10^{-3}	1.2×10^{-3}	4.9×10^{-4}	5.3×10^{-3}	6.7×10^{-1}

			Male 15 y old (breathing rate = 1.38 m³ h⁻¹)					
0.0006	4.5×10^{-1}	4.4×10^{-1}	3.0×10^{-2}	3.0×10^{-2}	2.0×10^{-2}	2.0×10^{-2}	3.2×10^{-4}	9.9×10^{-1}
0.001	4.0×10^{-1}	4.0×10^{-1}	4.0×10^{-2}	4.0×10^{-2}	5.0×10^{-2}	5.0×10^{-2}	4.0×10^{-3}	9.8×10^{-1}
0.002	3.0×10^{-1}	3.2×10^{-1}	4.2×10^{-2}	4.2×10^{-2}	1.1×10^{-1}	1.1×10^{-1}	4.7×10^{-2}	9.6×10^{-1}
0.005	1.5×10^{-1}	1.7×10^{-1}	2.6×10^{-2}	2.6×10^{-2}	1.3×10^{-1}	1.3×10^{-1}	2.8×10^{-1}	9.1×10^{-1}
0.01	8.6×10^{-2}	9.8×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	8.9×10^{-2}	8.9×10^{-2}	4.8×10^{-1}	8.7×10^{-1}
0.02	5.3×10^{-2}	5.9×10^{-2}	8.4×10^{-3}	8.4×10^{-3}	5.9×10^{-2}	5.9×10^{-2}	4.8×10^{-1}	7.3×10^{-1}
0.05	3.2×10^{-2}	3.4×10^{-2}	4.9×10^{-3}	4.9×10^{-3}	3.4×10^{-2}	3.4×10^{-2}	3.0×10^{-1}	4.4×10^{-1}
0.1	3.3×10^{-2}	3.4×10^{-2}	3.5×10^{-3}	3.5×10^{-3}	2.2×10^{-2}	2.2×10^{-2}	2.0×10^{-1}	3.1×10^{-1}
0.2	5.9×10^{-2}	6.7×10^{-2}	3.3×10^{-3}	3.3×10^{-3}	1.4×10^{-2}	1.4×10^{-2}	1.4×10^{-1}	3.0×10^{-1}
0.5	9.7×10^{-2}	1.2×10^{-1}	4.1×10^{-3}	4.0×10^{-3}	1.0×10^{-2}	9.9×10^{-3}	1.1×10^{-1}	3.6×10^{-1}
0.7	1.3×10^{-1}	1.7×10^{-1}	5.2×10^{-3}	4.9×10^{-3}	8.3×10^{-3}	8.2×10^{-3}	1.0×10^{-1}	4.3×10^{-1}
1	1.8×10^{-1}	2.3×10^{-1}	6.8×10^{-3}	6.1×10^{-3}	7.3×10^{-3}	7.1×10^{-3}	9.4×10^{-2}	5.3×10^{-1}
2	2.7×10^{-1}	3.4×10^{-1}	1.0×10^{-2}	7.7×10^{-3}	6.6×10^{-3}	5.8×10^{-3}	7.7×10^{-2}	7.2×10^{-1}
3	3.1×10^{-1}	3.9×10^{-1}	1.1×10^{-2}	7.5×10^{-3}	6.2×10^{-3}	4.9×10^{-3}	6.3×10^{-2}	7.9×10^{-1}
5	$\mathbf{3.5\times10^{-1}}$	$\mathbf{4.1\times10^{-1}}$	$\mathbf{1.1\times10^{-2}}$	$\mathbf{6.0\times10^{-3}}$	$\mathbf{5.2\times10^{-3}}$	$\mathbf{3.6\times10^{-3}}$	$\mathbf{4.2\times10^{-2}}$	$\mathbf{8.3\times10^{-1}}$
7	3.6×10^{-1}	4.1×10^{-1}	1.1×10^{-2}	4.6×10^{-3}	4.2×10^{-3}	2.6×10^{-3}	2.9×10^{-2}	8.2×10^{-1}
10	3.5×10^{-1}	3.9×10^{-1}	8.9×10^{-3}	3.1×10^{-3}	3.1×10^{-3}	1.7×10^{-3}	1.8×10^{-2}	7.8×10^{-1}
15	3.4×10^{-1}	3.6×10^{-1}	6.6×10^{-3}	1.7×10^{-3}	1.9×10^{-3}	8.9×10^{-4}	8.9×10^{-3}	7.2×10^{-1}
20	3.2×10^{-1}	3.4×10^{-1}	4.9×10^{-3}	1.0×10^{-3}	1.2×10^{-3}	5.2×10^{-4}	5.0×10^{-3}	6.7×10^{-1}
			Female 15 y old (breathing rate = 1.30 m³ h⁻¹)					
0.0006	4.5×10^{-1}	4.4×10^{-1}	3.0×10^{-2}	3.0×10^{-2}	2.0×10^{-2}	2.0×10^{-2}	3.0×10^{-4}	9.9×10^{-1}
0.001	4.0×10^{-1}	4.0×10^{-1}	4.0×10^{-2}	4.0×10^{-2}	4.9×10^{-2}	4.9×10^{-2}	3.9×10^{-3}	9.8×10^{-1}
0.002	3.0×10^{-1}	3.2×10^{-1}	4.3×10^{-2}	4.3×10^{-2}	1.1×10^{-1}	1.1×10^{-1}	4.6×10^{-2}	9.6×10^{-1}
0.005	1.5×10^{-1}	1.7×10^{-1}	2.6×10^{-2}	2.6×10^{-2}	1.3×10^{-1}	1.3×10^{-1}	2.8×10^{-1}	9.2×10^{-1}
0.01	8.6×10^{-2}	9.8×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	9.0×10^{-2}	9.0×10^{-2}	4.8×10^{-1}	8.7×10^{-1}
0.02	5.3×10^{-2}	5.9×10^{-2}	8.5×10^{-3}	8.5×10^{-3}	6.0×10^{-2}	6.0×10^{-2}	4.8×10^{-1}	7.3×10^{-1}
0.05	3.2×10^{-2}	3.4×10^{-2}	5.0×10^{-3}	5.0×10^{-3}	3.4×10^{-2}	3.4×10^{-2}	3.0×10^{-1}	4.5×10^{-1}
0.1	3.4×10^{-2}	3.5×10^{-2}	3.6×10^{-3}	3.6×10^{-3}	2.2×10^{-2}	2.2×10^{-2}	2.0×10^{-1}	3.2×10^{-1}
0.2	6.2×10^{-2}	7.1×10^{-2}	3.3×10^{-3}	3.3×10^{-3}	1.4×10^{-2}	1.4×10^{-2}	1.4×10^{-1}	3.0×10^{-1}
0.5	1.0×10^{-1}	1.2×10^{-1}	4.2×10^{-3}	4.1×10^{-3}	1.0×10^{-2}	9.9×10^{-3}	1.1×10^{-1}	3.7×10^{-1}
0.7	1.4×10^{-1}	1.8×10^{-1}	5.3×10^{-3}	5.0×10^{-3}	8.2×10^{-3}	8.1×10^{-3}	1.0×10^{-1}	4.4×10^{-1}
1	1.8×10^{-1}	2.4×10^{-1}	6.8×10^{-3}	6.1×10^{-3}	7.1×10^{-3}	6.9×10^{-3}	9.3×10^{-2}	5.4×10^{-1}
2	2.7×10^{-1}	3.5×10^{-1}	9.9×10^{-3}	7.6×10^{-3}	6.3×10^{-3}	5.5×10^{-3}	7.6×10^{-2}	7.3×10^{-1}
3	3.2×10^{-1}	3.9×10^{-1}	1.1×10^{-2}	7.4×10^{-3}	5.8×10^{-3}	4.7×10^{-3}	6.1×10^{-2}	8.0×10^{-1}
5	$\mathbf{3.5\times10^{-1}}$	$\mathbf{4.2\times10^{-1}}$	$\mathbf{1.1\times10^{-2}}$	$\mathbf{5.9\times10^{-3}}$	$\mathbf{4.8\times10^{-3}}$	$\mathbf{3.4\times10^{-3}}$	$\mathbf{4.0\times10^{-2}}$	$\mathbf{8.3\times10^{-1}}$
7	3.6×10^{-1}	4.1×10^{-1}	1.0×10^{-2}	4.5×10^{-3}	3.9×10^{-3}	2.4×10^{-3}	2.7×10^{-2}	8.2×10^{-1}
10	3.6×10^{-1}	3.9×10^{-1}	8.4×10^{-3}	3.0×10^{-3}	2.8×10^{-3}	1.6×10^{-3}	1.7×10^{-2}	7.8×10^{-1}
15	3.4×10^{-1}	3.6×10^{-1}	6.2×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	8.2×10^{-4}	8.3×10^{-3}	7.2×10^{-1}
20	3.2×10^{-1}	3.4×10^{-1}	4.6×10^{-3}	1.0×10^{-3}	1.1×10^{-3}	4.8×10^{-4}	4.7×10^{-3}	6.7×10^{-1}

Continued overleaf

Table F.5.—(*continued*)

AMTD (μm)	ET_1	ET_2	$BB_{fast+seq}$	BB_{slow}	$bb_{fast+seq}$	bb_{slow}	AI	Total
			Child 10 y old (breathing rate = 1.12 $m^3 h^{-1}$)					
0.0006	4.5×10^{-1}	4.4×10^{-1}	3.1×10^{-2}	3.1×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	2.9×10^{-4}	9.9×10^{-1}
0.001	4.0×10^{-1}	4.0×10^{-1}	4.1×10^{-2}	4.1×10^{-2}	4.8×10^{-2}	4.8×10^{-2}	3.8×10^{-3}	9.8×10^{-1}
0.002	3.0×10^{-1}	3.2×10^{-1}	4.4×10^{-2}	4.4×10^{-2}	1.1×10^{-1}	1.1×10^{-1}	4.5×10^{-2}	9.6×10^{-1}
0.005	1.5×10^{-1}	1.7×10^{-1}	2.7×10^{-2}	2.7×10^{-2}	1.3×10^{-1}	1.3×10^{-1}	2.8×10^{-1}	9.1×10^{-1}
0.01	8.7×10^{-2}	9.8×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	8.9×10^{-2}	8.9×10^{-2}	4.7×10^{-1}	8.6×10^{-1}
0.02	5.3×10^{-2}	5.9×10^{-2}	8.8×10^{-3}	8.8×10^{-3}	6.0×10^{-2}	6.0×10^{-2}	4.7×10^{-1}	7.2×10^{-1}
0.05	3.3×10^{-2}	3.5×10^{-2}	5.1×10^{-3}	5.1×10^{-3}	3.4×10^{-2}	3.4×10^{-2}	2.9×10^{-1}	4.4×10^{-1}
0.1	3.9×10^{-2}	4.0×10^{-2}	3.7×10^{-3}	3.7×10^{-3}	2.2×10^{-2}	2.2×10^{-2}	1.9×10^{-1}	3.2×10^{-1}
0.2	7.3×10^{-2}	8.6×10^{-2}	3.6×10^{-3}	3.5×10^{-3}	1.4×10^{-2}	1.4×10^{-2}	1.3×10^{-1}	3.2×10^{-1}
0.5	1.2×10^{-1}	1.5×10^{-1}	4.4×10^{-3}	4.3×10^{-3}	9.6×10^{-3}	9.6×10^{-3}	1.0×10^{-1}	4.0×10^{-1}
0.7	1.6×10^{-1}	2.0×10^{-1}	5.4×10^{-3}	5.2×10^{-3}	7.7×10^{-3}	7.6×10^{-3}	9.0×10^{-2}	4.8×10^{-1}
1	2.1×10^{-1}	2.7×10^{-1}	6.8×10^{-3}	6.2×10^{-3}	6.4×10^{-3}	6.3×10^{-3}	8.0×10^{-2}	5.8×10^{-1}
2	3.0×10^{-1}	3.8×10^{-1}	9.3×10^{-3}	7.4×10^{-3}	5.2×10^{-3}	4.6×10^{-3}	6.1×10^{-2}	7.6×10^{-1}
3	3.4×10^{-1}	4.1×10^{-1}	1.0×10^{-2}	7.1×10^{-3}	4.6×10^{-3}	3.8×10^{-3}	4.7×10^{-2}	8.3×10^{-1}
5	**3.7×10^{-1}**	**4.3×10^{-1}**	**9.7×10^{-3}**	**5.5×10^{-3}**	**3.6×10^{-3}**	**2.7×10^{-3}**	**3.0×10^{-2}**	**8.5×10^{-1}**
7	3.7×10^{-1}	4.2×10^{-1}	8.6×10^{-3}	4.1×10^{-3}	2.9×10^{-3}	1.9×10^{-3}	2.0×10^{-2}	8.3×10^{-1}
10	3.6×10^{-1}	4.0×10^{-1}	7.0×10^{-3}	2.8×10^{-3}	2.0×10^{-3}	1.2×10^{-3}	1.2×10^{-2}	7.8×10^{-1}
15	3.4×10^{-1}	3.6×10^{-1}	5.0×10^{-3}	1.5×10^{-3}	1.2×10^{-3}	6.3×10^{-4}	5.7×10^{-3}	7.2×10^{-1}
20	3.3×10^{-1}	3.4×10^{-1}	3.7×10^{-3}	8.9×10^{-4}	7.7×10^{-4}	3.6×10^{-4}	3.1×10^{-3}	6.7×10^{-1}
			Child 5 y old (breathing rate = 0.57 $m^3 h^{-1}$)					
0.0006	4.6×10^{-1}	4.5×10^{-1}	3.2×10^{-2}	3.2×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	4.7×10^{-5}	9.9×10^{-1}
0.001	4.1×10^{-1}	4.1×10^{-1}	4.7×10^{-2}	4.7×10^{-2}	3.5×10^{-2}	3.5×10^{-2}	1.1×10^{-3}	9.8×10^{-1}
0.002	3.1×10^{-1}	3.3×10^{-1}	5.5×10^{-2}	5.5×10^{-2}	9.5×10^{-2}	9.5×10^{-2}	2.3×10^{-2}	9.6×10^{-1}
0.005	1.6×10^{-1}	1.8×10^{-1}	3.6×10^{-2}	3.6×10^{-2}	1.3×10^{-1}	1.3×10^{-1}	2.1×10^{-1}	8.9×10^{-1}
0.01	9.1×10^{-2}	1.0×10^{-1}	2.0×10^{-2}	2.0×10^{-2}	1.0×10^{-1}	1.0×10^{-1}	4.0×10^{-1}	8.4×10^{-1}
0.02	5.5×10^{-2}	6.1×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	6.9×10^{-2}	6.9×10^{-2}	4.3×10^{-1}	7.1×10^{-1}
0.05	3.4×10^{-2}	3.6×10^{-2}	6.8×10^{-3}	6.8×10^{-3}	4.0×10^{-2}	4.0×10^{-2}	2.8×10^{-1}	4.5×10^{-1}
0.1	3.8×10^{-2}	4.0×10^{-2}	4.8×10^{-3}	4.8×10^{-3}	2.6×10^{-2}	2.6×10^{-2}	1.9×10^{-1}	3.3×10^{-1}
0.2	7.1×10^{-2}	8.4×10^{-2}	4.0×10^{-3}	4.0×10^{-3}	1.6×10^{-2}	1.6×10^{-2}	1.3×10^{-1}	3.2×10^{-1}
0.5	1.1×10^{-1}	1.4×10^{-1}	4.3×10^{-3}	4.2×10^{-3}	1.1×10^{-2}	1.1×10^{-2}	1.0×10^{-1}	3.9×10^{-1}
0.7	1.5×10^{-1}	2.0×10^{-1}	4.9×10^{-3}	4.7×10^{-3}	8.9×10^{-3}	8.9×10^{-3}	9.0×10^{-2}	4.7×10^{-1}
1	2.0×10^{-1}	2.6×10^{-1}	5.9×10^{-3}	5.4×10^{-3}	7.2×10^{-3}	7.1×10^{-3}	8.0×10^{-2}	5.7×10^{-1}
2	2.9×10^{-1}	3.7×10^{-1}	8.0×10^{-3}	6.3×10^{-3}	5.5×10^{-3}	4.9×10^{-3}	6.1×10^{-2}	7.5×10^{-1}
3	3.4×10^{-1}	4.1×10^{-1}	8.7×10^{-3}	6.0×10^{-3}	4.8×10^{-3}	3.9×10^{-3}	4.8×10^{-2}	8.2×10^{-1}
5	**3.7×10^{-1}**	**4.3×10^{-1}**	**8.5×10^{-3}**	**4.7×10^{-3}**	**3.7×10^{-3}**	**2.7×10^{-3}**	**3.1×10^{-2}**	**8.4×10^{-1}**
7	3.7×10^{-1}	4.2×10^{-1}	7.7×10^{-3}	3.5×10^{-3}	2.9×10^{-3}	1.9×10^{-3}	2.1×10^{-2}	8.2×10^{-1}
10	3.6×10^{-1}	3.9×10^{-1}	6.4×10^{-3}	2.4×10^{-3}	2.1×10^{-3}	1.2×10^{-3}	1.2×10^{-2}	7.8×10^{-1}
15	3.4×10^{-1}	3.6×10^{-1}	4.6×10^{-3}	1.3×10^{-3}	1.3×10^{-3}	6.3×10^{-4}	6.1×10^{-3}	7.2×10^{-1}
20	3.3×10^{-1}	3.4×10^{-1}	3.5×10^{-3}	7.7×10^{-4}	8.2×10^{-4}	3.6×10^{-4}	3.4×10^{-3}	6.7×10^{-1}

Infant 1 y old (breathing rate = 0.35 m^3 h^{-1})								
0.0006	4.6×10^{-1}	4.5×10^{-1}	3.6×10^{-2}	3.6×10^{-2}	7.9×10^{-3}	7.9×10^{-3}	1.3×10^{-5}	$1.0\times10^{+0}$
0.001	4.1×10^{-1}	4.1×10^{-1}	5.5×10^{-2}	5.5×10^{-2}	2.7×10^{-2}	2.7×10^{-2}	4.7×10^{-4}	9.9×10^{-1}
0.002	3.1×10^{-1}	3.3×10^{-1}	6.8×10^{-2}	6.8×10^{-2}	8.7×10^{-2}	8.7×10^{-2}	1.5×10^{-2}	9.7×10^{-1}
0.005	1.6×10^{-1}	1.8×10^{-1}	4.7×10^{-2}	4.7×10^{-2}	1.4×10^{-1}	1.4×10^{-1}	1.8×10^{-1}	9.1×10^{-1}
0.01	9.1×10^{-2}	1.0×10^{-1}	2.6×10^{-2}	2.6×10^{-2}	1.1×10^{-1}	1.1×10^{-1}	3.9×10^{-1}	8.6×10^{-1}
0.02	5.3×10^{-2}	5.8×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	7.2×10^{-2}	7.2×10^{-2}	4.9×10^{-1}	7.7×10^{-1}
0.05	3.4×10^{-2}	3.5×10^{-2}	8.4×10^{-3}	8.4×10^{-3}	4.2×10^{-2}	4.2×10^{-2}	3.6×10^{-1}	5.3×10^{-1}
0.1	4.8×10^{-2}	5.2×10^{-2}	5.9×10^{-3}	5.9×10^{-3}	2.8×10^{-2}	2.8×10^{-2}	2.5×10^{-1}	4.2×10^{-1}
0.2	9.4×10^{-2}	1.2×10^{-1}	4.8×10^{-3}	4.8×10^{-3}	1.7×10^{-2}	1.7×10^{-2}	1.7×10^{-1}	4.2×10^{-1}
0.5	1.5×10^{-1}	1.9×10^{-1}	4.8×10^{-3}	4.7×10^{-3}	1.2×10^{-2}	1.2×10^{-2}	1.3×10^{-1}	5.0×10^{-1}
0.7	1.9×10^{-1}	2.5×10^{-1}	5.1×10^{-3}	5.0×10^{-3}	8.8×10^{-3}	8.7×10^{-3}	1.0×10^{-1}	5.8×10^{-1}
1	2.4×10^{-1}	3.2×10^{-1}	5.7×10^{-3}	5.3×10^{-3}	6.5×10^{-3}	6.4×10^{-3}	8.5×10^{-2}	6.7×10^{-1}
2	3.3×10^{-1}	4.1×10^{-1}	6.7×10^{-3}	5.6×10^{-3}	3.9×10^{-3}	3.7×10^{-3}	5.5×10^{-2}	8.2×10^{-1}
3	3.7×10^{-1}	4.4×10^{-1}	6.8×10^{-3}	5.0×10^{-3}	2.9×10^{-3}	2.6×10^{-3}	3.9×10^{-2}	8.7×10^{-1}
5	**3.9×10^{-1}**	**4.4×10^{-1}**	**6.2×10^{-3}**	**3.8×10^{-3}**	**2.0×10^{-3}**	**1.6×10^{-3}**	**2.3×10^{-2}**	**8.7×10^{-1}**
7	3.9×10^{-1}	4.2×10^{-1}	5.4×10^{-3}	2.8×10^{-3}	1.5×10^{-3}	1.1×10^{-3}	1.4×10^{-2}	8.4×10^{-1}
10	3.7×10^{-1}	4.0×10^{-1}	4.3×10^{-3}	1.8×10^{-3}	1.0×10^{-3}	6.5×10^{-4}	8.1×10^{-3}	7.9×10^{-1}
15	3.5×10^{-1}	3.6×10^{-1}	3.0×10^{-3}	9.6×10^{-4}	5.7×10^{-4}	3.2×10^{-4}	3.8×10^{-3}	7.2×10^{-1}
20	3.3×10^{-1}	3.4×10^{-1}	2.2×10^{-3}	5.6×10^{-4}	3.5×10^{-4}	1.8×10^{-4}	2.0×10^{-3}	6.7×10^{-1}
Infant 3 mo old (breathing rate = 0.19 m^3 h^{-1})								
0.0006	4.6×10^{-1}	4.5×10^{-1}	3.6×10^{-2}	3.6×10^{-2}	3.5×10^{-3}	3.5×10^{-3}	6.6×10^{-7}	$1.0\times10^{+0}$
0.001	4.2×10^{-1}	4.2×10^{-1}	6.0×10^{-2}	6.0×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	6.4×10^{-5}	9.9×10^{-1}
0.002	3.2×10^{-1}	3.4×10^{-1}	8.3×10^{-2}	8.3×10^{-2}	6.9×10^{-2}	6.9×10^{-2}	5.0×10^{-3}	9.7×10^{-1}
0.005	1.7×10^{-1}	1.9×10^{-1}	6.2×10^{-2}	6.2×10^{-2}	1.5×10^{-1}	1.5×10^{-1}	1.2×10^{-1}	9.0×10^{-1}
0.01	9.6×10^{-2}	1.1×10^{-1}	3.6×10^{-2}	3.6×10^{-2}	1.3×10^{-1}	1.3×10^{-1}	3.1×10^{-1}	8.3×10^{-1}
0.02	5.4×10^{-2}	6.0×10^{-2}	2.0×10^{-2}	2.0×10^{-2}	8.6×10^{-2}	8.6×10^{-2}	4.3×10^{-1}	7.5×10^{-1}
0.05	3.4×10^{-2}	3.6×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	5.1×10^{-2}	5.1×10^{-2}	3.4×10^{-1}	5.3×10^{-1}
0.1	4.7×10^{-2}	5.1×10^{-2}	8.0×10^{-3}	8.0×10^{-3}	3.4×10^{-2}	3.4×10^{-2}	2.4×10^{-1}	4.2×10^{-1}
0.2	9.3×10^{-2}	1.1×10^{-1}	5.9×10^{-3}	5.9×10^{-3}	2.1×10^{-2}	2.1×10^{-2}	1.7×10^{-1}	4.3×10^{-1}
0.5	1.5×10^{-1}	1.9×10^{-1}	5.2×10^{-3}	5.2×10^{-3}	1.4×10^{-2}	1.4×10^{-2}	1.3×10^{-1}	5.0×10^{-1}
0.7	1.9×10^{-1}	2.5×10^{-1}	5.2×10^{-3}	5.0×10^{-3}	1.1×10^{-2}	1.1×10^{-2}	1.0×10^{-1}	5.7×10^{-1}
1	2.4×10^{-1}	3.1×10^{-1}	5.4×10^{-3}	5.1×10^{-3}	7.9×10^{-3}	7.8×10^{-3}	8.4×10^{-2}	6.6×10^{-1}
2	3.3×10^{-1}	4.1×10^{-1}	6.0×10^{-3}	4.9×10^{-3}	4.4×10^{-3}	4.2×10^{-3}	5.4×10^{-2}	8.1×10^{-1}
3	3.7×10^{-1}	4.4×10^{-1}	6.0×10^{-3}	4.4×10^{-3}	3.2×10^{-3}	2.9×10^{-3}	3.9×10^{-2}	8.6×10^{-1}
5	**3.9×10^{-1}**	**4.4×10^{-1}**	**5.5×10^{-3}**	**3.3×10^{-3}**	**2.1×10^{-3}**	**1.7×10^{-3}**	**2.2×10^{-2}**	**8.6×10^{-1}**
7	3.9×10^{-1}	4.2×10^{-1}	4.9×10^{-3}	2.4×10^{-3}	1.5×10^{-3}	1.1×10^{-3}	1.4×10^{-2}	8.4×10^{-1}
10	3.7×10^{-1}	4.0×10^{-1}	3.9×10^{-3}	1.6×10^{-3}	1.0×10^{-3}	6.5×10^{-4}	8.2×10^{-3}	7.9×10^{-1}
15	3.5×10^{-1}	3.6×10^{-1}	2.8×10^{-3}	8.4×10^{-4}	5.7×10^{-4}	3.2×10^{-4}	3.8×10^{-3}	7.2×10^{-1}
20	3.3×10^{-1}	3.4×10^{-1}	2.1×10^{-3}	5.0×10^{-4}	3.6×10^{-4}	1.8×10^{-4}	2.1×10^{-3}	6.7×10^{-1}

Table F.6. Fractional deposition in regions of the respiratory tract for subjects (normal nose augmenters) engaged in heavy exercize as a function of aerosol size

AMTD (μm)	ET_1	ET_2	$BB_{fast+seq}$	BB_{slow}	$bb_{fast+seq}$	bb_{slow}	AI	Total
				Adult male (breathing rate = 3.00 m^3 h^{-1})				
0.0006	2.2×10^{-1}	5.4×10^{-1}	4.8×10^{-2}	4.8×10^{-2}	6.0×10^{-2}	6.0×10^{-2}	4.1×10^{-3}	9.9×10^{-1}
0.001	2.0×10^{-1}	4.6×10^{-1}	5.0×10^{-2}	5.0×10^{-2}	1.0×10^{-1}	1.0×10^{-1}	2.3×10^{-2}	9.8×10^{-1}
0.002	1.5×10^{-1}	3.3×10^{-1}	4.0×10^{-2}	4.0×10^{-2}	1.4×10^{-1}	1.4×10^{-1}	1.2×10^{-1}	9.6×10^{-1}
0.005	7.7×10^{-2}	1.6×10^{-1}	2.0×10^{-2}	2.0×10^{-2}	1.2×10^{-1}	1.2×10^{-1}	4.2×10^{-1}	9.3×10^{-1}
0.01	4.3×10^{-2}	9.1×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	7.4×10^{-2}	7.4×10^{-2}	5.9×10^{-1}	8.9×10^{-1}
0.02	2.7×10^{-2}	5.6×10^{-2}	6.0×10^{-3}	6.0×10^{-3}	4.8×10^{-2}	4.8×10^{-2}	5.3×10^{-1}	7.2×10^{-1}
0.05	1.6×10^{-2}	3.3×10^{-2}	3.4×10^{-3}	3.4×10^{-3}	2.7×10^{-2}	2.7×10^{-2}	3.1×10^{-1}	4.2×10^{-1}
0.1	1.7×10^{-2}	2.7×10^{-2}	3.0×10^{-3}	3.0×10^{-3}	1.7×10^{-2}	1.7×10^{-2}	2.0×10^{-1}	2.8×10^{-1}
0.2	2.9×10^{-2}	4.2×10^{-2}	5.5×10^{-3}	5.3×10^{-3}	1.1×10^{-2}	1.1×10^{-2}	1.4×10^{-1}	2.4×10^{-1}
0.5	4.8×10^{-2}	7.0×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.0×10^{-3}	8.8×10^{-3}	1.2×10^{-1}	2.8×10^{-1}
0.7	6.5×10^{-2}	1.0×10^{-1}	1.8×10^{-2}	1.5×10^{-2}	9.0×10^{-3}	8.6×10^{-3}	1.2×10^{-1}	3.3×10^{-1}
1	8.8×10^{-2}	1.4×10^{-1}	2.8×10^{-2}	2.2×10^{-2}	1.0×10^{-2}	9.1×10^{-3}	1.2×10^{-1}	4.2×10^{-1}
2	1.3×10^{-1}	2.5×10^{-1}	5.4×10^{-2}	3.4×10^{-2}	1.4×10^{-2}	1.1×10^{-2}	1.1×10^{-1}	6.1×10^{-1}
3	1.6×10^{-1}	3.1×10^{-1}	6.8×10^{-2}	3.7×10^{-2}	1.6×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	7.0×10^{-1}
5	**1.7×10^{-1}**	**3.9×10^{-1}**	**7.8×10^{-2}**	**3.3×10^{-2}**	**1.5×10^{-2}**	**9.3×10^{-3}**	**7.3×10^{-2}**	**7.7×10^{-1}**
7	1.8×10^{-1}	4.2×10^{-1}	7.5×10^{-2}	2.7×10^{-2}	1.3×10^{-2}	7.3×10^{-3}	5.3×10^{-2}	7.7×10^{-1}
10	1.8×10^{-1}	4.4×10^{-1}	6.6×10^{-2}	1.9×10^{-2}	9.6×10^{-3}	5.0×10^{-3}	3.4×10^{-2}	7.5×10^{-1}
15	1.7×10^{-1}	4.5×10^{-1}	5.0×10^{-2}	1.1×10^{-2}	6.0×10^{-3}	2.8×10^{-3}	1.8×10^{-2}	7.1×10^{-1}
20	1.6×10^{-1}	4.4×10^{-1}	3.7×10^{-2}	7.1×10^{-3}	3.9×10^{-3}	1.7×10^{-3}	1.0×10^{-2}	6.6×10^{-1}
				Adult female (breathing rate = 2.70 m^3 h^{-1})				
0.0006	2.2×10^{-1}	5.4×10^{-1}	4.9×10^{-2}	4.9×10^{-2}	5.9×10^{-2}	5.9×10^{-2}	3.2×10^{-3}	9.9×10^{-1}
0.001	2.0×10^{-1}	4.6×10^{-1}	5.0×10^{-2}	5.0×10^{-2}	1.0×10^{-1}	1.0×10^{-1}	1.9×10^{-2}	9.8×10^{-1}
0.002	1.5×10^{-1}	3.3×10^{-1}	4.1×10^{-2}	4.1×10^{-2}	1.5×10^{-1}	1.5×10^{-1}	1.1×10^{-1}	9.6×10^{-1}
0.005	7.7×10^{-2}	1.6×10^{-1}	2.0×10^{-2}	2.0×10^{-2}	1.2×10^{-1}	1.2×10^{-1}	4.0×10^{-1}	9.2×10^{-1}
0.01	4.4×10^{-2}	9.2×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	7.8×10^{-2}	7.8×10^{-2}	5.6×10^{-1}	8.7×10^{-1}
0.02	2.8×10^{-2}	5.8×10^{-2}	6.2×10^{-3}	6.2×10^{-3}	5.1×10^{-2}	5.1×10^{-2}	4.9×10^{-1}	6.9×10^{-1}
0.05	1.7×10^{-2}	3.3×10^{-2}	3.5×10^{-3}	3.5×10^{-3}	2.8×10^{-2}	2.8×10^{-2}	2.8×10^{-1}	4.0×10^{-1}
0.1	1.8×10^{-2}	2.8×10^{-2}	3.1×10^{-3}	3.1×10^{-3}	1.8×10^{-2}	1.8×10^{-2}	1.8×10^{-1}	2.7×10^{-1}
0.2	3.1×10^{-2}	4.5×10^{-2}	5.7×10^{-3}	5.6×10^{-3}	1.1×10^{-2}	1.1×10^{-2}	1.3×10^{-1}	2.4×10^{-1}
0.5	5.1×10^{-2}	7.6×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	9.2×10^{-3}	9.1×10^{-3}	1.1×10^{-1}	2.7×10^{-1}
0.7	6.9×10^{-2}	1.1×10^{-1}	1.8×10^{-2}	1.6×10^{-2}	9.0×10^{-3}	8.6×10^{-3}	1.0×10^{-1}	3.3×10^{-1}
1	9.2×10^{-2}	1.5×10^{-1}	2.8×10^{-2}	2.3×10^{-2}	9.9×10^{-3}	9.0×10^{-3}	1.0×10^{-1}	4.2×10^{-1}
2	1.4×10^{-1}	2.6×10^{-1}	5.4×10^{-2}	3.5×10^{-2}	1.3×10^{-2}	1.0×10^{-2}	9.7×10^{-2}	6.1×10^{-1}
3	1.6×10^{-1}	3.3×10^{-1}	6.7×10^{-2}	3.7×10^{-2}	1.4×10^{-2}	1.0×10^{-2}	8.6×10^{-2}	7.0×10^{-1}
5	**1.8×10^{-1}**	**4.0×10^{-1}**	**7.5×10^{-2}**	**3.3×10^{-2}**	**1.3×10^{-2}**	**8.7×10^{-3}**	**6.2×10^{-2}**	**7.7×10^{-1}**
7	1.8×10^{-1}	4.3×10^{-1}	7.2×10^{-2}	2.7×10^{-2}	1.1×10^{-2}	6.7×10^{-3}	4.5×10^{-2}	7.8×10^{-1}
10	1.8×10^{-1}	4.5×10^{-1}	6.2×10^{-2}	1.9×10^{-2}	8.5×10^{-3}	4.6×10^{-3}	2.9×10^{-2}	7.5×10^{-1}
15	1.7×10^{-1}	4.6×10^{-1}	4.6×10^{-2}	1.1×10^{-2}	5.2×10^{-3}	2.5×10^{-3}	1.5×10^{-2}	7.1×10^{-1}
20	1.6×10^{-1}	4.5×10^{-1}	3.4×10^{-2}	7.0×10^{-3}	3.4×10^{-3}	1.5×10^{-3}	8.6×10^{-3}	6.6×10^{-1}

Male 15 y old (breathing rate = $2.92\ m^3\ h^{-1}$)								
0.0006	2.2×10^{-1}	5.4×10^{-1}	4.7×10^{-2}	4.7×10^{-2}	5.9×10^{-2}	5.9×10^{-2}	4.6×10^{-3}	9.9×10^{-1}
0.001	2.0×10^{-1}	4.6×10^{-1}	4.9×10^{-2}	4.9×10^{-2}	9.9×10^{-2}	9.9×10^{-2}	2.5×10^{-2}	9.8×10^{-1}
0.002	1.5×10^{-1}	3.3×10^{-1}	3.9×10^{-2}	3.9×10^{-2}	1.4×10^{-1}	1.4×10^{-1}	1.3×10^{-1}	9.5×10^{-1}
0.005	7.7×10^{-2}	1.6×10^{-1}	1.9×10^{-2}	1.9×10^{-2}	1.1×10^{-1}	1.1×10^{-1}	4.2×10^{-1}	9.2×10^{-1}
0.01	4.4×10^{-2}	9.3×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	7.2×10^{-2}	7.2×10^{-2}	5.6×10^{-1}	8.6×10^{-1}
0.02	2.8×10^{-2}	5.8×10^{-2}	6.0×10^{-3}	6.0×10^{-3}	4.7×10^{-2}	4.7×10^{-2}	4.8×10^{-1}	6.7×10^{-1}
0.05	1.7×10^{-2}	3.3×10^{-2}	3.4×10^{-3}	3.4×10^{-3}	2.6×10^{-2}	2.6×10^{-2}	2.7×10^{-1}	3.8×10^{-1}
0.1	1.8×10^{-2}	2.8×10^{-2}	3.0×10^{-3}	3.0×10^{-3}	1.6×10^{-2}	1.6×10^{-2}	1.7×10^{-1}	2.6×10^{-1}
0.2	3.1×10^{-2}	4.5×10^{-2}	5.7×10^{-3}	5.5×10^{-3}	1.0×10^{-2}	1.0×10^{-2}	1.2×10^{-1}	2.3×10^{-1}
0.5	5.0×10^{-2}	7.5×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	8.7×10^{-3}	8.5×10^{-3}	1.0×10^{-1}	2.7×10^{-1}
0.7	6.9×10^{-2}	1.1×10^{-1}	1.8×10^{-2}	1.6×10^{-2}	8.8×10^{-3}	8.3×10^{-3}	9.6×10^{-2}	3.2×10^{-1}
1	9.1×10^{-2}	1.5×10^{-1}	2.8×10^{-2}	2.3×10^{-2}	1.0×10^{-2}	9.0×10^{-3}	9.6×10^{-2}	4.1×10^{-1}
2	1.4×10^{-1}	2.6×10^{-1}	5.4×10^{-2}	3.5×10^{-2}	1.4×10^{-2}	1.1×10^{-2}	9.2×10^{-2}	6.0×10^{-1}
3	1.6×10^{-1}	3.3×10^{-1}	6.7×10^{-2}	3.7×10^{-2}	1.5×10^{-2}	1.1×10^{-2}	8.1×10^{-2}	7.0×10^{-1}
5	**1.8×10^{-1}**	**4.0×10^{-1}**	**7.5×10^{-2}**	**3.3×10^{-2}**	**1.5×10^{-2}**	**9.4×10^{-3}**	**5.9×10^{-2}**	**7.7×10^{-1}**
7	1.8×10^{-1}	4.3×10^{-1}	7.2×10^{-2}	2.7×10^{-2}	1.2×10^{-2}	7.4×10^{-3}	4.2×10^{-2}	7.7×10^{-1}
10	1.8×10^{-1}	4.5×10^{-1}	6.2×10^{-2}	1.9×10^{-2}	9.3×10^{-3}	5.0×10^{-3}	2.7×10^{-2}	7.5×10^{-1}
15	1.7×10^{-1}	4.6×10^{-1}	4.6×10^{-2}	1.1×10^{-2}	5.8×10^{-3}	2.8×10^{-3}	1.4×10^{-2}	7.0×10^{-1}
20	1.6×10^{-1}	4.5×10^{-1}	3.4×10^{-2}	7.0×10^{-3}	3.7×10^{-3}	1.7×10^{-3}	8.0×10^{-3}	6.6×10^{-1}
Female 15 y old (breathing rate = $2.57\ m^3\ h^{-1}$)								
0.0006	2.2×10^{-1}	5.5×10^{-1}	4.9×10^{-2}	4.9×10^{-2}	5.7×10^{-2}	5.7×10^{-2}	3.9×10^{-3}	9.9×10^{-1}
0.001	2.0×10^{-1}	4.6×10^{-1}	5.0×10^{-2}	5.0×10^{-2}	9.7×10^{-2}	9.7×10^{-2}	2.2×10^{-2}	9.7×10^{-1}
0.002	1.5×10^{-1}	3.3×10^{-1}	4.1×10^{-2}	4.1×10^{-2}	1.4×10^{-1}	1.4×10^{-1}	1.2×10^{-1}	9.5×10^{-1}
0.005	7.7×10^{-2}	1.6×10^{-1}	2.0×10^{-2}	2.0×10^{-2}	1.1×10^{-1}	1.1×10^{-1}	4.0×10^{-1}	9.1×10^{-1}
0.01	4.4×10^{-2}	9.3×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	7.4×10^{-2}	7.4×10^{-2}	5.5×10^{-1}	8.6×10^{-1}
0.02	2.8×10^{-2}	5.9×10^{-2}	6.3×10^{-3}	6.3×10^{-3}	4.8×10^{-2}	4.8×10^{-2}	4.7×10^{-1}	6.7×10^{-1}
0.05	1.7×10^{-2}	3.4×10^{-2}	3.6×10^{-3}	3.6×10^{-3}	2.7×10^{-2}	2.7×10^{-2}	2.7×10^{-1}	3.8×10^{-1}
0.1	1.8×10^{-2}	2.9×10^{-2}	3.1×10^{-3}	3.1×10^{-3}	1.7×10^{-2}	1.7×10^{-2}	1.7×10^{-1}	2.6×10^{-1}
0.2	3.1×10^{-2}	4.5×10^{-2}	5.6×10^{-3}	5.5×10^{-3}	1.1×10^{-2}	1.1×10^{-2}	1.2×10^{-1}	2.3×10^{-1}
0.5	5.1×10^{-2}	7.6×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	8.9×10^{-3}	8.7×10^{-3}	1.0×10^{-1}	2.7×10^{-1}
0.7	6.9×10^{-2}	1.1×10^{-1}	1.8×10^{-2}	1.6×10^{-2}	8.9×10^{-3}	8.5×10^{-3}	9.6×10^{-2}	3.3×10^{-1}
1	9.2×10^{-2}	1.5×10^{-1}	2.8×10^{-2}	2.2×10^{-2}	1.0×10^{-2}	9.1×10^{-3}	9.6×10^{-2}	4.1×10^{-1}
2	1.4×10^{-1}	2.6×10^{-1}	5.2×10^{-2}	3.4×10^{-2}	1.4×10^{-2}	1.1×10^{-2}	9.2×10^{-2}	6.0×10^{-1}
3	1.6×10^{-1}	3.3×10^{-1}	6.5×10^{-2}	3.6×10^{-2}	1.5×10^{-2}	1.1×10^{-2}	8.1×10^{-2}	7.0×10^{-1}
5	**1.8×10^{-1}**	**4.0×10^{-1}**	**7.3×10^{-2}**	**3.2×10^{-2}**	**1.5×10^{-2}**	**9.3×10^{-3}**	**5.9×10^{-2}**	**7.7×10^{-1}**
7	1.8×10^{-1}	4.4×10^{-1}	7.0×10^{-2}	2.6×10^{-2}	1.2×10^{-2}	7.3×10^{-3}	4.2×10^{-2}	7.7×10^{-1}
10	1.8×10^{-1}	4.5×10^{-1}	6.0×10^{-2}	1.9×10^{-2}	9.3×10^{-3}	5.0×10^{-3}	2.7×10^{-2}	7.5×10^{-1}
15	1.7×10^{-1}	4.6×10^{-1}	4.5×10^{-2}	1.1×10^{-2}	5.8×10^{-3}	2.8×10^{-3}	1.4×10^{-2}	7.0×10^{-1}
20	1.6×10^{-1}	4.5×10^{-1}	3.3×10^{-2}	6.7×10^{-3}	3.7×10^{-3}	1.7×10^{-3}	8.1×10^{-3}	6.6×10^{-1}

Continued overleaf

Table F.6.—(*continued*)

AMTD (μm)	ET_1	ET_2	$BB_{fast+seq}$	BB_{slow}	$bb_{fast+seq}$	bb_{slow}	AI	Total
				Child 10 y old (breathing rate = 2.03 m³ h⁻¹)				
0.0006	2.3×10^{-1}	5.5×10^{-1}	5.1×10^{-2}	5.1×10^{-2}	5.3×10^{-2}	5.3×10^{-2}	3.0×10^{-3}	9.9×10^{-1}
0.001	2.0×10^{-1}	4.6×10^{-1}	5.4×10^{-2}	5.4×10^{-2}	9.3×10^{-2}	9.3×10^{-2}	1.8×10^{-2}	9.8×10^{-1}
0.002	1.5×10^{-1}	3.3×10^{-1}	4.4×10^{-2}	4.4×10^{-2}	1.4×10^{-1}	1.4×10^{-1}	1.1×10^{-1}	9.5×10^{-1}
0.005	7.8×10^{-2}	1.7×10^{-1}	2.2×10^{-2}	2.2×10^{-2}	1.2×10^{-1}	1.2×10^{-1}	3.9×10^{-1}	9.1×10^{-1}
0.01	4.5×10^{-2}	9.4×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	7.6×10^{-2}	7.6×10^{-2}	5.4×10^{-1}	8.6×10^{-1}
0.02	2.8×10^{-2}	5.9×10^{-2}	6.8×10^{-3}	6.8×10^{-3}	5.0×10^{-2}	5.0×10^{-2}	4.8×10^{-1}	6.8×10^{-1}
0.05	1.7×10^{-2}	3.4×10^{-2}	3.9×10^{-3}	3.9×10^{-3}	2.8×10^{-2}	2.8×10^{-2}	2.8×10^{-1}	3.9×10^{-1}
0.1	1.9×10^{-2}	3.0×10^{-2}	3.4×10^{-3}	3.4×10^{-3}	1.7×10^{-2}	1.7×10^{-2}	1.8×10^{-1}	2.7×10^{-1}
0.2	3.5×10^{-2}	5.0×10^{-2}	6.0×10^{-3}	5.9×10^{-3}	1.1×10^{-2}	1.1×10^{-2}	1.2×10^{-1}	2.4×10^{-1}
0.5	5.6×10^{-2}	8.5×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	9.0×10^{-3}	8.9×10^{-3}	1.0×10^{-1}	2.8×10^{-1}
0.7	7.6×10^{-2}	1.2×10^{-1}	1.8×10^{-2}	1.6×10^{-2}	8.8×10^{-3}	8.4×10^{-3}	9.6×10^{-2}	3.4×10^{-1}
1	9.9×10^{-2}	1.7×10^{-1}	2.8×10^{-2}	2.3×10^{-2}	9.7×10^{-3}	8.8×10^{-3}	9.4×10^{-2}	4.3×10^{-1}
2	1.4×10^{-1}	2.8×10^{-1}	5.2×10^{-2}	3.5×10^{-2}	1.3×10^{-2}	1.0×10^{-2}	8.8×10^{-2}	6.2×10^{-1}
3	1.7×10^{-1}	3.5×10^{-1}	6.3×10^{-2}	3.7×10^{-2}	1.4×10^{-2}	1.0×10^{-2}	7.6×10^{-2}	7.1×10^{-1}
5	$\mathbf{1.8\times10^{-1}}$	$\mathbf{4.2\times10^{-1}}$	$\mathbf{6.9\times10^{-2}}$	$\mathbf{3.2\times10^{-2}}$	$\mathbf{1.3\times10^{-2}}$	$\mathbf{8.6\times10^{-3}}$	$\mathbf{5.4\times10^{-2}}$	$\mathbf{7.8\times10^{-1}}$
7	1.8×10^{-1}	4.5×10^{-1}	6.5×10^{-2}	2.6×10^{-2}	1.1×10^{-2}	6.7×10^{-3}	3.8×10^{-2}	7.8×10^{-1}
10	1.8×10^{-1}	4.7×10^{-1}	5.5×10^{-2}	1.8×10^{-2}	8.0×10^{-3}	4.5×10^{-3}	2.4×10^{-2}	7.6×10^{-1}
15	1.7×10^{-1}	4.7×10^{-1}	4.1×10^{-2}	1.0×10^{-2}	4.9×10^{-3}	2.5×10^{-3}	1.2×10^{-2}	7.1×10^{-1}
20	1.6×10^{-1}	4.6×10^{-1}	3.0×10^{-2}	6.6×10^{-3}	3.1×10^{-3}	1.5×10^{-3}	7.0×10^{-3}	6.7×10^{-1}

ANNEXE G. SPECIFIC ABSORBED FRACTIONS OF PHOTON ENERGY

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List of Tables

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Table G.1. Specific absorbed fraction of photon energy (in kg^{-1}) for the newborn (3.4 kg) with the ET airways as the source

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	0.0	9.4×10^{-8}	2.6×10^{-4}	1.0×10^{-2}	1.8×10^{-2}	1.7×10^{-2}	1.6×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	9.6×10^{-3}
Brain	0.0	1.1×10^{-4}	3.7×10^{-3}	3.1×10^{-2}	3.9×10^{-2}	2.6×10^{-2}	2.6×10^{-2}	2.7×10^{-2}	2.5×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.0×10^{-2}
Breasts	0.0	6.9×10^{-5}	9.1×10^{-3}	4.1×10^{-2}	3.7×10^{-2}	3.3×10^{-2}	3.2×10^{-2}	3.4×10^{-2}	3.3×10^{-2}	3.2×10^{-2}	3.0×10^{-2}	2.5×10^{-2}
Gall Bl Wall	0.0	2.8×10^{-8}	1.2×10^{-4}	6.1×10^{-3}	1.4×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.7×10^{-3}	8.0×10^{-3}
GI Tract:												
LLI Wall	0.0	0.0	1.3×10^{-6}	4.6×10^{-4}	2.6×10^{-3}	3.3×10^{-3}	3.6×10^{-3}	3.9×10^{-3}	3.8×10^{-3}	3.7×10^{-3}	3.6×10^{-3}	3.0×10^{-3}
SI Wall	0.0	0.0	6.1×10^{-6}	1.7×10^{-3}	3.2×10^{-3}	4.3×10^{-3}	4.4×10^{-3}	5.1×10^{-3}	5.1×10^{-3}	4.9×10^{-3}	4.7×10^{-3}	4.5×10^{-3}
Stomach Wall	0.0	1.3×10^{-7}	2.4×10^{-4}	1.3×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	8.9×10^{-3}
ULI Wall	0.0	2.2×10^{-10}	9.9×10^{-6}	1.6×10^{-3}	4.1×10^{-3}	6.3×10^{-3}	6.2×10^{-3}	6.1×10^{-3}	6.1×10^{-3}	5.9×10^{-3}	5.8×10^{-3}	4.8×10^{-3}
Heart Wall	8.0×10^{-10}	7.5×10^{-4}	1.7×10^{-2}	8.6×10^{-2}	8.0×10^{-2}	5.0×10^{-2}	4.5×10^{-2}	4.6×10^{-2}	4.9×10^{-2}	4.4×10^{-2}	3.9×10^{-2}	3.2×10^{-2}
Kidneys	0.0	3.0×10^{-9}	3.9×10^{-5}	3.7×10^{-3}	8.2×10^{-3}	8.5×10^{-3}	7.6×10^{-3}	8.4×10^{-3}	9.0×10^{-3}	8.4×10^{-3}	8.0×10^{-3}	6.4×10^{-3}
Liver	0.0	2.4×10^{-7}	3.2×10^{-4}	1.1×10^{-2}	1.8×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.0×10^{-2}
Lungs(a)	1.2×10^{-7}	3.1×10^{-3}	5.3×10^{-2}	1.3×10^{-1}	9.5×10^{-2}	4.9×10^{-2}	4.7×10^{-2}	5.0×10^{-2}	4.6×10^{-2}	4.3×10^{-2}	4.0×10^{-2}	3.1×10^{-2}
ET Airways(b)	5.3×10^{2}	2.8×10^{2}	1.4×10^{2}	49	15	8.7	9.4	10	9.9	9.0	8.3	6.8
Muscle	1.3×10^{-1}	2.6×10^{-1}	3.1×10^{-1}	2.4×10^{-1}	1.1×10^{-1}	6.5×10^{-2}	6.6×10^{-2}	6.8×10^{-2}	6.4×10^{-2}	5.9×10^{-2}	5.5×10^{-2}	4.4×10^{-2}
Ovaries	0.0	0.0	9.8×10^{-7}	5.3×10^{-4}	3.1×10^{-3}	3.9×10^{-3}	4.1×10^{-3}	4.4×10^{-3}	4.3×10^{-3}	4.1×10^{-3}	4.0×10^{-3}	3.4×10^{-3}
Pancreas	0.0	1.1×10^{-7}	2.8×10^{-4}	9.8×10^{-3}	1.2×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	9.9×10^{-3}
Skeleton:												
Active Marrow	3.2×10^{-6}	1.1×10^{-3}	1.1×10^{-2}	3.8×10^{-2}	3.7×10^{-2}	2.6×10^{-2}	2.3×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.6×10^{-2}
Bone Surfaces	1.4×10^{-6}	5.9×10^{-3}	6.5×10^{-2}	2.3×10^{-1}	2.0×10^{-1}	6.8×10^{-2}	3.5×10^{-2}	2.9×10^{-2}	2.7×10^{-2}	2.5×10^{-2}	2.4×10^{-2}	2.1×10^{-2}
Skin	7.1×10^{-7}	2.0×10^{-3}	1.8×10^{-2}	4.5×10^{-2}	3.2×10^{-2}	2.0×10^{-2}	2.1×10^{-2}	2.2×10^{-2}	2.2×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.9×10^{-2}
Spleen	0.0	3.7×10^{-8}	1.4×10^{-4}	1.0×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	8.3×10^{-3}
Testes	0.0	0.0	1.9×10^{-8}	7.3×10^{-5}	9.4×10^{-4}	1.6×10^{-3}	2.0×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	1.9×10^{-3}
Thymus	1.1×10^{-2}	4.4×10^{-1}	9.6×10^{-1}	1.0	4.7×10^{-1}	2.6×10^{-1}	2.6×10^{-1}	2.8×10^{-1}	2.5×10^{-1}	2.4×10^{-1}	2.4×10^{-1}	2.0×10^{-1}
Thyroid	0.0	1.1×10^{-4}	3.7×10^{-3}	3.1×10^{-2}	3.9×10^{-2}	2.6×10^{-2}	2.6×10^{-2}	2.7×10^{-2}	2.5×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.0×10^{-2}
Urinary Bl Wall	0.0	0.0	2.4×10^{-7}	2.5×10^{-4}	2.0×10^{-3}	2.8×10^{-3}	3.1×10^{-3}	3.4×10^{-3}	3.3×10^{-3}	3.2×10^{-3}	3.2×10^{-3}	2.7×10^{-3}
Uterus	0.0	0.0	8.7×10^{-7}	5.0×10^{-4}	3.0×10^{-3}	3.8×10^{-3}	4.0×10^{-3}	4.3×10^{-3}	4.2×10^{-3}	4.0×10^{-3}	3.9×10^{-3}	3.3×10^{-3}
Whole Body	2.8×10^{-1}	2.8×10^{-1}	2.7×10^{-1}	2.0×10^{-1}	1.0×10^{-1}	5.6×10^{-2}	5.5×10^{-2}	5.7×10^{-2}	5.4×10^{-2}	5.0×10^{-2}	4.7×10^{-2}	3.8×10^{-2}

(a) Lungs include BB, bb, AI, and LN_{TH}.

(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.2. Specific absorbed fraction of photon energy (in kg^{-1}) for the 1-y old (9.8 kg) with the ET airways as the source

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	0.0	1.0×10^{-10}	7.4×10^{-6}	1.5×10^{-3}	5.8×10^{-3}	7.0×10^{-3}	6.9×10^{-3}	6.5×10^{-3}	6.1×10^{-3}	5.7×10^{-3}	5.5×10^{-3}	4.7×10^{-3}
Brain	0.0	2.2×10^{-6}	2.8×10^{-4}	7.1×10^{-3}	1.5×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	9.4×10^{-3}
Breasts	0.0	6.3×10^{-7}	7.2×10^{-4}	1.6×10^{-2}	2.0×10^{-2}	1.8×10^{-2}	1.6×10^{-2}	1.7×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.2×10^{-2}
Gall Bl Wall	0.0	0.0	1.8×10^{-6}	6.6×10^{-4}	3.5×10^{-3}	4.2×10^{-3}	4.3×10^{-3}	4.6×10^{-3}	4.5×10^{-3}	4.3×10^{-3}	4.2×10^{-3}	3.6×10^{-3}
GI Tract:												
LLI Wall	0.0	0.0	6.5×10^{-9}	2.8×10^{-5}	4.6×10^{-4}	9.5×10^{-4}	1.2×10^{-3}	1.4×10^{-3}	1.5×10^{-3}	1.5×10^{-3}	1.5×10^{-3}	1.3×10^{-3}
SI Wall	0.0	0.0	4.3×10^{-6}	1.0×10^{-4}	7.4×10^{-4}	1.5×10^{-3}	1.6×10^{-3}	1.6×10^{-3}	1.8×10^{-3}	1.9×10^{-3}	2.0×10^{-3}	2.0×10^{-3}
Stomach Wall	0.0	2.3×10^{-10}	7.3×10^{-6}	1.8×10^{-3}	4.4×10^{-3}	5.8×10^{-3}	5.4×10^{-3}	6.1×10^{-3}	6.2×10^{-3}	5.9×10^{-3}	5.6×10^{-3}	4.2×10^{-3}
ULI Wall	0.0	0.0	8.1×10^{-8}	1.3×10^{-4}	1.3×10^{-3}	1.7×10^{-3}	2.1×10^{-3}	2.5×10^{-3}	2.6×10^{-3}	2.6×10^{-3}	2.5×10^{-3}	2.2×10^{-3}
Heart Wall	0.0	1.0×10^{-5}	3.1×10^{-3}	2.0×10^{-2}	3.3×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	2.2×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.8×10^{-2}	1.5×10^{-2}
Kidneys	0.0	0.0	6.1×10^{-7}	1.1×10^{-3}	3.2×10^{-3}	3.1×10^{-3}	2.6×10^{-3}	3.5×10^{-3}	3.7×10^{-3}	3.9×10^{-3}	4.0×10^{-3}	3.0×10^{-3}
Liver	0.0	4.5×10^{-10}	1.0×10^{-5}	2.6×10^{-3}	6.2×10^{-3}	5.9×10^{-3}	6.0×10^{-3}	6.4×10^{-3}	5.9×10^{-3}	5.9×10^{-3}	5.9×10^{-3}	4.9×10^{-3}
Lungs$^{(a)}$	3.6×10^{-10}	2.1×10^{-4}	1.2×10^{-2}	5.0×10^{-2}	4.7×10^{-2}	2.9×10^{-2}	2.9×10^{-2}	2.3×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	1.6×10^{-2}
ET Airways$^{(b)}$	3.9×10^{2}	2.1×10^{2}	1.1×10^{2}	37	12	6.9	7.7	8.7	8.2	7.5	6.9	5.5
Muscle	4.8×10^{-2}	9.7×10^{-2}	1.2×10^{-1}	1.0×10^{-1}	5.7×10^{-2}	3.4×10^{-2}	3.4×10^{-2}	3.4×10^{-2}	3.2×10^{-2}	3.0×10^{-2}	2.7×10^{-2}	2.3×10^{-2}
Ovaries	0.0	0.0	3.2×10^{-9}	3.0×10^{-5}	5.4×10^{-4}	1.1×10^{-3}	1.4×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.5×10^{-3}
Pancreas	0.0	1.1×10^{-10}	7.5×10^{-6}	1.5×10^{-3}	5.7×10^{-3}	7.2×10^{-3}	5.8×10^{-3}	6.0×10^{-3}	6.1×10^{-3}	5.8×10^{-3}	5.7×10^{-3}	4.7×10^{-3}
Skeleton:												
Active Marrow	1.1×10^{-7}	1.5×10^{-4}	2.2×10^{-3}	1.2×10^{-2}	1.6×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.9×10^{-3}	7.8×10^{-3}
Bone Surfaces	2.5×10^{-8}	8.1×10^{-4}	1.2×10^{-2}	7.0×10^{-2}	8.5×10^{-2}	3.7×10^{-2}	1.9×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	9.6×10^{-3}
Skin	7.8×10^{-6}	2.9×10^{-4}	3.7×10^{-3}	1.4×10^{-2}	1.3×10^{-2}	9.5×10^{-3}	9.8×10^{-3}	1.1×10^{-2}	1.1×10^{-2}	9.7×10^{-3}	8.8×10^{-3}	7.5×10^{-3}
Spleen	0.0	0.0	3.4×10^{-6}	3.0×10^{-3}	4.9×10^{-3}	6.3×10^{-3}	6.1×10^{-3}	5.6×10^{-3}	4.9×10^{-3}	4.6×10^{-3}	4.4×10^{-3}	4.0×10^{-3}
Testes	0.0	0.0	0.0	2.1×10^{-6}	1.1×10^{-4}	3.6×10^{-4}	5.4×10^{-4}	7.3×10^{-4}	8.2×10^{-4}	8.5×10^{-4}	8.7×10^{-4}	8.0×10^{-4}
Thymus	1.4×10^{-4}	5.7×10^{-2}	2.6×10^{-1}	3.9×10^{-1}	2.1×10^{-1}	1.3×10^{-1}	1.2×10^{-1}	1.2×10^{-1}	1.1×10^{-1}	1.0×10^{-1}	9.6×10^{-2}	7.7×10^{-2}
Thyroid	0.0	2.2×10^{-6}	2.8×10^{-4}	7.1×10^{-3}	1.5×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	9.4×10^{-3}
Urinary Bl Wall	0.0	0.0	4.6×10^{-10}	1.1×10^{-5}	2.9×10^{-4}	7.2×10^{-4}	9.6×10^{-4}	1.2×10^{-3}	1.3×10^{-3}	1.3×10^{-3}	1.3×10^{-3}	1.2×10^{-3}
Uterus	0.0	0.0	2.7×10^{-9}	2.7×10^{-5}	5.2×10^{-4}	1.1×10^{-3}	1.4×10^{-3}	1.6×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.5×10^{-3}
Whole Body	1.0×10^{-1}	1.0×10^{-1}	1.0×10^{-1}	8.3×10^{-2}	5.0×10^{-2}	3.0×10^{-2}	2.8×10^{-2}	2.8×10^{-2}	2.7×10^{-2}	2.5×10^{-2}	2.3×10^{-2}	1.9×10^{-2}

(a) Lungs include BB, bb, AI, and LN$_{TH}$.
(b) ET airways include ET$_1$, ET$_2$, and LN$_{ET}$.

Table G.3. Specific absorbed fraction of photon energy (in kg^{-1}) for the 5-y old (19 kg) with the ET airways as the source

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	0.0	0.0	1.9×10^{-7}	2.2×10^{-4}	1.8×10^{-3}	3.0×10^{-3}	2.9×10^{-3}	3.2×10^{-3}	3.2×10^{-3}	3.1×10^{-3}	3.0×10^{-3}	2.6×10^{-3}
Brains	0.0	5.6×10^{-7}	2.5×10^{-4}	2.9×10^{-3}	1.0×10^{-2}	9.8×10^{-3}	9.6×10^{-3}	9.9×10^{-3}	9.9×10^{-3}	9.7×10^{-3}	9.2×10^{-3}	7.2×10^{-3}
Breasts	0.0	4.5×10^{-9}	5.2×10^{-5}	4.0×10^{-3}	1.1×10^{-2}	1.2×10^{-2}	9.0×10^{-3}	9.3×10^{-3}	9.3×10^{-3}	8.7×10^{-3}	8.2×10^{-3}	6.8×10^{-3}
Gall Bl Wall	0.0	0.0	4.1×10^{-8}	8.3×10^{-5}	9.5×10^{-4}	1.6×10^{-3}	1.9×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	1.9×10^{-3}
GI Tract :												
LLI Wall	0.0	0.0	0.0	1.5×10^{-6}	7.1×10^{-5}	2.4×10^{-4}	3.8×10^{-4}	5.3×10^{-4}	6.2×10^{-4}	6.5×10^{-4}	6.8×10^{-4}	6.3×10^{-4}
SI Wall	0.0	0.0	2.1×10^{-10}	6.5×10^{-6}	2.8×10^{-6}	4.6×10^{-6}	6.1×10^{-6}	7.9×10^{-6}	8.6×10^{-6}	8.8×10^{-6}	9.0×10^{-6}	9.0×10^{-4}
Stomach Wall	0.0	0.0	1.6×10^{-7}	1.6×10^{-4}	1.0×10^{-3}	2.6×10^{-3}	2.7×10^{-3}	2.3×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	2.2×10^{-3}
ULI Wall	0.0	0.0	4.5×10^{-10}	9.6×10^{-6}	2.6×10^{-4}	5.0×10^{-4}	7.7×10^{-4}	1.1×10^{-3}	1.2×10^{-3}	1.2×10^{-3}	1.2×10^{-3}	1.1×10^{-3}
Heart Wall	0.0	1.1×10^{-7}	1.4×10^{-4}	5.7×10^{-3}	1.2×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	7.8×10^{-3}
Kidneys	0.0	0.0	8.5×10^{-9}	4.3×10^{-5}	1.2×10^{-3}	1.7×10^{-3}	1.8×10^{-3}	1.8×10^{-3}	1.9×10^{-3}	1.8×10^{-3}	1.8×10^{-3}	1.6×10^{-3}
Liver	0.0	0.0	2.6×10^{-7}	6.7×10^{-4}	2.2×10^{-3}	3.2×10^{-3}	2.8×10^{-3}	3.0×10^{-3}	3.1×10^{-3}	2.9×10^{-3}	2.7×10^{-3}	2.2×10^{-3}
Lungs(a)	0.0	3.0×10^{-5}	2.5×10^{-3}	1.9×10^{-2}	2.5×10^{-2}	1.7×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.0×10^{-2}
ET Airways(b)	1.2×10^{2}	1.2×10^{2}	68	24	7.7	4.6	5.1	5.7	5.4	5.0	4.6	3.4
Muscle	1.9×10^{-2}	4.3×10^{-2}	5.6×10^{-2}	5.3×10^{-2}	3.1×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.8×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.2×10^{-2}
Ovaries	0.0	0.0	0.0	1.3×10^{-6}	8.3×10^{-5}	2.9×10^{-4}	4.5×10^{-4}	6.3×10^{-4}	7.2×10^{-4}	7.5×10^{-4}	7.8×10^{-4}	7.2×10^{-4}
Pancreas	0.0	0.0	1.5×10^{-7}	2.0×10^{-4}	2.3×10^{-3}	2.6×10^{-3}	2.9×10^{-3}	3.1×10^{-3}	3.0×10^{-3}	3.0×10^{-3}	2.9×10^{-3}	2.5×10^{-3}
Skeleton :												
Active Marrow	1.9×10^{-9}	2.2×10^{-5}	7.8×10^{-4}	5.4×10^{-3}	9.1×10^{-3}	7.9×10^{-3}	7.3×10^{-3}	7.3×10^{-3}	6.6×10^{-3}	6.3×10^{-3}	6.0×10^{-3}	5.1×10^{-3}
Bone Surfaces	4.2×10^{-9}	1.1×10^{-4}	4.9×10^{-3}	3.6×10^{-2}	5.3×10^{-2}	2.6×10^{-2}	1.4×10^{-2}	1.0×10^{-2}	9.0×10^{-3}	8.6×10^{-3}	8.2×10^{-3}	6.9×10^{-3}
Skin	5.0×10^{-10}	7.4×10^{-5}	1.4×10^{-3}	5.1×10^{-3}	6.5×10^{-3}	5.2×10^{-3}	5.1×10^{-3}	5.6×10^{-3}	5.7×10^{-3}	5.5×10^{-3}	5.2×10^{-3}	4.2×10^{-3}
Spleen	0.0	0.0	6.7×10^{-8}	1.2×10^{-4}	1.8×10^{-3}	2.5×10^{-3}	2.7×10^{-3}	2.7×10^{-3}	2.6×10^{-3}	2.4×10^{-3}	2.3×10^{-3}	2.1×10^{-3}
Testes	0.0	0.0	0.0	4.6×10^{-8}	1.1×10^{-5}	6.7×10^{-5}	1.3×10^{-4}	2.3×10^{-4}	3.0×10^{-4}	3.4×10^{-4}	3.6×10^{-4}	3.6×10^{-4}
Thymus	1.9×10^{-8}	1.7×10^{-3}	2.9×10^{-2}	1.1×10^{-1}	8.3×10^{-2}	5.3×10^{-2}	5.2×10^{-2}	5.4×10^{-2}	4.6×10^{-2}	4.3×10^{-2}	4.0×10^{-2}	3.4×10^{-2}
Thyroid	0.0	5.6×10^{-7}	2.5×10^{-4}	2.9×10^{-3}	1.0×10^{-2}	9.8×10^{-3}	9.6×10^{-3}	9.9×10^{-3}	9.9×10^{-3}	9.7×10^{-3}	9.2×10^{-3}	7.2×10^{-3}
Urinary Bl Wall	0.0	0.0	0.0	3.6×10^{-7}	3.7×10^{-5}	1.6×10^{-4}	2.8×10^{-4}	4.2×10^{-4}	5.0×10^{-4}	5.4×10^{-4}	5.7×10^{-4}	5.4×10^{-4}
Uterus	0.0	0.0	0.0	1.2×10^{-6}	7.7×10^{-5}	2.8×10^{-4}	4.4×10^{-4}	6.1×10^{-4}	7.0×10^{-4}	7.3×10^{-4}	7.6×10^{-4}	7.0×10^{-4}
Whole Body	5.0×10^{-2}	5.0×10^{-2}	5.0×10^{-2}	4.4×10^{-2}	2.8×10^{-2}	1.8×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.1×10^{-2}

(a) Lungs include BB, bb, AI, and LN_{TH}.
(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.4. Specific absorbed fraction of photon energy (in kg^{-1}) for the 10-y old (32 kg) with the ET airways as the source

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	0.0	0.0	5.5×10^{-9}	3.6×10^{-5}	6.0×10^{-4}	1.2×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.8×10^{-3}	1.8×10^{-3}	1.8×10^{-3}	1.6×10^{-3}
Brain	0.0	2.0×10^{-7}	1.3×10^{-4}	1.9×10^{-3}	7.2×10^{-3}	8.4×10^{-3}	7.9×10^{-3}	8.4×10^{-3}	8.2×10^{-3}	7.8×10^{-3}	7.4×10^{-3}	6.2×10^{-3}
Breasts	0.0	0.0	4.0×10^{-6}	1.0×10^{-3}	4.8×10^{-3}	5.0×10^{-3}	5.3×10^{-3}	5.5×10^{-3}	5.4×10^{-3}	5.2×10^{-3}	5.0×10^{-3}	4.2×10^{-3}
Gall Bl Wall	0.0	0.0	7.2×10^{-10}	9.9×10^{-6}	2.5×10^{-4}	6.3×10^{-4}	8.6×10^{-4}	1.1×10^{-3}	1.2×10^{-3}	1.2×10^{-3}	1.2×10^{-3}	1.1×10^{-3}
GI Tract :												
LLI Wall	0.0	0.0	0.0	8.9×10^{-8}	1.2×10^{-5}	6.5×10^{-5}	1.3×10^{-4}	2.1×10^{-4}	2.7×10^{-4}	3.1×10^{-4}	3.3×10^{-4}	3.4×10^{-4}
SI Wall	0.0	0.0	0.0	4.6×10^{-7}	4.1×10^{-5}	1.5×10^{-4}	3.1×10^{-4}	5.0×10^{-4}	5.7×10^{-4}	5.9×10^{-4}	5.9×10^{-4}	6.1×10^{-4}
Stomach Wall	0.0	0.0	4.2×10^{-9}	2.3×10^{-5}	4.9×10^{-4}	7.5×10^{-4}	1.0×10^{-3}	1.2×10^{-3}	1.3×10^{-3}	1.3×10^{-3}	1.3×10^{-3}	1.3×10^{-3}
ULI Wall	0.0	0.0	0.0	7.4×10^{-7}	5.4×10^{-5}	2.0×10^{-4}	3.4×10^{-4}	4.9×10^{-4}	5.7×10^{-4}	6.2×10^{-4}	6.4×10^{-4}	6.0×10^{-4}
Heart Wall	0.0	1.2×10^{-9}	1.1×10^{-5}	1.3×10^{-3}	4.8×10^{-3}	5.7×10^{-3}	5.5×10^{-3}	6.5×10^{-3}	6.0×10^{-3}	5.4×10^{-3}	5.1×10^{-3}	4.5×10^{-3}
Kidneys	0.0	0.0	1.4×10^{-10}	5.1×10^{-6}	2.2×10^{-4}	6.2×10^{-4}	7.0×10^{-4}	7.7×10^{-4}	8.4×10^{-4}	9.5×10^{-4}	1.0×10^{-3}	9.4×10^{-4}
Liver	0.0	0.0	8.0×10^{-9}	1.9×10^{-4}	9.6×10^{-4}	1.5×10^{-3}	1.4×10^{-3}	1.5×10^{-3}	1.7×10^{-3}	1.8×10^{-3}	1.8×10^{-3}	1.5×10^{-3}
Lungs[(a)]	0.0	2.8×10^{-6}	5.2×10^{-4}	8.0×10^{-3}	1.4×10^{-2}	1.1×10^{-2}	9.4×10^{-3}	8.8×10^{-3}	8.2×10^{-3}	8.0×10^{-3}	7.9×10^{-3}	6.8×10^{-3}
ET Airways[(b)]	1.0×10^{2}	63	36	14	4.4	2.6	2.9	3.2	3.0	2.8	2.6	2.0
Muscle	8.9×10^{-3}	2.1×10^{-2}	3.0×10^{-2}	3.0×10^{-2}	1.9×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.4×10^{-3}	7.5×10^{-3}
Ovaries	0.0	0.0	0.0	6.5×10^{-8}	1.3×10^{-5}	7.7×10^{-5}	1.5×10^{-4}	2.5×10^{-4}	3.3×10^{-4}	3.6×10^{-4}	3.9×10^{-4}	3.9×10^{-4}
Pancreas	0.0	0.0	3.2×10^{-9}	2.8×10^{-5}	5.2×10^{-4}	1.1×10^{-3}	1.5×10^{-3}	1.6×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.6×10^{-3}	1.4×10^{-3}
Skeleton :												
Active Marrow	2.9×10^{-10}	1.5×10^{-5}	4.1×10^{-4}	3.3×10^{-3}	6.1×10^{-3}	5.7×10^{-3}	5.3×10^{-3}	5.4×10^{-3}	5.0×10^{-3}	4.6×10^{-3}	4.4×10^{-3}	3.8×10^{-3}
Bone Surfaces	1.2×10^{-10}	8.7×10^{-5}	2.7×10^{-3}	2.2×10^{-2}	3.3×10^{-2}	1.7×10^{-2}	9.3×10^{-3}	6.9×10^{-3}	6.4×10^{-3}	5.9×10^{-3}	5.6×10^{-3}	4.8×10^{-3}
Skin	0.0	3.8×10^{-5}	8.3×10^{-4}	3.6×10^{-3}	4.0×10^{-3}	3.6×10^{-3}	3.7×10^{-3}	4.1×10^{-3}	4.0×10^{-3}	3.9×10^{-3}	3.7×10^{-3}	2.9×10^{-3}
Spleen	0.0	0.0	1.6×10^{-9}	1.7×10^{-5}	8.2×10^{-4}	1.2×10^{-3}	1.5×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.6×10^{-3}	1.5×10^{-3}	1.2×10^{-3}
Testes	0.0	0.0	0.0	1.1×10^{-9}	1.1×10^{-6}	1.3×10^{-5}	3.4×10^{-5}	7.7×10^{-5}	1.2×10^{-4}	1.4×10^{-4}	1.7×10^{-4}	1.8×10^{-4}
Thymus	0.0	5.4×10^{-5}	3.9×10^{-3}	2.6×10^{-2}	4.1×10^{-2}	2.9×10^{-2}	2.5×10^{-2}	2.5×10^{-2}	2.5×10^{-2}	2.5×10^{-2}	2.4×10^{-2}	1.8×10^{-2}
Thyroid	0.0	2.0×10^{-7}	1.3×10^{-4}	1.9×10^{-3}	7.2×10^{-3}	8.4×10^{-3}	7.9×10^{-3}	8.4×10^{-3}	8.2×10^{-3}	7.8×10^{-3}	7.4×10^{-3}	6.2×10^{-3}
Urinary Bl Wall	0.0	0.0	0.0	1.3×10^{-8}	4.8×10^{-6}	3.7×10^{-5}	8.3×10^{-5}	1.6×10^{-4}	2.1×10^{-4}	2.5×10^{-4}	2.7×10^{-4}	2.8×10^{-4}
Uterus	0.0	0.0	0.0	5.5×10^{-8}	1.2×10^{-5}	7.2×10^{-5}	1.4×10^{-4}	2.4×10^{-4}	3.1×10^{-4}	3.5×10^{-4}	3.8×10^{-4}	3.8×10^{-4}
Whole Body	3.0×10^{-2}	3.0×10^{-2}	3.0×10^{-2}	2.6×10^{-2}	1.8×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	9.7×10^{-3}	9.0×10^{-3}	8.4×10^{-3}	6.9×10^{-3}

(a) Lungs include BB, bb, AI, and LN_{TH}.

(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.5. Specific absorbed fraction of photon energy (in kg^{-1}) for the 15-y old or adult female (55–58 kg) with the ET airways as the source

Target	Energy, MeV											
	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	0.0	0.0	0.0	4.2×10^{-6}	1.6×10^{-4}	4.6×10^{-4}	6.8×10^{-4}	8.3×10^{-4}	9.6×10^{-4}	9.9×10^{-4}	1.0×10^{-3}	9.2×10^{-4}
Brain	0.0	1.0×10^{-7}	8.4×10^{-5}	1.3×10^{-3}	5.8×10^{-3}	7.3×10^{-3}	6.9×10^{-3}	7.3×10^{-3}	7.2×10^{-3}	6.9×10^{-3}	6.6×10^{-3}	5.4×10^{-3}
Breasts	0.0	0.0	2.9×10^{-7}	2.5×10^{-4}	1.5×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.4×10^{-3}	2.7×10^{-3}	2.8×10^{-3}	2.8×10^{-3}	2.5×10^{-3}
Gall Bl Wall	0.0	0.0	0.0	6.7×10^{-7}	4.9×10^{-5}	1.9×10^{-4}	3.2×10^{-4}	4.7×10^{-4}	5.5×10^{-4}	5.9×10^{-4}	6.2×10^{-4}	5.8×10^{-4}
GI Tract:												
LLI Wall	0.0	0.0	0.0	3.2×10^{-9}	1.5×10^{-6}	1.4×10^{-5}	3.4×10^{-5}	7.3×10^{-5}	1.1×10^{-4}	1.4×10^{-4}	1.6×10^{-4}	1.7×10^{-4}
SI Wall	0.0	0.0	0.0	2.1×10^{-8}	6.1×10^{-6}	5.8×10^{-5}	7.9×10^{-5}	1.2×10^{-4}	1.6×10^{-4}	1.9×10^{-4}	2.2×10^{-4}	3.0×10^{-4}
Stomach Wall	0.0	0.0	0.0	2.4×10^{-6}	1.0×10^{-4}	2.8×10^{-4}	4.8×10^{-4}	6.6×10^{-4}	7.5×10^{-4}	7.8×10^{-4}	7.8×10^{-4}	7.2×10^{-4}
ULI Wall	0.0	0.0	0.0	3.7×10^{-8}	8.5×10^{-6}	5.4×10^{-5}	1.1×10^{-4}	1.9×10^{-4}	2.6×10^{-4}	3.0×10^{-4}	3.2×10^{-4}	3.2×10^{-4}
Heart Wall	0.0	0.0	5.9×10^{-7}	1.9×10^{-4}	2.0×10^{-3}	2.7×10^{-3}	2.6×10^{-3}	2.7×10^{-3}	2.9×10^{-3}	3.0×10^{-3}	3.0×10^{-3}	2.7×10^{-3}
Kidneys	0.0	0.0	0.0	4.2×10^{-7}	3.8×10^{-5}	1.8×10^{-4}	3.5×10^{-4}	5.0×10^{-4}	5.6×10^{-4}	5.7×10^{-4}	5.7×10^{-4}	5.2×10^{-4}
Liver	0.0	0.0	1.4×10^{-10}	4.1×10^{-6}	2.5×10^{-4}	6.6×10^{-4}	7.6×10^{-4}	8.6×10^{-4}	9.3×10^{-4}	9.8×10^{-4}	9.9×10^{-4}	9.2×10^{-4}
Lungs[(a)]	0.0	6.3×10^{-8}	6.9×10^{-5}	2.3×10^{-3}	6.7×10^{-3}	6.2×10^{-3}	5.4×10^{-3}	5.1×10^{-3}	5.1×10^{-3}	4.7×10^{-3}	4.4×10^{-3}	4.1×10^{-3}
ET Airways[(b)]	66	43	26	10	3.4	2.0	2.2	2.4	2.3	2.1	1.9	1.5
Muscle	4.5×10^{-3}	1.1×10^{-2}	1.6×10^{-2}	1.7×10^{-2}	1.2×10^{-2}	7.7×10^{-3}	7.3×10^{-3}	7.2×10^{-3}	6.7×10^{-3}	6.2×10^{-3}	5.7×10^{-3}	4.8×10^{-3}
Ovaries	0.0	0.0	0.0	1.8×10^{-9}	1.5×10^{-6}	1.6×10^{-5}	4.1×10^{-5}	8.9×10^{-5}	1.3×10^{-4}	1.6×10^{-4}	1.8×10^{-4}	2.0×10^{-4}
Pancreas	0.0	0.0	0.0	3.0×10^{-6}	1.3×10^{-4}	3.8×10^{-4}	5.6×10^{-4}	7.4×10^{-4}	8.8×10^{-4}	9.1×10^{-4}	9.3×10^{-4}	8.3×10^{-4}
Skeleton:												
Active Marrow	2.9×10^{-7}	1.8×10^{-5}	3.3×10^{-4}	2.4×10^{-3}	4.8×10^{-3}	4.7×10^{-3}	4.4×10^{-3}	4.5×10^{-3}	4.1×10^{-3}	3.8×10^{-3}	3.7×10^{-3}	3.2×10^{-3}
Bone Surfaces	1.2×10^{-9}	1.3×10^{-4}	2.4×10^{-3}	1.6×10^{-2}	2.5×10^{-2}	1.3×10^{-2}	7.4×10^{-3}	5.2×10^{-3}	4.8×10^{-3}	4.6×10^{-3}	4.4×10^{-3}	3.7×10^{-3}
Skin	0.0	2.1×10^{-5}	4.8×10^{-4}	2.5×10^{-3}	3.0×10^{-3}	2.6×10^{-3}	2.8×10^{-3}	2.9×10^{-3}	2.8×10^{-3}	2.7×10^{-3}	2.5×10^{-3}	2.4×10^{-3}
Spleen	0.0	0.0	0.0	1.7×10^{-6}	8.8×10^{-5}	5.3×10^{-4}	8.4×10^{-4}	8.7×10^{-4}	8.2×10^{-4}	7.8×10^{-4}	7.5×10^{-4}	6.8×10^{-4}
Testes	0.0	0.0	0.0	0.0	6.0×10^{-8}	1.5×10^{-6}	6.1×10^{-6}	2.0×10^{-5}	3.9×10^{-5}	5.3×10^{-5}	6.6×10^{-5}	8.5×10^{-5}
Thymus	0.0	1.7×10^{-7}	1.8×10^{-4}	6.2×10^{-3}	1.2×10^{-2}	1.5×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	9.9×10^{-3}	9.3×10^{-3}	7.6×10^{-3}
Thyroid	0.0	1.0×10^{-7}	8.4×10^{-5}	1.3×10^{-3}	5.8×10^{-3}	7.3×10^{-3}	6.9×10^{-3}	7.3×10^{-3}	7.2×10^{-3}	6.9×10^{-3}	6.6×10^{-3}	5.4×10^{-3}
Urinary Bl Wall	0.0	0.0	0.0	2.6×10^{-10}	4.3×10^{-7}	6.4×10^{-6}	2.0×10^{-5}	4.9×10^{-5}	8.1×10^{-5}	1.0×10^{-4}	1.2×10^{-4}	1.4×10^{-4}
Uterus	0.0	0.0	0.0	1.5×10^{-9}	1.3×10^{-6}	1.4×10^{-5}	3.8×10^{-5}	8.4×10^{-5}	1.3×10^{-4}	1.5×10^{-4}	1.8×10^{-4}	1.9×10^{-4}
Whole Body	1.7×10^{-2}	1.7×10^{-2}	1.7×10^{-2}	1.6×10^{-2}	1.1×10^{-2}	7.4×10^{-3}	6.7×10^{-3}	6.6×10^{-3}	6.2×10^{-3}	5.7×10^{-3}	5.3×10^{-3}	4.4×10^{-3}

(a) Lungs include BB, bb, AI, and LN_{TH}.

(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.6. Specific absorbed fraction of photon energy (in kg^{-1}) for the adult male (70 kg) with the ET airways as the source

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	0.0	0.0	0.0	1.3×10^{-6}	7.9×10^{-5}	3.8×10^{-4}	4.4×10^{-4}	5.6×10^{-4}	6.9×10^{-4}	7.3×10^{-4}	7.6×10^{-4}	7.0×10^{-4}
Brain	0.0	6.0×10^{-8}	6.0×10^{-5}	1.0×10^{-3}	4.8×10^{-3}	6.7×10^{-3}	6.8×10^{-3}	7.0×10^{-3}	6.5×10^{-3}	6.4×10^{-3}	6.2×10^{-3}	5.0×10^{-3}
Breasts	0.0	0.0	4.8×10^{-8}	8.7×10^{-5}	6.2×10^{-4}	1.5×10^{-3}	1.5×10^{-3}	1.8×10^{-3}	2.0×10^{-3}	2.1×10^{-3}	2.1×10^{-3}	2.1×10^{-3}
Gall Bl Wall	0.0	0.0	0.0	1.5×10^{-7}	1.9×10^{-5}	9.9×10^{-5}	1.8×10^{-4}	2.9×10^{-4}	3.7×10^{-4}	4.1×10^{-4}	4.3×10^{-4}	4.2×10^{-4}
GI Tract :												
LLI Wall	0.0	0.0	0.0	5.0×10^{-10}	4.6×10^{-7}	5.7×10^{-6}	1.7×10^{-5}	4.1×10^{-5}	6.8×10^{-5}	8.7×10^{-5}	1.0×10^{-4}	1.2×10^{-4}
SI Wall	0.0	0.0	0.0	3.6×10^{-9}	2.0×10^{-6}	1.9×10^{-5}	3.2×10^{-5}	5.9×10^{-5}	9.2×10^{-5}	1.2×10^{-4}	1.4×10^{-4}	2.1×10^{-4}
Stomach Wall	0.0	0.0	0.0	6.7×10^{-7}	4.4×10^{-5}	1.2×10^{-4}	2.8×10^{-4}	4.0×10^{-4}	4.8×10^{-4}	5.4×10^{-4}	5.6×10^{-4}	5.4×10^{-4}
ULI Wall	0.0	0.0	0.0	6.6×10^{-9}	2.9×10^{-6}	2.5×10^{-5}	5.8×10^{-5}	1.2×10^{-4}	1.7×10^{-4}	2.0×10^{-4}	2.2×10^{-4}	2.3×10^{-4}
Heart Wall	0.0	0.0	1.2×10^{-7}	1.0×10^{-4}	1.0×10^{-3}	2.2×10^{-3}	2.1×10^{-3}	2.3×10^{-3}	2.3×10^{-3}	2.3×10^{-3}	2.3×10^{-3}	2.0×10^{-3}
Kidneys	0.0	0.0	0.0	1.0×10^{-7}	1.6×10^{-5}	9.1×10^{-5}	2.3×10^{-4}	3.7×10^{-4}	4.1×10^{-4}	4.2×10^{-4}	4.2×10^{-4}	4.0×10^{-4}
Liver	0.0	0.0	0.0	1.1×10^{-6}	2.0×10^{-4}	3.7×10^{-4}	5.2×10^{-4}	6.1×10^{-4}	6.4×10^{-4}	6.5×10^{-4}	6.7×10^{-4}	7.3×10^{-4}
Lungs[a]	0.0	2.8×10^{-8}	3.5×10^{-5}	1.7×10^{-3}	4.6×10^{-3}	4.6×10^{-3}	4.1×10^{-3}	4.2×10^{-3}	4.0×10^{-3}	3.9×10^{-3}	3.8×10^{-3}	3.0×10^{-3}
ET Airways[b]	41	28	18	7.2	2.5	1.4	1.5	1.7	1.6	1.5	1.3	1.0
Muscle	3.0×10^{-3}	7.9×10^{-3}	1.2×10^{-2}	1.2×10^{-2}	8.6×10^{-3}	5.8×10^{-3}	5.5×10^{-3}	5.5×10^{-3}	5.1×10^{-3}	4.8×10^{-3}	4.5×10^{-3}	3.7×10^{-3}
Ovaries	0.0	0.0	0.0	2.3×10^{-10}	4.2×10^{-7}	6.3×10^{-6}	1.9×10^{-5}	4.9×10^{-5}	8.1×10^{-5}	1.0×10^{-4}	1.2×10^{-4}	1.4×10^{-4}
Pancreas	0.0	0.0	0.0	8.1×10^{-7}	5.9×10^{-5}	2.9×10^{-4}	4.7×10^{-4}	5.6×10^{-4}	6.5×10^{-4}	6.7×10^{-4}	6.7×10^{-4}	6.3×10^{-4}
Skeleton:												
Active Marrow	1.2×10^{-6}	3.3×10^{-5}	3.4×10^{-4}	2.0×10^{-3}	3.9×10^{-3}	4.0×10^{-3}	3.9×10^{-3}	3.9×10^{-3}	3.6×10^{-3}	3.4×10^{-3}	3.2×10^{-3}	2.7×10^{-3}
Bone Surfaces	9.9×10^{-6}	2.7×10^{-4}	2.9×10^{-3}	1.5×10^{-2}	2.2×10^{-2}	1.2×10^{-2}	6.6×10^{-3}	4.8×10^{-3}	4.5×10^{-3}	4.2×10^{-3}	3.9×10^{-3}	3.3×10^{-3}
Skin	0.0	2.4×10^{-5}	5.1×10^{-4}	2.2×10^{-3}	2.4×10^{-3}	2.1×10^{-3}	2.3×10^{-3}	2.4×10^{-3}	2.5×10^{-3}	2.4×10^{-3}	2.3×10^{-3}	1.8×10^{-3}
Spleen	0.0	0.0	0.0	4.5×10^{-7}	2.5×10^{-4}	3.5×10^{-4}	4.5×10^{-4}	5.5×10^{-4}	5.8×10^{-4}	5.7×10^{-4}	5.6×10^{-4}	5.3×10^{-4}
Testes	0.0	0.0	0.0	0.0	1.1×10^{-8}	4.4×10^{-7}	2.2×10^{-6}	8.9×10^{-6}	2.0×10^{-5}	3.0×10^{-5}	4.0×10^{-5}	5.5×10^{-5}
Thymus	0.0	6.4×10^{-9}	3.2×10^{-5}	3.2×10^{-3}	6.9×10^{-3}	8.5×10^{-3}	7.5×10^{-3}	7.0×10^{-3}	7.7×10^{-3}	7.5×10^{-3}	7.1×10^{-3}	5.3×10^{-3}
Thyroid	0.0	6.0×10^{-8}	6.0×10^{-5}	1.0×10^{-3}	4.8×10^{-3}	6.7×10^{-3}	6.8×10^{-3}	7.0×10^{-3}	6.5×10^{-3}	6.4×10^{-3}	6.2×10^{-3}	5.0×10^{-3}
Urinary Bl Wall	0.0	0.0	0.0	0.0	1.1×10^{-7}	2.3×10^{-6}	8.5×10^{-6}	2.5×10^{-5}	4.8×10^{-5}	6.4×10^{-5}	7.8×10^{-5}	9.7×10^{-5}
Uterus	0.0	0.0	0.0	1.8×10^{-10}	3.6×10^{-7}	5.7×10^{-6}	1.8×10^{-5}	4.6×10^{-5}	7.7×10^{-5}	9.8×10^{-5}	1.2×10^{-4}	1.4×10^{-4}
Whole Body	1.4×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	8.8×10^{-3}	5.9×10^{-3}	5.3×10^{-3}	5.2×10^{-3}	4.9×10^{-3}	4.6×10^{-3}	4.3×10^{-3}	3.6×10^{-3}

(a) Lungs include BB, bb, AI, and LN_{TH}.

(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.7. Specific absorbed fraction of photon energy (in kg^{-1}) for the newborn (3.4 kg) with the ET airways as the target

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	0.0	9.4×10^{-8}	2.6×10^{-4}	1.0×10^{-2}	1.8×10^{-2}	1.7×10^{-2}	1.6×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	9.6×10^{-3}
Brain	0.0	1.1×10^{-4}	3.7×10^{-3}	3.1×10^{-2}	3.9×10^{-2}	2.6×10^{-2}	2.6×10^{-2}	2.7×10^{-2}	2.5×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.0×10^{-2}
Breasts	0.0	6.9×10^{-5}	9.1×10^{-3}	4.1×10^{-2}	3.7×10^{-2}	3.3×10^{-2}	3.2×10^{-2}	3.4×10^{-2}	3.3×10^{-2}	3.2×10^{-2}	3.0×10^{-2}	2.5×10^{-2}
Gall Bl Cont	0.0	2.7×10^{-8}	1.2×10^{-4}	6.1×10^{-3}	1.4×10^{-2}	1.4×10^{-2}	1.0×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.7×10^{-3}	8.0×10^{-3}
GI Tract:												
LLI Cont	0.0	0.0	1.7×10^{-6}	5.7×10^{-4}	3.1×10^{-3}	3.7×10^{-3}	4.1×10^{-3}	4.2×10^{-3}	4.1×10^{-3}	4.0×10^{-3}	3.9×10^{-3}	3.3×10^{-3}
SI Cont	0.0	0.0	6.1×10^{-6}	1.7×10^{-3}	3.2×10^{-3}	4.3×10^{-3}	4.4×10^{-3}	5.1×10^{-3}	5.1×10^{-3}	4.9×10^{-3}	4.7×10^{-3}	4.5×10^{-3}
Stomach Cont	0.0	8.8×10^{-8}	2.1×10^{-4}	8.7×10^{-3}	1.1×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.9×10^{-3}	9.6×10^{-3}	9.4×10^{-3}	9.2×10^{-3}	8.9×10^{-3}
ULI Cont	0.0	2.0×10^{-10}	9.7×10^{-6}	1.6×10^{-3}	4.6×10^{-3}	8.1×10^{-3}	8.5×10^{-3}	7.2×10^{-3}	6.2×10^{-3}	5.9×10^{-3}	5.8×10^{-3}	4.8×10^{-3}
Heart Cont	3.8×10^{-10}	7.4×10^{-4}	2.3×10^{-2}	1.0×10^{-1}	1.0×10^{-1}	5.6×10^{-2}	5.5×10^{-2}	5.4×10^{-2}	5.0×10^{-2}	4.5×10^{-2}	4.2×10^{-2}	3.6×10^{-2}
Heart Wall	8.0×10^{-10}	7.5×10^{-4}	1.7×10^{-2}	8.6×10^{-2}	8.0×10^{-2}	5.0×10^{-2}	4.5×10^{-2}	4.6×10^{-2}	4.9×10^{-2}	4.4×10^{-2}	3.9×10^{-2}	3.2×10^{-2}
Kidneys	0.0	3.0×10^{-9}	3.9×10^{-5}	3.7×10^{-3}	8.2×10^{-3}	8.5×10^{-3}	7.6×10^{-3}	8.4×10^{-3}	9.0×10^{-3}	8.4×10^{-3}	8.0×10^{-3}	6.4×10^{-3}
Liver	0.0	2.4×10^{-7}	3.2×10^{-4}	1.1×10^{-2}	1.8×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.0×10^{-2}
Lungs[(a)]	1.1×10^{-7}	2.9×10^{-3}	5.1×10^{-2}	1.3×10^{-1}	9.2×10^{-2}	4.9×10^{-2}	4.7×10^{-2}	5.0×10^{-2}	4.6×10^{-2}	4.3×10^{-2}	4.0×10^{-2}	3.1×10^{-2}
ET Airways[(b)]	5.3×10^{2}	2.8×10^{2}	1.4×10^{2}	49	15	8.7	9.4	10	9.9	9.0	8.3	6.8
Muscle	1.3×10^{-1}	2.6×10^{-1}	3.1×10^{-1}	2.4×10^{-1}	1.1×10^{-1}	6.5×10^{-2}	6.6×10^{-2}	6.8×10^{-2}	6.4×10^{-2}	5.9×10^{-2}	5.5×10^{-2}	4.4×10^{-2}
Ovaries	0.0	0.0	9.8×10^{-7}	5.3×10^{-4}	3.1×10^{-3}	3.9×10^{-3}	4.1×10^{-3}	4.4×10^{-3}	4.3×10^{-3}	4.1×10^{-3}	4.0×10^{-3}	3.4×10^{-3}
Pancreas	0.0	1.1×10^{-7}	2.8×10^{-4}	9.8×10^{-3}	1.2×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	9.9×10^{-3}
Skeleton:												
Active Marrow	1.2×10^{-6}	1.4×10^{-3}	1.2×10^{-2}	3.7×10^{-2}	3.5×10^{-2}	2.4×10^{-2}	2.2×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.6×10^{-2}
Whole Skeleton	5.2×10^{-7}	1.5×10^{-3}	1.2×10^{-2}	3.9×10^{-2}	3.8×10^{-2}	2.6×10^{-2}	2.4×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	2.0×10^{-2}	1.7×10^{-2}
Spleen	0.0	3.7×10^{-8}	1.4×10^{-4}	1.0×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	8.3×10^{-3}
Testes	0.0	0.0	1.9×10^{-8}	7.3×10^{-5}	9.4×10^{-4}	1.6×10^{-3}	2.0×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	1.9×10^{-3}
Thymus	1.1×10^{-2}	4.4×10^{-1}	9.6×10^{-1}	1.0	4.7×10^{-1}	2.6×10^{-1}	2.6×10^{-1}	2.8×10^{-1}	2.5×10^{-1}	2.4×10^{-1}	2.4×10^{-1}	2.0×10^{-1}
Thyroid	0.0	1.1×10^{-4}	3.7×10^{-3}	3.1×10^{-2}	3.9×10^{-2}	2.6×10^{-2}	2.6×10^{-2}	2.7×10^{-2}	2.5×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.0×10^{-2}
Urinary Bl Cont	0.0	0.0	2.2×10^{-7}	2.5×10^{-4}	2.0×10^{-3}	2.8×10^{-3}	3.1×10^{-3}	3.1×10^{-3}	3.0×10^{-3}	2.9×10^{-3}	2.9×10^{-3}	2.7×10^{-3}
Uterus	0.0	0.0	8.7×10^{-7}	5.0×10^{-4}	3.0×10^{-3}	3.8×10^{-3}	4.0×10^{-3}	4.3×10^{-3}	4.2×10^{-3}	4.0×10^{-3}	3.9×10^{-3}	3.3×10^{-3}
Whole Body	2.8×10^{-1}	2.8×10^{-1}	2.6×10^{-1}	1.8×10^{-1}	9.0×10^{-2}	5.3×10^{-2}	5.5×10^{-2}	5.7×10^{-2}	5.4×10^{-2}	5.0×10^{-2}	4.7×10^{-2}	3.8×10^{-2}

(a) Lungs include BB, bb, AI, and LN_{TH}.

(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.8. Specific absorbed fraction of photon energy (in kg^{-1}) for the 1-y old (9.8 kg) with the ET airways as the target

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	0.0	1.0×10^{-10}	7.4×10^{-6}	1.5×10^{-3}	5.8×10^{-3}	7.0×10^{-3}	6.9×10^{-3}	6.5×10^{-3}	6.1×10^{-3}	5.7×10^{-3}	5.5×10^{-3}	4.7×10^{-3}
Brain	0.0	2.2×10^{-6}	2.8×10^{-4}	7.1×10^{-3}	1.5×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	9.4×10^{-3}
Breasts	0.0	6.3×10^{-7}	7.2×10^{-4}	1.6×10^{-2}	2.0×10^{-2}	1.8×10^{-2}	1.6×10^{-2}	1.7×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.2×10^{-2}
Gall Bl Cont	0.0	0.0	1.4×10^{-6}	5.9×10^{-4}	3.3×10^{-3}	4.0×10^{-3}	4.2×10^{-3}	4.5×10^{-3}	4.4×10^{-3}	4.2×10^{-3}	4.1×10^{-3}	3.5×10^{-3}
GI Tract:												
LLI Cont	0.0	0.0	8.8×10^{-9}	3.6×10^{-5}	5.5×10^{-4}	1.1×10^{-3}	1.3×10^{-3}	1.6×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.4×10^{-3}
SI Cont	0.0	0.0	4.3×10^{-8}	1.0×10^{-4}	7.4×10^{-4}	1.5×10^{-3}	1.6×10^{-3}	1.6×10^{-3}	1.8×10^{-3}	1.9×10^{-3}	2.0×10^{-3}	2.0×10^{-3}
Stomach Cont	0.0	1.2×10^{-10}	5.6×10^{-6}	1.1×10^{-3}	3.5×10^{-3}	5.2×10^{-3}	5.0×10^{-3}	4.9×10^{-3}	4.7×10^{-3}	4.5×10^{-3}	4.4×10^{-3}	4.2×10^{-3}
ULI Cont	0.0	0.0	7.7×10^{-8}	1.3×10^{-4}	1.8×10^{-3}	2.1×10^{-3}	2.4×10^{-3}	2.6×10^{-3}	2.6×10^{-3}	2.6×10^{-3}	2.5×10^{-3}	2.2×10^{-3}
Heart Cont	0.0	9.7×10^{-6}	2.9×10^{-3}	2.7×10^{-2}	3.9×10^{-2}	2.5×10^{-2}	2.5×10^{-2}	2.5×10^{-2}	2.2×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.7×10^{-2}
Heart Wall	0.0	1.0×10^{-5}	3.1×10^{-3}	2.0×10^{-2}	3.3×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	2.2×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.8×10^{-2}	1.5×10^{-2}
Kidneys	0.0	0.0	6.1×10^{-7}	1.1×10^{-3}	3.2×10^{-3}	3.1×10^{-3}	2.6×10^{-3}	3.5×10^{-3}	3.7×10^{-3}	3.9×10^{-3}	4.0×10^{-3}	3.0×10^{-3}
Liver	0.0	4.5×10^{-10}	1.0×10^{-5}	2.6×10^{-3}	6.2×10^{-3}	5.9×10^{-3}	6.0×10^{-3}	6.4×10^{-3}	5.9×10^{-3}	5.9×10^{-3}	5.9×10^{-3}	4.9×10^{-3}
Lungs(a)	3.1×10^{-10}	1.9×10^{-4}	1.0×10^{-2}	4.5×10^{-2}	4.3×10^{-2}	2.9×10^{-2}	2.9×10^{-2}	2.3×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	1.6×10^{-2}
ET Airways(b)	3.9×10^{2}	2.1×10^{2}	1.1×10^{2}	37	12	6.9	7.7	8.7	8.2	7.5	6.9	5.5
Muscle	4.8×10^{-2}	9.7×10^{-2}	1.2×10^{-1}	1.0×10^{-1}	5.7×10^{-2}	3.4×10^{-2}	3.4×10^{-2}	3.4×10^{-2}	3.2×10^{-2}	3.0×10^{-2}	2.7×10^{-2}	2.3×10^{-2}
Ovaries	0.0	0.0	3.2×10^{-9}	3.0×10^{-5}	5.4×10^{-4}	1.1×10^{-3}	1.4×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.5×10^{-3}
Pancreas	0.0	1.1×10^{-10}	7.5×10^{-6}	1.5×10^{-3}	5.7×10^{-3}	7.2×10^{-3}	5.8×10^{-3}	6.0×10^{-3}	6.1×10^{-3}	5.8×10^{-3}	5.7×10^{-3}	4.7×10^{-3}
Skeleton:												
Active Marrow	3.3×10^{-8}	2.0×10^{-4}	2.3×10^{-3}	1.1×10^{-2}	1.6×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.9×10^{-3}	7.7×10^{-3}
Whole Skeleton	7.4×10^{-9}	1.9×10^{-4}	2.2×10^{-3}	1.1×10^{-2}	1.6×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	8.0×10^{-3}
Spleen	0.0	0.0	3.4×10^{-6}	3.0×10^{-3}	4.9×10^{-3}	6.3×10^{-3}	6.1×10^{-3}	5.6×10^{-3}	4.9×10^{-3}	4.6×10^{-3}	4.4×10^{-3}	4.0×10^{-3}
Testes	0.0	0.0	0.0	2.1×10^{-6}	1.1×10^{-4}	3.6×10^{-4}	5.4×10^{-4}	7.3×10^{-4}	8.2×10^{-4}	8.5×10^{-4}	8.7×10^{-4}	8.0×10^{-4}
Thymus	1.4×10^{-4}	5.7×10^{-2}	2.6×10^{-1}	3.9×10^{-1}	2.1×10^{-1}	1.3×10^{-1}	1.2×10^{-1}	1.2×10^{-1}	1.1×10^{-1}	1.0×10^{-1}	9.6×10^{-2}	7.7×10^{-2}
Thyroid	0.0	2.2×10^{-6}	2.8×10^{-4}	7.1×10^{-3}	1.5×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	9.4×10^{-3}
Urinary Bl Cont	0.0	0.0	4.2×10^{-10}	1.1×10^{-5}	2.9×10^{-4}	5.3×10^{-4}	9.5×10^{-4}	1.2×10^{-3}	1.3×10^{-3}	1.3×10^{-3}	1.3×10^{-3}	1.2×10^{-3}
Uterus	0.0	0.0	2.7×10^{-9}	2.7×10^{-5}	5.2×10^{-4}	1.1×10^{-3}	1.4×10^{-3}	1.6×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.5×10^{-3}
Whole Body	1.0×10^{-1}	1.0×10^{-1}	9.7×10^{-2}	7.5×10^{-2}	4.4×10^{-2}	2.8×10^{-2}	2.8×10^{-2}	2.8×10^{-2}	2.7×10^{-2}	2.5×10^{-2}	2.3×10^{-2}	1.9×10^{-2}

(a) Lungs include BB, bb, AI, and LN_{TH}.
(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.9. Specific absorbed fraction of photon energy (in kg^{-1}) for the 5-y old (19 kg) with the ET airways as the target

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	0.0	0.0	1.9×10^{-7}	2.2×10^{-4}	1.8×10^{-3}	3.0×10^{-3}	2.9×10^{-3}	3.2×10^{-3}	3.2×10^{-3}	3.1×10^{-3}	3.0×10^{-3}	2.6×10^{-3}
Brain	0.0	5.6×10^{-7}	2.5×10^{-4}	2.9×10^{-3}	1.0×10^{-2}	9.8×10^{-3}	9.6×10^{-3}	9.9×10^{-3}	9.9×10^{-3}	9.7×10^{-3}	9.2×10^{-3}	7.2×10^{-3}
Breasts	0.0	4.5×10^{-9}	5.2×10^{-5}	4.0×10^{-3}	1.1×10^{-2}	1.2×10^{-2}	9.0×10^{-3}	9.3×10^{-3}	9.3×10^{-3}	8.7×10^{-3}	8.2×10^{-3}	6.8×10^{-3}
Gall Bl Cont	0.0	0.0	2.4×10^{-8}	6.8×10^{-5}	8.6×10^{-4}	1.5×10^{-3}	1.8×10^{-3}	2.1×10^{-3}	2.1×10^{-3}	2.1×10^{-3}	2.1×10^{-3}	1.8×10^{-3}
GI Tract:												
LLI Cont	0.0	0.0	0.0	1.9×10^{-6}	8.8×10^{-5}	2.9×10^{-4}	4.4×10^{-4}	6.0×10^{-4}	6.9×10^{-4}	7.2×10^{-4}	7.5×10^{-4}	6.9×10^{-4}
SI Cont	0.0	0.0	2.1×10^{-10}	6.5×10^{-6}	2.8×10^{-6}	4.6×10^{-6}	6.1×10^{-6}	7.9×10^{-6}	8.6×10^{-6}	8.8×10^{-6}	9.0×10^{-6}	9.0×10^{-6}
Stomach Cont	0.0	0.0	1.1×10^{-7}	1.4×10^{-4}	1.6×10^{-3}	2.0×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	2.2×10^{-3}
ULI Cont	0.0	0.0	4.2×10^{-10}	9.5×10^{-6}	2.6×10^{-4}	5.9×10^{-4}	9.3×10^{-4}	1.1×10^{-3}	1.2×10^{-3}	1.2×10^{-3}	1.2×10^{-3}	1.1×10^{-3}
Heart Cont	0.0	9.6×10^{-8}	1.6×10^{-4}	6.4×10^{-3}	1.5×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	8.6×10^{-3}
Heart Wall	0.0	1.1×10^{-7}	1.4×10^{-4}	5.7×10^{-3}	1.2×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	7.8×10^{-3}.
Kidneys	0.0	0.0	8.5×10^{-9}	4.3×10^{-5}	1.2×10^{-3}	1.7×10^{-3}	1.8×10^{-3}	1.8×10^{-3}	1.9×10^{-3}	1.8×10^{-3}	1.8×10^{-3}	1.6×10^{-3}
Liver	0.0	0.0	2.6×10^{-7}	6.7×10^{-4}	2.2×10^{-3}	3.2×10^{-3}	2.8×10^{-3}	3.0×10^{-3}	3.1×10^{-3}	2.9×10^{-3}	2.7×10^{-3}	2.2×10^{-3}
Lungs$^{(a)}$	0.0	2.6×10^{-5}	2.2×10^{-3}	1.7×10^{-2}	2.3×10^{-2}	1.7×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.0×10^{-2}
ET Airways$^{(b)}$	2.2×10^{2}	1.2×10^{2}	68	24	7.7	4.6	5.1	5.7	5.4	5.0	4.6	3.4
Muscle	1.9×10^{-2}	4.3×10^{-2}	5.6×10^{-2}	5.3×10^{-2}	3.1×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.8×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.2×10^{-2}
Ovaries	0.0	0.0	0.0	1.3×10^{-6}	8.3×10^{-5}	2.9×10^{-4}	4.5×10^{-4}	6.3×10^{-4}	7.2×10^{-4}	7.5×10^{-4}	7.8×10^{-4}	7.2×10^{-4}
Pancreas	0.0	0.0	1.5×10^{-7}	2.0×10^{-4}	2.3×10^{-3}	2.6×10^{-3}	2.9×10^{-3}	3.1×10^{-3}	3.0×10^{-3}	3.0×10^{-3}	2.9×10^{-3}	2.5×10^{-3}
Skeleton:												
Active Marrow	5.6×10^{-10}	4.8×10^{-5}	8.0×10^{-4}	5.1×10^{-3}	8.7×10^{-3}	7.3×10^{-3}	6.8×10^{-3}	7.3×10^{-3}	6.6×10^{-3}	6.3×10^{-3}	6.0×10^{-3}	5.1×10^{-3}
Whole Skeleton	1.3×10^{-9}	4.4×10^{-5}	8.5×10^{-4}	5.8×10^{-3}	9.9×10^{-3}	8.4×10^{-3}	7.7×10^{-3}	8.3×10^{-3}	7.5×10^{-3}	7.1×10^{-3}	6.8×10^{-3}	5.8×10^{-3}
Spleen	0.0	0.0	6.7×10^{-8}	1.2×10^{-4}	1.8×10^{-3}	2.5×10^{-3}	2.7×10^{-3}	2.7×10^{-3}	2.6×10^{-3}	2.4×10^{-3}	2.3×10^{-3}	2.1×10^{-3}
Testes	0.0	0.0	0.0	4.6×10^{-8}	1.1×10^{-5}	6.7×10^{-5}	1.3×10^{-4}	2.3×10^{-4}	3.0×10^{-4}	3.4×10^{-4}	3.6×10^{-4}	3.6×10^{-4}
Thymus	1.9×10^{-8}	1.7×10^{-3}	2.9×10^{-2}	1.1×10^{-1}	8.3×10^{-2}	5.3×10^{-2}	5.2×10^{-2}	5.4×10^{-2}	4.6×10^{-2}	4.3×10^{-2}	4.0×10^{-2}	3.4×10^{-2}
Thyroid	0.0	5.6×10^{-7}	2.5×10^{-4}	2.9×10^{-3}	1.0×10^{-2}	9.8×10^{-3}	9.6×10^{-3}	9.9×10^{-3}	9.9×10^{-3}	9.7×10^{-3}	9.2×10^{-3}	7.2×10^{-3}
Urinary Bl Cont	0.0	0.0	0.0	3.5×10^{-7}	3.6×10^{-5}	1.6×10^{-4}	2.8×10^{-4}	4.2×10^{-4}	5.0×10^{-4}	5.4×10^{-4}	5.7×10^{-4}	5.4×10^{-4}
Uterus	0.0	0.0	0.0	1.2×10^{-6}	7.7×10^{-5}	2.8×10^{-4}	4.4×10^{-4}	6.1×10^{-4}	7.0×10^{-4}	7.3×10^{-4}	7.6×10^{-4}	7.0×10^{-4}
Whole Body	5.0×10^{-2}	5.0×10^{-2}	4.8×10^{-2}	3.9×10^{-2}	2.5×10^{-2}	1.7×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.1×10^{-2}

(a) Lungs include BB, bb, AI, and LN_{TH}.

(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.10. Specific absorbed fraction of photon energy (in kg^{-1}) for the 10-y old (32 kg) with the ET airways as the target

Target	Energy, MeV											
	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	0.0	0.0	5.5×10^{-9}	3.6×10^{-5}	6.0×10^{-4}	1.2×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.8×10^{-3}	1.8×10^{-3}	1.8×10^{-3}	1.6×10^{-3}
Brain	0.0	2.0×10^{-7}	1.3×10^{-4}	1.9×10^{-3}	7.2×10^{-3}	8.4×10^{-3}	7.9×10^{-3}	8.4×10^{-3}	8.2×10^{-3}	7.8×10^{-3}	7.4×10^{-3}	6.2×10^{-3}
Breasts	0.0	0.0	4.0×10^{-6}	1.0×10^{-3}	4.8×10^{-3}	5.0×10^{-3}	5.3×10^{-3}	5.5×10^{-3}	5.4×10^{-3}	5.2×10^{-3}	5.0×10^{-3}	4.2×10^{-3}
Gall Bl Cont	0.0	0.0	3.6×10^{-10}	7.6×10^{-4}	2.2×10^{-4}	5.8×10^{-4}	8.1×10^{-4}	1.0×10^{-3}	1.1×10^{-3}	1.2×10^{-3}	1.1×10^{-3}	1.0×10^{-3}
GI Tract:												
LLI Cont	0.0	0.0	0.0	1.2×10^{-7}	1.5×10^{-5}	7.9×10^{-5}	1.5×10^{-4}	2.5×10^{-4}	3.1×10^{-4}	3.5×10^{-4}	3.7×10^{-4}	3.7×10^{-4}
SI Cont	0.0	0.0	0.0	4.6×10^{-7}	4.1×10^{-5}	1.5×10^{-4}	3.1×10^{-4}	5.0×10^{-4}	5.7×10^{-4}	5.9×10^{-4}	5.9×10^{-4}	6.1×10^{-4}
Stomach Cont	0.0	0.0	2.6×10^{-9}	1.9×10^{-5}	4.4×10^{-4}	6.1×10^{-4}	8.1×10^{-4}	1.1×10^{-3}	1.2×10^{-3}	1.2×10^{-3}	1.3×10^{-3}	1.3×10^{-3}
ULI Cont	0.0	0.0	0.0	7.2×10^{-7}	5.3×10^{-5}	2.0×10^{-4}	4.1×10^{-4}	4.9×10^{-4}	5.7×10^{-4}	6.2×10^{-4}	6.4×10^{-4}	6.0×10^{-4}
Heart Cont	0.0	9.4×10^{-10}	1.3×10^{-5}	2.0×10^{-3}	6.2×10^{-3}	6.6×10^{-3}	6.1×10^{-3}	7.0×10^{-3}	6.2×10^{-3}	6.0×10^{-3}	5.8×10^{-3}	5.0×10^{-3}
Heart Wall	0.0	1.2×10^{-9}	1.1×10^{-5}	1.3×10^{-3}	4.8×10^{-3}	5.7×10^{-3}	5.5×10^{-3}	6.5×10^{-3}	6.0×10^{-3}	5.4×10^{-3}	5.1×10^{-3}	4.5×10^{-3}
Kidneys	0.0	0.0	1.4×10^{-10}	5.1×10^{-6}	2.2×10^{-4}	6.2×10^{-4}	7.0×10^{-4}	7.7×10^{-4}	8.4×10^{-4}	9.5×10^{-4}	1.0×10^{-3}	9.4×10^{-4}
Liver	0.0	0.0	8.0×10^{-9}	1.9×10^{-4}	9.6×10^{-4}	1.5×10^{-3}	1.4×10^{-3}	1.5×10^{-3}	1.7×10^{-3}	1.8×10^{-3}	1.8×10^{-3}	1.5×10^{-3}
Lungs[(a)]	0.0	2.5×10^{-6}	4.6×10^{-4}	7.1×10^{-3}	1.3×10^{-2}	1.1×10^{-2}	9.4×10^{-3}	8.8×10^{-3}	8.2×10^{-3}	8.0×10^{-3}	7.9×10^{-3}	6.8×10^{-3}
ET Airways[(b)]	1.0×10^{2}	63	36	14	4.4	2.6	2.9	3.2	3.0	2.8	2.6	2.0
Muscle	8.9×10^{-3}	2.1×10^{-2}	3.0×10^{-2}	3.0×10^{-2}	1.9×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.4×10^{-3}	7.5×10^{-3}
Ovaries	0.0	0.0	0.0	6.5×10^{-8}	1.3×10^{-5}	7.7×10^{-5}	1.5×10^{-4}	2.5×10^{-4}	3.3×10^{-4}	3.6×10^{-4}	3.9×10^{-4}	3.9×10^{-4}
Pancreas	0.0	0.0	3.2×10^{-9}	2.8×10^{-5}	5.2×10^{-4}	1.1×10^{-3}	1.5×10^{-3}	1.6×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.6×10^{-3}	1.4×10^{-3}
Skeleton:												
Active Marrow	0.0	1.8×10^{-5}	4.1×10^{-4}	3.3×10^{-3}	5.7×10^{-3}	5.3×10^{-3}	4.9×10^{-3}	5.4×10^{-3}	5.0×10^{-3}	4.6×10^{-3}	4.4×10^{-3}	3.8×10^{-3}
Whole Skeleton	0.0	1.9×10^{-5}	4.6×10^{-4}	3.5×10^{-3}	6.2×10^{-3}	5.6×10^{-3}	5.2×10^{-3}	5.7×10^{-3}	5.3×10^{-3}	4.9×10^{-3}	4.6×10^{-3}	4.0×10^{-3}
Spleen	0.0	0.0	1.6×10^{-9}	1.7×10^{-5}	8.2×10^{-4}	1.2×10^{-3}	1.5×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.6×10^{-3}	1.5×10^{-3}	1.2×10^{-3}
Testes	0.0	0.0	0.0	1.1×10^{-9}	1.1×10^{-6}	1.3×10^{-5}	3.4×10^{-5}	7.7×10^{-5}	1.2×10^{-4}	1.4×10^{-4}	1.7×10^{-4}	1.8×10^{-4}
Thymus	0.0	5.4×10^{-5}	3.9×10^{-3}	2.6×10^{-2}	4.1×10^{-2}	2.9×10^{-2}	2.5×10^{-2}	2.5×10^{-2}	2.5×10^{-2}	2.5×10^{-2}	2.4×10^{-2}	1.8×10^{-2}
Thyroid	0.0	2.0×10^{-7}	1.3×10^{-4}	1.9×10^{-3}	7.2×10^{-3}	8.4×10^{-3}	7.9×10^{-3}	8.4×10^{-3}	8.2×10^{-3}	7.8×10^{-3}	7.4×10^{-3}	6.2×10^{-3}
Urinary Bl Cont	0.0	0.0	0.0	1.3×10^{-8}	4.8×10^{-6}	3.7×10^{-5}	8.3×10^{-5}	1.5×10^{-4}	2.1×10^{-4}	2.5×10^{-4}	2.7×10^{-4}	2.8×10^{-4}
Uterus	0.0	0.0	0.0	5.5×10^{-8}	1.2×10^{-5}	7.2×10^{-5}	1.4×10^{-4}	2.4×10^{-4}	3.1×10^{-4}	3.5×10^{-4}	3.8×10^{-4}	3.8×10^{-4}
Whole Body	3.0×10^{-2}	3.0×10^{-2}	2.9×10^{-2}	2.4×10^{-2}	1.6×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	9.7×10^{-3}	9.0×10^{-3}	8.4×10^{-3}	6.9×10^{-3}

(a) Lungs include BB, bb, AI, and LN_{TH}.

(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.11. Specific absorbed fraction of photon energy (in kg^{-1}) for the 15-y old or adult female (55–58 kg) with the ET airways as the target

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	0.0	0.0	0.0	4.2×10^{-6}	1.6×10^{-4}	4.6×10^{-4}	6.8×10^{-4}	8.3×10^{-4}	9.6×10^{-4}	9.9×10^{-4}	1.0×10^{-3}	9.2×10^{-4}
Brain	0.0	1.0×10^{-7}	8.4×10^{-5}	1.3×10^{-3}	5.8×10^{-3}	7.3×10^{-3}	6.9×10^{-3}	7.3×10^{-3}	7.2×10^{-3}	6.9×10^{-3}	6.6×10^{-3}	5.4×10^{-3}
Breasts	0.0	0.0	2.9×10^{-7}	2.5×10^{-4}	1.5×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.4×10^{-3}	2.7×10^{-3}	2.8×10^{-3}	2.8×10^{-3}	2.5×10^{-3}
Gall Bl Cont	0.0	0.0	0.0	5.1×10^{-7}	4.3×10^{-5}	1.8×10^{-4}	3.6×10^{-4}	4.9×10^{-4}	5.3×10^{-4}	5.6×10^{-4}	5.9×10^{-4}	5.6×10^{-4}
GI Tract:												
LLI Cont	0.0	0.0	0.0	4.4×10^{-9}	2.0×10^{-6}	1.7×10^{-5}	4.3×10^{-5}	8.8×10^{-5}	1.3×10^{-4}	1.6×10^{-4}	1.8×10^{-4}	1.9×10^{-4}
SI Cont	0.0	0.0	0.0	2.1×10^{-8}	6.1×10^{-6}	5.8×10^{-5}	7.9×10^{-5}	1.2×10^{-4}	1.6×10^{-4}	1.9×10^{-4}	2.2×10^{-4}	3.0×10^{-4}
Stomach Cont	0.0	0.0	0.0	2.0×10^{-6}	9.3×10^{-5}	2.8×10^{-4}	5.0×10^{-4}	6.6×10^{-4}	6.8×10^{-4}	6.9×10^{-4}	7.0×10^{-4}	7.2×10^{-4}
ULI Cont	0.0	0.0	0.0	3.6×10^{-8}	8.4×10^{-6}	5.4×10^{-5}	1.1×10^{-4}	2.0×10^{-4}	2.6×10^{-4}	2.9×10^{-4}	3.2×10^{-4}	3.2×10^{-4}
Heart Cont	0.0	0.0	6.5×10^{-7}	2.4×10^{-4}	2.2×10^{-3}	4.0×10^{-3}	3.6×10^{-3}	3.0×10^{-3}	3.4×10^{-3}	3.3×10^{-3}	3.2×10^{-3}	3.0×10^{-3}
Heart Wall	0.0	0.0	5.9×10^{-7}	1.9×10^{-4}	2.0×10^{-3}	2.7×10^{-3}	2.6×10^{-3}	2.7×10^{-3}	2.9×10^{-3}	3.0×10^{-3}	3.0×10^{-3}	2.7×10^{-3}
Kidneys	0.0	0.0	0.0	4.2×10^{-7}	3.8×10^{-5}	1.8×10^{-4}	3.5×10^{-4}	5.0×10^{-4}	5.6×10^{-4}	5.7×10^{-4}	5.7×10^{-4}	5.2×10^{-4}
Liver	0.0	0.0	1.4×10^{-10}	4.1×10^{-6}	2.5×10^{-4}	6.6×10^{-4}	7.6×10^{-4}	8.6×10^{-4}	9.3×10^{-4}	9.8×10^{-4}	9.9×10^{-4}	9.2×10^{-4}
Lungs[a]	0.0	5.6×10^{-8}	6.1×10^{-5}	2.1×10^{-3}	6.2×10^{-3}	6.1×10^{-3}	5.4×10^{-3}	5.1×10^{-3}	5.1×10^{-3}	4.7×10^{-3}	4.4×10^{-3}	4.1×10^{-3}
ET Airways[b]	66	43	26	10	3.4	2.0	2.2	2.4	2.3	2.1	1.9	1.5
Muscle	4.5×10^{-3}	1.1×10^{-2}	1.6×10^{-2}	1.7×10^{-2}	1.2×10^{-2}	7.7×10^{-3}	7.3×10^{-3}	7.2×10^{-3}	6.7×10^{-3}	6.2×10^{-3}	5.7×10^{-3}	4.8×10^{-3}
Ovaries	0.0	0.0	0.0	1.8×10^{-9}	1.5×10^{-6}	1.6×10^{-5}	4.1×10^{-5}	8.9×10^{-5}	1.3×10^{-4}	1.6×10^{-4}	1.8×10^{-4}	2.0×10^{-4}
Pancreas	0.0	0.0	0.0	3.0×10^{-6}	1.3×10^{-4}	3.8×10^{-4}	5.6×10^{-4}	7.4×10^{-4}	8.8×10^{-4}	9.1×10^{-4}	9.3×10^{-4}	8.3×10^{-4}
Skeleton:												
Active Marrow	2.1×10^{-7}	1.6×10^{-5}	3.4×10^{-4}	2.2×10^{-3}	4.3×10^{-3}	4.4×10^{-3}	4.2×10^{-3}	4.4×10^{-3}	4.1×10^{-3}	3.8×10^{-3}	3.7×10^{-3}	3.2×10^{-3}
Whole Skeleton	3.5×10^{-10}	2.1×10^{-5}	4.1×10^{-4}	2.5×10^{-3}	4.5×10^{-3}	4.3×10^{-3}	4.1×10^{-3}	4.4×10^{-3}	4.0×10^{-3}	3.8×10^{-3}	3.6×10^{-3}	3.1×10^{-3}
Spleen	0.0	0.0	0.0	1.7×10^{-6}	8.8×10^{-5}	5.3×10^{-4}	8.4×10^{-4}	8.7×10^{-4}	8.2×10^{-4}	7.8×10^{-4}	7.5×10^{-4}	6.8×10^{-4}
Testes	0.0	0.0	0.0	0.0	6.0×10^{-8}	1.5×10^{-6}	6.1×10^{-6}	2.0×10^{-5}	3.9×10^{-5}	5.3×10^{-5}	6.6×10^{-5}	8.5×10^{-5}
Thymus	0.0	1.7×10^{-7}	1.8×10^{-4}	6.2×10^{-3}	1.2×10^{-2}	1.5×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	9.9×10^{-3}	9.3×10^{-3}	7.6×10^{-3}
Thyroid	0.0	1.0×10^{-7}	8.4×10^{-5}	1.3×10^{-3}	5.8×10^{-3}	7.3×10^{-3}	6.9×10^{-3}	7.3×10^{-3}	7.2×10^{-3}	6.9×10^{-3}	6.6×10^{-3}	5.4×10^{-3}
Urinary Bl Cont	0.0	0.0	0.0	2.4×10^{-10}	4.2×10^{-7}	6.3×10^{-6}	1.9×10^{-5}	4.9×10^{-5}	8.1×10^{-5}	1.0×10^{-4}	1.2×10^{-4}	1.4×10^{-4}
Uterus	0.0	0.0	0.0	1.5×10^{-9}	1.3×10^{-6}	1.4×10^{-5}	3.8×10^{-5}	8.4×10^{-5}	1.3×10^{-4}	1.5×10^{-4}	1.8×10^{-4}	1.9×10^{-4}
Whole Body	1.7×10^{-2}	1.7×10^{-2}	1.7×10^{-2}	1.4×10^{-2}	1.0×10^{-2}	7.0×10^{-3}	6.7×10^{-3}	6.6×10^{-3}	6.2×10^{-3}	5.7×10^{-3}	5.3×10^{-3}	4.4×10^{-3}

(a) Lungs include BB, bb, AI, and LN_{TH}.

(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.12. Specific absorbed fraction of photon energy (in kg^{-1}) for the adult male (70 kg) with the ET airways as the target

Target	Energy, MeV											
	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	0.0	0.0	0.0	1.3×10^{-6}	7.9×10^{-5}	3.8×10^{-4}	4.4×10^{-4}	5.6×10^{-4}	6.9×10^{-4}	7.3×10^{-4}	7.6×10^{-4}	7.0×10^{-4}
Brain	0.0	6.0×10^{-8}	6.0×10^{-5}	1.0×10^{-3}	4.8×10^{-3}	6.7×10^{-3}	6.8×10^{-3}	7.0×10^{-3}	6.5×10^{-3}	6.4×10^{-3}	6.2×10^{-3}	5.0×10^{-3}
Breasts	0.0	0.0	4.8×10^{-8}	8.7×10^{-5}	6.2×10^{-4}	1.5×10^{-3}	1.5×10^{-3}	1.8×10^{-3}	2.0×10^{-3}	2.1×10^{-3}	2.1×10^{-3}	2.1×10^{-3}
Gall Bl Cont	0.0	0.0	0.0	1.1×10^{-7}	1.7×10^{-5}	9.0×10^{-5}	1.7×10^{-4}	2.9×10^{-4}	3.6×10^{-4}	4.0×10^{-4}	4.2×10^{-4}	4.1×10^{-4}
GI Tract:												
LLI Cont	0.0	0.0	0.0	6.7×10^{-10}	6.0×10^{-7}	7.2×10^{-6}	2.0×10^{-5}	4.9×10^{-5}	7.9×10^{-5}	1.0×10^{-4}	1.2×10^{-4}	1.4×10^{-4}
SI Cont	0.0	0.0	0.0	3.6×10^{-9}	2.0×10^{-6}	1.9×10^{-5}	3.2×10^{-5}	5.9×10^{-5}	9.2×10^{-5}	1.2×10^{-4}	1.4×10^{-4}	2.1×10^{-4}
Stomach Cont	0.0	0.0	0.0	5.3×10^{-7}	4.0×10^{-5}	9.7×10^{-5}	1.8×10^{-4}	3.0×10^{-4}	3.9×10^{-4}	4.3×10^{-4}	4.6×10^{-4}	5.3×10^{-4}
ULI Cont	0.0	0.0	0.0	6.3×10^{-9}	2.9×10^{-6}	2.5×10^{-5}	5.8×10^{-5}	1.2×10^{-4}	1.7×10^{-4}	2.0×10^{-4}	2.2×10^{-4}	2.3×10^{-4}
Heart Cont	0.0	0.0	1.3×10^{-7}	2.0×10^{-4}	1.5×10^{-3}	2.7×10^{-3}	2.4×10^{-3}	2.3×10^{-3}	2.2×10^{-3}	2.3×10^{-3}	2.4×10^{-3}	2.3×10^{-3}
Heart Wall	0.0	0.0	1.2×10^{-7}	1.0×10^{-4}	1.0×10^{-3}	2.2×10^{-3}	2.1×10^{-3}	2.3×10^{-3}	2.3×10^{-3}	2.3×10^{-3}	2.3×10^{-3}	2.0×10^{-3}
Kidneys	0.0	0.0	0.0	1.0×10^{-7}	1.6×10^{-5}	9.1×10^{-5}	2.3×10^{-4}	3.7×10^{-4}	4.1×10^{-4}	4.2×10^{-4}	4.2×10^{-4}	4.0×10^{-4}
Liver	0.0	0.0	0.0	1.1×10^{-6}	2.0×10^{-4}	3.7×10^{-4}	5.2×10^{-4}	6.1×10^{-4}	6.4×10^{-4}	6.5×10^{-4}	6.7×10^{-4}	7.3×10^{-4}
Lungs$^{(a)}$	0.0	2.5×10^{-8}	3.1×10^{-5}	1.5×10^{-3}	4.3×10^{-3}	4.6×10^{-3}	4.1×10^{-3}	4.2×10^{-3}	4.0×10^{-3}	3.9×10^{-3}	3.8×10^{-3}	3.0×10^{-3}
ET Airways$^{(b)}$	41	28	18	7.2	2.5	1.4	1.5	1.7	1.6	1.5	1.3	1.0
Muscle	3.0×10^{-3}	7.9×10^{-3}	1.2×10^{-2}	1.2×10^{-2}	8.6×10^{-3}	5.8×10^{-3}	5.5×10^{-3}	5.5×10^{-3}	5.1×10^{-3}	4.8×10^{-3}	4.5×10^{-3}	3.7×10^{-3}
Ovaries	0.0	0.0	0.0	2.3×10^{-10}	4.2×10^{-7}	6.3×10^{-6}	1.9×10^{-5}	4.9×10^{-5}	8.1×10^{-5}	1.0×10^{-4}	1.2×10^{-4}	1.4×10^{-4}
Pancreas	0.0	0.0	0.0	8.1×10^{-7}	5.9×10^{-5}	2.9×10^{-4}	4.7×10^{-4}	5.6×10^{-4}	6.5×10^{-4}	6.7×10^{-4}	6.7×10^{-4}	6.3×10^{-4}
Skeleton:												
Active Marrow	7.5×10^{-7}	2.7×10^{-5}	3.3×10^{-4}	1.8×10^{-3}	3.6×10^{-3}	3.8×10^{-3}	3.7×10^{-3}	3.9×10^{-3}	3.6×10^{-3}	3.4×10^{-3}	3.2×10^{-3}	2.7×10^{-3}
Whole Skeleton	1.2×10^{-6}	4.1×10^{-5}	4.9×10^{-4}	2.4×10^{-3}	4.0×10^{-3}	3.9×10^{-3}	3.7×10^{-3}	4.0×10^{-3}	3.7×10^{-3}	3.5×10^{-3}	3.3×10^{-3}	2.7×10^{-3}
Spleen	0.0	0.0	0.0	4.5×10^{-7}	2.5×10^{-4}	3.5×10^{-4}	4.5×10^{-4}	5.5×10^{-4}	5.8×10^{-4}	5.7×10^{-4}	5.6×10^{-4}	5.3×10^{-4}
Testes	0.0	0.0	0.0	0.0	1.1×10^{-8}	4.4×10^{-7}	2.2×10^{-6}	8.9×10^{-6}	2.0×10^{-5}	3.0×10^{-5}	4.0×10^{-5}	5.5×10^{-5}
Thymus	0.0	6.4×10^{-9}	3.2×10^{-5}	3.2×10^{-3}	6.9×10^{-3}	8.5×10^{-3}	7.5×10^{-3}	7.0×10^{-3}	7.7×10^{-3}	7.5×10^{-3}	7.1×10^{-3}	5.3×10^{-3}
Thyroid	0.0	6.0×10^{-8}	6.0×10^{-5}	1.0×10^{-3}	4.8×10^{-3}	6.7×10^{-3}	6.8×10^{-3}	7.0×10^{-3}	6.5×10^{-3}	6.4×10^{-3}	6.2×10^{-3}	5.0×10^{-3}
Urinary Bl Cont	0.0	0.0	0.0	0.0	1.1×10^{-7}	2.3×10^{-6}	8.4×10^{-6}	2.5×10^{-5}	4.7×10^{-5}	6.4×10^{-5}	7.8×10^{-5}	9.7×10^{-5}
Uterus	0.0	0.0	0.0	1.8×10^{-10}	3.6×10^{-7}	5.7×10^{-6}	1.8×10^{-5}	4.6×10^{-5}	7.7×10^{-5}	9.8×10^{-5}	1.2×10^{-4}	1.4×10^{-4}
Whole Body	1.4×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.1×10^{-2}	7.9×10^{-3}	5.6×10^{-3}	5.3×10^{-3}	5.2×10^{-3}	4.9×10^{-3}	4.6×10^{-3}	4.3×10^{-3}	3.6×10^{-3}

(a) Lungs include BB, bb, AI, and LN_{TH}.
(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.13. Specific absorbed fraction of photon energy (in kg^{-1}) for the newborn (3.4 kg) with the lungs as the source

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	3.1×10^{-2}	2.7×10^{-1}	4.6×10^{-1}	3.8×10^{-1}	2.0×10^{-1}	1.2×10^{-1}	1.2×10^{-1}	1.1×10^{-1}	1.1×10^{-1}	9.4×10^{-2}	8.5×10^{-2}	7.2×10^{-2}
Brain	0.0	1.7×10^{-7}	1.2×10^{-4}	3.2×10^{-3}	6.7×10^{-3}	5.6×10^{-3}	5.6×10^{-3}	7.3×10^{-3}	7.9×10^{-3}	7.7×10^{-3}	7.3×10^{-3}	6.4×10^{-3}
Breasts	6.8×10^{-3}	1.3×10^{-1}	3.1×10^{-1}	2.8×10^{-1}	1.3×10^{-1}	8.1×10^{-2}	8.4×10^{-2}	8.5×10^{-2}	8.5×10^{-2}	8.4×10^{-2}	8.0×10^{-2}	6.0×10^{-2}
Gall Bl Wall	4.3×10^{-7}	3.2×10^{-3}	4.3×10^{-2}	1.3×10^{-1}	8.7×10^{-2}	5.5×10^{-2}	5.1×10^{-2}	5.0×10^{-2}	5.0×10^{-2}	4.4×10^{-2}	3.9×10^{-2}	3.4×10^{-2}
GI Tract:												
LLI Wall	0.0	2.1×10^{-4}	4.8×10^{-4}	7.9×10^{-3}	1.1×10^{-2}	9.2×10^{-3}	8.8×10^{-3}	1.1×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	8.2×10^{-3}
SI Wall	0.0	2.6×10^{-5}	2.5×10^{-3}	2.4×10^{-2}	3.1×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.5×10^{-2}
Stomach Wall	2.0×10^{-3}	3.8×10^{-2}	1.1×10^{-1}	1.6×10^{-1}	9.7×10^{-2}	6.0×10^{-2}	5.7×10^{-2}	5.8×10^{-2}	4.7×10^{-2}	4.5×10^{-2}	4.4×10^{-2}	3.6×10^{-2}
ULI Wall	0.0	4.9×10^{-5}	6.1×10^{-3}	2.9×10^{-2}	3.2×10^{-2}	2.2×10^{-2}	2.1×10^{-2}	2.3×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.6×10^{-2}
Heart Wall	8.5×10^{-2}	4.1×10^{-1}	6.8×10^{-1}	5.6×10^{-1}	2.6×10^{-1}	1.5×10^{-1}	1.5×10^{-1}	1.5×10^{-1}	1.4×10^{-1}	1.3×10^{-1}	1.2×10^{-1}	9.1×10^{-2}
Kidneys	2.1×10^{-4}	5.9×10^{-3}	4.2×10^{-2}	9.8×10^{-2}	7.2×10^{-2}	4.6×10^{-2}	4.6×10^{-2}	5.0×10^{-2}	4.1×10^{-2}	4.0×10^{-2}	3.9×10^{-2}	3.1×10^{-2}
Liver	4.1×10^{-2}	2.0×10^{-1}	3.1×10^{-1}	2.6×10^{-1}	1.3×10^{-1}	7.8×10^{-2}	7.7×10^{-2}	8.1×10^{-2}	7.4×10^{-2}	6.6×10^{-2}	6.0×10^{-2}	5.3×10^{-2}
Lungs(a)	15	8.7	4.9	1.8	6.1×10^{-1}	3.4×10^{-1}	3.5×10^{-1}	3.9×10^{-1}	3.6×10^{-1}	3.3×10^{-1}	3.0×10^{-1}	2.3×10^{-1}
ET Airways(b)	1.1×10^{-7}	2.9×10^{-3}	5.1×10^{-2}	1.3×10^{-1}	9.2×10^{-2}	4.9×10^{-2}	4.7×10^{-2}	5.0×10^{-2}	4.6×10^{-2}	4.3×10^{-2}	4.0×10^{-2}	3.1×10^{-2}
Muscle	9.7×10^{-2}	1.8×10^{-1}	2.0×10^{-1}	1.4×10^{-1}	7.1×10^{-2}	4.2×10^{-2}	4.3×10^{-2}	4.5×10^{-2}	4.3×10^{-2}	4.0×10^{-2}	3.7×10^{-2}	2.9×10^{-2}
Ovaries	0.0	4.9×10^{-7}	4.3×10^{-4}	6.0×10^{-3}	1.6×10^{-2}	1.2×10^{-2}	1.3×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	9.6×10^{-3}
Pancreas	1.1×10^{-4}	4.8×10^{-2}	1.8×10^{-1}	2.7×10^{-1}	1.5×10^{-1}	9.1×10^{-2}	9.0×10^{-2}	8.7×10^{-2}	8.3×10^{-2}	7.8×10^{-2}	7.4×10^{-2}	6.4×10^{-2}
Skeleton:												
Active Marrow	2.9×10^{-3}	2.9×10^{-2}	6.7×10^{-2}	8.0×10^{-2}	5.2×10^{-2}	3.4×10^{-2}	3.5×10^{-2}	3.5×10^{-2}	3.2×10^{-2}	3.0×10^{-2}	2.7×10^{-2}	2.3×10^{-2}
Bone Surfaces	1.9×10^{-2}	2.1×10^{-1}	5.1×10^{-1}	6.4×10^{-1}	3.4×10^{-1}	1.0×10^{-1}	5.8×10^{-2}	5.2×10^{-2}	4.7×10^{-2}	4.3×10^{-2}	4.0×10^{-2}	3.5×10^{-2}
Skin	3.7×10^{-3}	1.4×10^{-2}	3.7×10^{-2}	5.0×10^{-2}	3.3×10^{-2}	2.1×10^{-2}	2.3×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.2×10^{-2}	2.1×10^{-2}	1.9×10^{-2}
Spleen	2.0×10^{-2}	1.6×10^{-1}	3.2×10^{-1}	2.8×10^{-1}	1.5×10^{-1}	7.9×10^{-2}	7.7×10^{-2}	7.9×10^{-2}	7.3×10^{-2}	6.5×10^{-2}	5.8×10^{-2}	4.7×10^{-2}
Testes	0.0	0.0	5.0×10^{-6}	9.9×10^{-4}	2.4×10^{-3}	3.3×10^{-3}	3.7×10^{-3}	4.0×10^{-3}	4.2×10^{-3}	4.3×10^{-3}	4.3×10^{-3}	4.2×10^{-3}
Thymus	1.3×10^{-4}	3.8×10^{-2}	1.6×10^{-1}	2.5×10^{-1}	1.4×10^{-1}	8.1×10^{-2}	7.8×10^{-2}	7.8×10^{-2}	7.8×10^{-2}	6.9×10^{-2}	6.1×10^{-2}	4.9×10^{-2}
Thyroid	1.1×10^{-7}	2.9×10^{-3}	5.1×10^{-2}	1.3×10^{-1}	9.2×10^{-2}	4.9×10^{-2}	4.7×10^{-2}	5.0×10^{-2}	4.6×10^{-2}	4.3×10^{-2}	4.0×10^{-2}	3.1×10^{-2}
Urinary Bl Wall	0.0	1.7×10^{-8}	6.8×10^{-5}	3.5×10^{-3}	6.1×10^{-3}	7.5×10^{-3}	7.9×10^{-3}	8.3×10^{-3}	8.1×10^{-3}	7.8×10^{-3}	7.4×10^{-3}	6.5×10^{-3}
Uterus	0.0	2.6×10^{-7}	3.2×10^{-4}	6.6×10^{-3}	1.6×10^{-2}	1.0×10^{-2}	1.1×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.2×10^{-3}
Whole Body	2.8×10^{-1}	2.7×10^{-1}	2.5×10^{-1}	1.8×10^{-1}	8.6×10^{-2}	4.7×10^{-2}	4.6×10^{-2}	4.8×10^{-2}	4.5×10^{-2}	4.2×10^{-2}	3.9×10^{-2}	3.1×10^{-2}

(a) Lungs include BB, bb, AI, and LN_{TH}.
(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.14. Specific absorbed fraction of photon energy (in kg^{-1}) for the 1-y old (9.8 kg) with the lungs as the source

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	1.8×10^{-3}	4.8×10^{-2}	1.2×10^{-1}	1.4×10^{-1}	9.1×10^{-2}	5.8×10^{-2}	5.4×10^{-2}	5.7×10^{-2}	5.0×10^{-2}	4.6×10^{-2}	4.3×10^{-2}	3.3×10^{-2}
Brain	0.0	1.3×10^{-9}	7.3×10^{-6}	5.5×10^{-4}	2.0×10^{-3}	2.3×10^{-3}	2.4×10^{-3}	3.4×10^{-3}	3.7×10^{-3}	3.6×10^{-3}	3.4×10^{-3}	3.1×10^{-3}
Breasts	7.8×10^{-4}	2.8×10^{-2}	1.0×10^{-1}	1.2×10^{-1}	7.1×10^{-2}	4.4×10^{-2}	4.7×10^{-2}	4.8×10^{-2}	4.5×10^{-2}	4.2×10^{-2}	3.9×10^{-2}	3.3×10^{-2}
Gall Bl Wall	1.4×10^{-9}	2.3×10^{-4}	7.5×10^{-3}	4.3×10^{-2}	3.2×10^{-2}	1.9×10^{-2}	1.7×10^{-2}	1.9×10^{-2}	1.8×10^{-2}	1.7×10^{-2}	1.6×10^{-2}	1.3×10^{-2}
GI Tract:												
LLI Wall	0.0	1.8×10^{-8}	3.3×10^{-5}	1.8×10^{-3}	3.1×10^{-3}	4.6×10^{-3}	5.3×10^{-3}	5.2×10^{-3}	4.7×10^{-3}	4.3×10^{-3}	4.0×10^{-3}	3.4×10^{-3}
SI Wall	0.0	3.6×10^{-7}	2.5×10^{-4}	4.6×10^{-3}	1.1×10^{-2}	9.0×10^{-3}	8.6×10^{-3}	8.6×10^{-3}	8.5×10^{-3}	8.8×10^{-3}	8.7×10^{-3}	6.7×10^{-3}
Stomach Wall	4.5×10^{-3}	1.4×10^{-2}	3.3×10^{-2}	5.7×10^{-2}	4.9×10^{-2}	3.0×10^{-2}	2.7×10^{-2}	2.6×10^{-2}	2.5×10^{-2}	2.4×10^{-2}	2.2×10^{-2}	1.9×10^{-2}
ULI Wall	0.0	7.5×10^{-7}	4.3×10^{-4}	5.1×10^{-3}	1.5×10^{-2}	1.2×10^{-2}	8.7×10^{-3}	1.1×10^{-2}	9.6×10^{-3}	8.4×10^{-3}	7.7×10^{-3}	6.6×10^{-3}
Heart Wall	1.4×10^{-2}	1.1×10^{-1}	2.3×10^{-1}	2.5×10^{-1}	1.4×10^{-1}	8.1×10^{-2}	7.8×10^{-2}	8.2×10^{-2}	7.5×10^{-2}	6.8×10^{-2}	6.2×10^{-2}	4.9×10^{-2}
Kidneys	1.5×10^{-8}	5.9×10^{-4}	9.5×10^{-3}	3.3×10^{-2}	3.0×10^{-2}	2.2×10^{-2}	2.2×10^{-2}	2.1×10^{-2}	2.2×10^{-2}	2.1×10^{-2}	1.9×10^{-2}	1.5×10^{-2}
Liver	9.3×10^{-3}	6.0×10^{-2}	1.1×10^{-1}	1.1×10^{-1}	6.8×10^{-2}	4.3×10^{-2}	4.0×10^{-2}	4.1×10^{-2}	3.9×10^{-2}	3.5×10^{-2}	3.2×10^{-2}	2.6×10^{-2}
Lungs(a)	5.8	3.8	2.3	9.3×10^{-1}	3.2×10^{-1}	1.8×10^{-1}	1.8×10^{-1}	2.0×10^{-1}	1.8×10^{-1}	1.7×10^{-1}	1.5×10^{-1}	1.2×10^{-1}
ET Airways(b)	3.1×10^{-10}	1.9×10^{-4}	1.0×10^{-2}	4.5×10^{-2}	4.3×10^{-2}	2.9×10^{-2}	2.9×10^{-2}	2.3×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	1.6×10^{-2}
Muscle	2.6×10^{-2}	5.8×10^{-2}	7.1×10^{-2}	5.8×10^{-2}	3.3×10^{-2}	2.1×10^{-2}	2.1×10^{-2}	2.2×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.8×10^{-2}	1.4×10^{-2}
Ovaries	0.0	1.0×10^{-9}	1.8×10^{-5}	1.0×10^{-3}	4.2×10^{-3}	5.5×10^{-3}	4.8×10^{-3}	5.2×10^{-3}	4.8×10^{-3}	4.7×10^{-3}	4.6×10^{-3}	4.4×10^{-3}
Pancreas	3.3×10^{-6}	8.4×10^{-3}	5.2×10^{-2}	1.1×10^{-1}	7.4×10^{-2}	4.8×10^{-2}	4.5×10^{-2}	4.0×10^{-2}	3.8×10^{-2}	3.5×10^{-2}	3.3×10^{-2}	2.6×10^{-2}
Skeleton:												
Active Marrow	4.8×10^{-4}	6.3×10^{-3}	1.9×10^{-2}	3.0×10^{-2}	2.5×10^{-2}	1.8×10^{-2}	1.7×10^{-2}	1.8×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.2×10^{-2}
Bone Surfaces	2.7×10^{-3}	4.0×10^{-2}	1.3×10^{-1}	2.2×10^{-1}	1.5×10^{-1}	5.2×10^{-2}	2.8×10^{-2}	2.4×10^{-2}	2.2×10^{-2}	2.1×10^{-2}	2.0×10^{-2}	1.6×10^{-2}
Skin	3.1×10^{-5}	2.9×10^{-3}	8.3×10^{-3}	1.7×10^{-2}	1.4×10^{-2}	9.7×10^{-3}	1.0×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.6×10^{-3}	8.8×10^{-3}
Spleen	2.4×10^{-3}	3.7×10^{-2}	9.4×10^{-2}	1.1×10^{-1}	6.8×10^{-2}	4.2×10^{-2}	4.1×10^{-2}	4.1×10^{-2}	3.7×10^{-2}	3.4×10^{-2}	3.1×10^{-2}	2.1×10^{-2}
Testes	0.0	0.0	4.7×10^{-8}	1.0×10^{-4}	5.2×10^{-4}	1.2×10^{-3}	1.5×10^{-3}	1.6×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}
Thymus	3.9×10^{-6}	6.3×10^{-3}	5.1×10^{-2}	1.1×10^{-1}	7.8×10^{-2}	4.7×10^{-2}	4.4×10^{-2}	4.4×10^{-2}	4.2×10^{-2}	4.0×10^{-2}	3.8×10^{-2}	2.9×10^{-2}
Thyroid	3.1×10^{-10}	1.9×10^{-4}	1.0×10^{-2}	4.5×10^{-2}	4.3×10^{-2}	2.9×10^{-2}	2.9×10^{-2}	2.3×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	1.6×10^{-2}
Urinary Bl Wall	0.0	0.0	1.6×10^{-6}	5.7×10^{-4}	2.4×10^{-3}	3.1×10^{-3}	3.1×10^{-3}	3.1×10^{-3}	3.3×10^{-3}	3.2×10^{-3}	3.1×10^{-3}	2.7×10^{-3}
Uterus	0.0	3.9×10^{-10}	1.2×10^{-5}	1.1×10^{-3}	4.0×10^{-3}	4.9×10^{-3}	4.6×10^{-3}	5.2×10^{-3}	5.2×10^{-3}	5.0×10^{-3}	4.8×10^{-3}	4.2×10^{-3}
Whole Body	1.0×10^{-1}	1.0×10^{-1}	9.8×10^{-2}	7.7×10^{-2}	4.3×10^{-2}	2.5×10^{-2}	2.3×10^{-2}	2.3×10^{-2}	2.2×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.5×10^{-2}

(a) Lungs include BB, bb, AI, and LN_{TH}.
(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.15. Specific absorbed fraction of photon energy (in kg^{-1}) for the 5-y old (19 kg) with the lungs as the source

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	1.6×10^{-4}	1.3×10^{-2}	4.7×10^{-2}	7.0×10^{-2}	5.2×10^{-2}	3.5×10^{-2}	3.3×10^{-2}	3.1×10^{-2}	3.1×10^{-2}	2.8×10^{-2}	2.5×10^{-2}	1.8×10^{-2}
Brain	0.0	0.0	9.7×10^{-7}	1.4×10^{-4}	8.1×10^{-4}	1.4×10^{-3}	1.5×10^{-3}	2.0×10^{-3}	2.1×10^{-3}	2.0×10^{-3}	1.9×10^{-3}	2.1×10^{-3}
Breasts	1.0×10^{-4}	1.1×10^{-2}	5.0×10^{-2}	7.3×10^{-2}	4.8×10^{-2}	3.2×10^{-2}	3.2×10^{-2}	3.3×10^{-2}	3.1×10^{-2}	2.8×10^{-2}	2.5×10^{-2}	2.2×10^{-2}
Gall Bl Wall	0.0	3.0×10^{-5}	1.7×10^{-3}	1.5×10^{-2}	3.0×10^{-2}	1.6×10^{-2}	1.0×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	9.6×10^{-3}	7.9×10^{-3}
GI Tract:												
LLI Wall	0.0	0.0	1.5×10^{-6}	2.7×10^{-4}	1.4×10^{-3}	2.0×10^{-3}	2.1×10^{-3}	2.2×10^{-3}	2.1×10^{-3}	2.1×10^{-3}	2.0×10^{-3}	1.7×10^{-3}
SI Wall	0.0	3.6×10^{-9}	1.6×10^{-5}	1.4×10^{-3}	3.7×10^{-3}	4.1×10^{-3}	4.1×10^{-3}	4.6×10^{-3}	4.3×10^{-3}	4.2×10^{-3}	4.1×10^{-3}	3.6×10^{-3}
Stomach Wall	1.3×10^{-3}	5.0×10^{-3}	1.3×10^{-2}	2.6×10^{-2}	2.8×10^{-2}	1.9×10^{-2}	1.7×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.1×10^{-2}
ULI Wall	0.0	7.1×10^{-9}	2.9×10^{-5}	1.7×10^{-3}	4.7×10^{-3}	5.6×10^{-3}	4.9×10^{-3}	4.7×10^{-3}	4.9×10^{-3}	4.7×10^{-3}	4.4×10^{-3}	3.5×10^{-3}
Heart Wall	3.1×10^{-3}	4.2×10^{-2}	1.1×10^{-1}	1.4×10^{-1}	9.1×10^{-2}	5.6×10^{-2}	5.2×10^{-2}	5.1×10^{-2}	4.6×10^{-2}	4.2×10^{-2}	3.9×10^{-2}	3.0×10^{-2}
Kidneys	1.5×10^{-7}	4.0×10^{-5}	2.1×10^{-3}	1.0×10^{-2}	1.6×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.8×10^{-3}	7.9×10^{-3}
Liver	2.3×10^{-3}	2.2×10^{-2}	4.6×10^{-2}	5.7×10^{-2}	4.0×10^{-2}	2.5×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.2×10^{-2}	2.0×10^{-2}	1.8×10^{-2}	1.4×10^{-2}
Lungs(a)	3.0	2.1	1.3	5.7×10^{-1}	2.1×10^{-1}	1.2×10^{-1}	1.2×10^{-1}	1.2×10^{-1}	1.2×10^{-1}	1.0×10^{-1}	9.5×10^{-2}	7.5×10^{-2}
ET Airways(b)	0.0	2.6×10^{-5}	2.2×10^{-3}	1.7×10^{-2}	2.3×10^{-2}	1.7×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.0×10^{-2}
Muscle	1.0×10^{-2}	2.5×10^{-2}	3.3×10^{-2}	3.0×10^{-2}	1.8×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.8×10^{-3}	8.2×10^{-3}
Ovaries	0.0	0.0	4.5×10^{-7}	2.7×10^{-4}	1.5×10^{-3}	2.3×10^{-3}	2.1×10^{-3}	2.6×10^{-3}	2.8×10^{-3}	2.7×10^{-3}	2.5×10^{-3}	2.3×10^{-3}
Pancreas	5.5×10^{-5}	1.4×10^{-3}	1.5×10^{-2}	4.7×10^{-2}	4.3×10^{-2}	2.8×10^{-2}	2.5×10^{-2}	2.4×10^{-2}	2.2×10^{-2}	2.1×10^{-2}	1.9×10^{-2}	1.5×10^{-2}
Skeleton:												
Active Marrow	1.7×10^{-4}	2.3×10^{-3}	7.8×10^{-3}	1.5×10^{-2}	1.4×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.6×10^{-3}	9.1×10^{-3}	7.4×10^{-3}
Bone Surfaces	7.4×10^{-4}	1.1×10^{-2}	4.1×10^{-2}	8.7×10^{-2}	7.1×10^{-2}	2.8×10^{-2}	1.5×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	8.1×10^{-3}
Skin	1.2×10^{-4}	8.6×10^{-4}	3.5×10^{-3}	7.7×10^{-3}	6.7×10^{-3}	5.5×10^{-3}	5.7×10^{-3}	6.7×10^{-3}	6.1×10^{-3}	5.9×10^{-3}	5.7×10^{-3}	5.2×10^{-3}
Spleen	4.9×10^{-4}	1.0×10^{-2}	3.5×10^{-2}	5.2×10^{-2}	3.7×10^{-2}	2.5×10^{-2}	2.4×10^{-2}	2.2×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.4×10^{-2}
Testes	0.0	0.0	2.2×10^{-10}	6.4×10^{-6}	1.6×10^{-4}	2.4×10^{-4}	3.5×10^{-4}	4.9×10^{-4}	6.0×10^{-4}	6.7×10^{-4}	7.1×10^{-4}	8.2×10^{-4}
Thymus	1.5×10^{-7}	1.6×10^{-3}	2.0×10^{-2}	6.2×10^{-2}	5.1×10^{-2}	3.4×10^{-2}	3.2×10^{-2}	3.1×10^{-2}	2.9×10^{-2}	2.6×10^{-2}	2.4×10^{-2}	2.1×10^{-2}
Thyroid	0.0	2.6×10^{-5}	2.2×10^{-3}	1.7×10^{-2}	2.3×10^{-2}	1.7×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.0×10^{-2}
Urinary Bl Wall	0.0	0.0	2.3×10^{-8}	5.8×10^{-5}	5.7×10^{-4}	1.0×10^{-3}	1.2×10^{-3}	1.5×10^{-3}	1.5×10^{-3}	1.6×10^{-3}	1.6×10^{-3}	1.4×10^{-3}
Uterus	0.0	0.0	2.6×10^{-7}	2.2×10^{-4}	1.1×10^{-3}	1.8×10^{-3}	1.9×10^{-3}	2.4×10^{-3}	2.4×10^{-3}	2.4×10^{-3}	2.3×10^{-3}	2.2×10^{-3}
Whole Body	5.0×10^{-2}	5.0×10^{-2}	4.9×10^{-2}	4.0×10^{-2}	2.4×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	8.9×10^{-3}

(a) Lungs include BB, bb, AI, and LN_{TH}.

(b) ET airways include ET_1, ET_2, and LN_{ET}

Table G.16. Specific absorbed fraction of photon energy (in kg^{-1}) for the 10-y old (32 kg) with the lungs as the source

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	4.3×10^{-6}	4.2×10^{-3}	1.8×10^{-2}	3.8×10^{-2}	3.3×10^{-2}	2.4×10^{-2}	2.1×10^{-2}	2.1×10^{-2}	1.9×10^{-2}	1.7×10^{-2}	1.5×10^{-2}	1.1×10^{-2}
Brain	0.0	0.0	1.5×10^{-7}	7.8×10^{-5}	4.6×10^{-4}	8.6×10^{-4}	9.1×10^{-4}	1.2×10^{-3}	1.4×10^{-3}	1.5×10^{-3}	1.5×10^{-3}	1.4×10^{-3}
Breasts	2.7×10^{-5}	5.2×10^{-3}	2.9×10^{-2}	5.1×10^{-2}	3.4×10^{-2}	2.3×10^{-2}	2.3×10^{-2}	2.4×10^{-2}	2.2×10^{-2}	2.1×10^{-2}	2.0×10^{-2}	1.6×10^{-2}
Gall Bl Wall	8.8×10^{-9}	4.9×10^{-6}	4.4×10^{-4}	6.1×10^{-3}	8.6×10^{-3}	9.3×10^{-3}	8.0×10^{-3}	6.7×10^{-3}	6.4×10^{-3}	6.2×10^{-3}	6.0×10^{-3}	5.0×10^{-3}
GI Tract:												
LLI Wall	0.0	0.0	9.4×10^{-8}	5.3×10^{-5}	5.3×10^{-4}	6.5×10^{-4}	7.9×10^{-4}	9.9×10^{-4}	1.1×10^{-3}	1.1×10^{-3}	1.1×10^{-3}	1.0×10^{-3}
SI Wall	0.0	0.0	1.3×10^{-6}	3.1×10^{-4}	1.5×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	2.5×10^{-3}	2.4×10^{-3}	2.4×10^{-3}	2.4×10^{-3}	2.0×10^{-3}
Stomach Wall	8.3×10^{-4}	2.8×10^{-3}	6.5×10^{-3}	1.4×10^{-2}	1.7×10^{-2}	1.3×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	9.3×10^{-3}	8.4×10^{-3}	7.9×10^{-3}	7.1×10^{-3}
ULI Wall	0.0	1.1×10^{-10}	2.7×10^{-6}	4.8×10^{-4}	1.8×10^{-3}	3.0×10^{-3}	3.0×10^{-3}	2.9×10^{-3}	2.6×10^{-3}	2.4×10^{-3}	2.3×10^{-3}	2.4×10^{-3}
Heart Wall	1.2×10^{-3}	2.0×10^{-2}	5.9×10^{-2}	8.6×10^{-2}	6.3×10^{-2}	4.1×10^{-2}	3.7×10^{-2}	3.5×10^{-2}	3.4×10^{-2}	3.0×10^{-2}	2.7×10^{-2}	2.2×10^{-2}
Kidneys	0.0	4.5×10^{-6}	5.3×10^{-4}	4.8×10^{-3}	8.4×10^{-3}	7.8×10^{-3}	7.3×10^{-3}	6.8×10^{-3}	7.1×10^{-3}	6.3×10^{-3}	5.7×10^{-3}	5.1×10^{-3}
Liver	7.7×10^{-4}	1.1×10^{-2}	2.6×10^{-2}	3.5×10^{-2}	2.7×10^{-2}	1.8×10^{-2}	1.7×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.1×10^{-2}
Lungs[(a)]	2.0	1.4	9.4×10^{-1}	4.2×10^{-1}	1.6×10^{-1}	8.7×10^{-2}	8.5×10^{-2}	8.9×10^{-2}	8.2×10^{-2}	7.4×10^{-2}	6.8×10^{-2}	5.5×10^{-2}
ET Airways[(b)]	0.0	2.5×10^{-6}	4.6×10^{-4}	7.1×10^{-3}	1.3×10^{-2}	1.1×10^{-2}	9.4×10^{-3}	8.8×10^{-3}	8.2×10^{-3}	8.0×10^{-3}	7.9×10^{-3}	6.8×10^{-3}
Muscle	5.0×10^{-3}	1.3×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.2×10^{-2}	8.2×10^{-3}	8.1×10^{-3}	8.0×10^{-3}	7.5×10^{-3}	7.0×10^{-3}	6.5×10^{-3}	5.4×10^{-3}
Ovaries	0.0	0.0	1.4×10^{-8}	4.2×10^{-5}	3.8×10^{-4}	9.3×10^{-4}	1.1×10^{-3}	1.2×10^{-3}	1.4×10^{-3}	1.5×10^{-3}	1.5×10^{-3}	1.3×10^{-3}
Pancreas	1.6×10^{-6}	1.7×10^{-4}	4.9×10^{-3}	2.2×10^{-2}	2.4×10^{-2}	1.8×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.0×10^{-2}
Skeleton:												
Active Marrow	4.9×10^{-5}	9.8×10^{-4}	4.1×10^{-3}	9.4×10^{-3}	1.0×10^{-2}	8.5×10^{-3}	8.4×10^{-3}	8.2×10^{-3}	7.8×10^{-3}	7.0×10^{-3}	6.5×10^{-3}	5.7×10^{-3}
Bone Surfaces	1.7×10^{-4}	3.9×10^{-3}	1.8×10^{-2}	4.5×10^{-2}	4.3×10^{-2}	1.8×10^{-2}	1.0×10^{-2}	7.6×10^{-3}	7.3×10^{-3}	6.6×10^{-3}	6.0×10^{-3}	5.4×10^{-3}
Skin	3.6×10^{-5}	3.4×10^{-4}	1.6×10^{-3}	4.3×10^{-3}	4.3×10^{-3}	3.6×10^{-3}	3.7×10^{-3}	3.9×10^{-3}	4.2×10^{-3}	4.1×10^{-3}	3.9×10^{-3}	3.3×10^{-3}
Spleen	7.0×10^{-4}	4.2×10^{-3}	1.5×10^{-2}	2.8×10^{-2}	2.4×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	9.4×10^{-3}
Testes	0.0	0.0	0.0	4.8×10^{-7}	3.1×10^{-5}	1.2×10^{-4}	2.4×10^{-4}	3.3×10^{-4}	4.2×10^{-4}	4.7×10^{-4}	4.8×10^{-4}	4.5×10^{-4}
Thymus	1.8×10^{-9}	3.6×10^{-4}	8.7×10^{-3}	3.9×10^{-2}	3.7×10^{-2}	2.6×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	1.9×10^{-2}	1.8×10^{-2}	1.4×10^{-2}
Thyroid	0.0	2.5×10^{-6}	4.6×10^{-4}	7.1×10^{-3}	1.3×10^{-2}	1.1×10^{-2}	9.4×10^{-3}	8.8×10^{-3}	8.2×10^{-3}	8.0×10^{-3}	7.9×10^{-3}	6.8×10^{-3}
Urinary Bl Wall	0.0	0.0	3.9×10^{-10}	6.8×10^{-6}	1.5×10^{-4}	3.7×10^{-4}	5.4×10^{-4}	7.1×10^{-4}	8.0×10^{-4}	8.3×10^{-4}	8.5×10^{-4}	7.8×10^{-4}
Uterus	0.0	0.0	6.8×10^{-9}	3.2×10^{-5}	4.6×10^{-4}	7.4×10^{-4}	9.3×10^{-4}	1.1×10^{-3}	1.1×10^{-3}	1.1×10^{-3}	1.2×10^{-3}	1.3×10^{-3}
Whole Body	3.0×10^{-2}	3.0×10^{-2}	2.9×10^{-2}	2.5×10^{-2}	1.6×10^{-2}	1.0×10^{-2}	9.0×10^{-3}	8.9×10^{-3}	8.4×10^{-3}	7.7×10^{-3}	7.2×10^{-3}	6.0×10^{-3}

(a) Lungs include BB, bb, AI, and LN_{TH}.
(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.17. Specific absorbed fraction of photon energy (in kg^{-1}) for the 15-y old or adult female (55–58 kg) with the lungs as the source

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	2.5×10^{-8}	7.4×10^{-4}	6.0×10^{-3}	1.8×10^{-2}	2.0×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	8.6×10^{-3}
Brain	0.0	0.0	1.4×10^{-8}	1.7×10^{-5}	1.9×10^{-4}	4.3×10^{-4}	6.2×10^{-4}	7.7×10^{-4}	8.9×10^{-4}	9.6×10^{-4}	9.8×10^{-4}	9.5×10^{-4}
Breasts	4.8×10^{-6}	2.4×10^{-4}	3.9×10^{-3}	1.6×10^{-2}	1.7×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	8.2×10^{-3}
Gall Bl Wall	1.9×10^{-10}	3.8×10^{-7}	8.2×10^{-5}	2.0×10^{-3}	5.9×10^{-3}	5.3×10^{-3}	4.9×10^{-3}	4.3×10^{-3}	3.9×10^{-3}	3.8×10^{-3}	3.7×10^{-3}	3.1×10^{-3}
GI Tract:												
LLI Wall	0.0	0.0	3.9×10^{-9}	8.7×10^{-6}	1.7×10^{-4}	2.5×10^{-4}	3.9×10^{-4}	6.2×10^{-4}	7.5×10^{-4}	7.6×10^{-4}	7.3×10^{-4}	5.9×10^{-4}
SI Wall	0.0	0.0	7.3×10^{-8}	6.4×10^{-5}	6.9×10^{-4}	1.1×10^{-3}	1.2×10^{-3}	1.2×10^{-3}	1.4×10^{-3}	1.5×10^{-3}	1.5×10^{-3}	1.4×10^{-3}
Stomach Wall	2.9×10^{-5}	3.8×10^{-4}	2.4×10^{-3}	9.2×10^{-3}	1.1×10^{-2}	8.7×10^{-3}	8.3×10^{-3}	7.7×10^{-3}	7.6×10^{-3}	6.8×10^{-3}	6.1×10^{-3}	4.8×10^{-3}
ULI Wall	0.0	0.0	1.7×10^{-7}	1.0×10^{-4}	1.0×10^{-3}	1.3×10^{-3}	1.4×10^{-3}	1.5×10^{-3}	1.6×10^{-3}	1.6×10^{-3}	1.5×10^{-3}	1.3×10^{-3}
Heart Wall	2.4×10^{-4}	6.9×10^{-3}	2.6×10^{-2}	5.1×10^{-2}	4.4×10^{-2}	3.0×10^{-2}	2.7×10^{-2}	2.5×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	2.0×10^{-2}	1.6×10^{-2}
Kidneys	3.0×10^{-10}	5.1×10^{-7}	1.0×10^{-4}	2.0×10^{-3}	4.4×10^{-3}	4.9×10^{-3}	4.9×10^{-3}	4.7×10^{-3}	4.5×10^{-3}	4.2×10^{-3}	4.0×10^{-3}	3.6×10^{-3}
Liver	2.2×10^{-4}	4.9×10^{-3}	1.5×10^{-2}	2.3×10^{-2}	1.9×10^{-2}	1.4×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.5×10^{-3}	7.7×10^{-3}
Lungs$^{(a)}$	1.4	1.1	7.0×10^{-1}	3.2×10^{-1}	1.2×10^{-1}	6.9×10^{-2}	6.7×10^{-2}	7.0×10^{-2}	6.4×10^{-2}	5.8×10^{-2}	5.4×10^{-2}	4.3×10^{-2}
ET Airways$^{(b)}$	0.0	5.6×10^{-8}	6.1×10^{-5}	2.1×10^{-3}	6.2×10^{-3}	6.1×10^{-3}	5.4×10^{-3}	5.1×10^{-3}	5.1×10^{-3}	4.7×10^{-3}	4.4×10^{-3}	4.1×10^{-3}
Muscle	2.6×10^{-3}	7.4×10^{-3}	1.2×10^{-2}	1.2×10^{-2}	8.7×10^{-3}	6.1×10^{-3}	5.8×10^{-3}	5.7×10^{-3}	5.3×10^{-3}	4.9×10^{-3}	4.6×10^{-3}	3.8×10^{-3}
Ovaries	0.0	0.0	2.4×10^{-10}	5.1×10^{-6}	1.6×10^{-4}	3.6×10^{-4}	4.5×10^{-4}	6.2×10^{-4}	7.2×10^{-4}	7.5×10^{-4}	7.6×10^{-4}	7.7×10^{-4}
Pancreas	1.5×10^{-7}	3.3×10^{-5}	1.5×10^{-3}	1.1×10^{-2}	1.6×10^{-2}	1.3×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	9.0×10^{-3}	8.0×10^{-3}	6.1×10^{-3}
Skeleton:												
Active Marrow	1.6×10^{-5}	2.3×10^{-4}	1.5×10^{-3}	5.2×10^{-3}	6.9×10^{-3}	6.4×10^{-3}	6.3×10^{-3}	6.4×10^{-3}	5.8×10^{-3}	5.3×10^{-3}	4.9×10^{-3}	4.2×10^{-3}
Bone Surfaces	4.7×10^{-5}	7.8×10^{-4}	5.7×10^{-3}	2.2×10^{-2}	2.6×10^{-2}	1.3×10^{-2}	7.2×10^{-3}	5.3×10^{-3}	4.7×10^{-3}	4.4×10^{-3}	4.1×10^{-3}	3.5×10^{-3}
Skin	2.4×10^{-6}	5.6×10^{-5}	5.2×10^{-4}	2.2×10^{-3}	2.6×10^{-3}	2.2×10^{-3}	2.3×10^{-3}	2.8×10^{-3}	2.6×10^{-3}	2.4×10^{-3}	2.3×10^{-3}	2.0×10^{-3}
Spleen	1.3×10^{-4}	1.2×10^{-3}	6.0×10^{-3}	1.5×10^{-2}	1.5×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.7×10^{-3}	9.3×10^{-3}	8.5×10^{-3}	7.9×10^{-3}	6.7×10^{-3}
Testes	0.0	0.0	0.0	1.8×10^{-8}	4.0×10^{-6}	2.7×10^{-5}	6.2×10^{-5}	1.3×10^{-4}	1.7×10^{-4}	1.9×10^{-4}	2.1×10^{-4}	2.4×10^{-4}
Thymus	0.0	2.7×10^{-5}	2.1×10^{-3}	1.8×10^{-2}	2.5×10^{-2}	1.9×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.0×10^{-2}
Thyroid	0.0	5.6×10^{-8}	6.1×10^{-5}	2.1×10^{-3}	6.2×10^{-3}	6.1×10^{-3}	5.4×10^{-3}	5.1×10^{-3}	5.1×10^{-3}	4.7×10^{-3}	4.4×10^{-3}	4.1×10^{-3}
Urinary Bl Wall	0.0	0.0	0.0	5.6×10^{-7}	3.1×10^{-5}	1.2×10^{-4}	2.1×10^{-4}	3.2×10^{-4}	3.9×10^{-4}	4.2×10^{-4}	4.5×10^{-4}	4.4×10^{-4}
Uterus	0.0	0.0	1.0×10^{-10}	3.6×10^{-6}	1.1×10^{-4}	3.3×10^{-4}	4.7×10^{-4}	5.4×10^{-4}	6.1×10^{-4}	6.4×10^{-4}	6.6×10^{-4}	7.3×10^{-4}
Whole Body	1.8×10^{-2}	1.8×10^{-2}	1.7×10^{-2}	1.6×10^{-2}	1.1×10^{-2}	7.3×10^{-3}	6.5×10^{-3}	6.3×10^{-3}	5.9×10^{-3}	5.4×10^{-3}	5.1×10^{-3}	4.2×10^{-3}

(a) Lungs include BB, bb, AI, and LN_{TH}.
(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.18. Specific absorbed fraction of photon energy (in kg^{-1}) for the adult male (70 kg) with the lungs as the source

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	3.7×10^{-5}	5.8×10^{-4}	4.1×10^{-3}	1.3×10^{-2}	1.4×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	9.5×10^{-3}	8.6×10^{-3}	8.1×10^{-3}	7.1×10^{-3}
Brain	0.0	0.0	7.5×10^{-9}	1.1×10^{-5}	1.6×10^{-4}	3.4×10^{-4}	4.4×10^{-4}	6.1×10^{-4}	7.3×10^{-4}	7.9×10^{-4}	8.1×10^{-4}	8.2×10^{-4}
Breasts	2.9×10^{-8}	4.7×10^{-4}	4.4×10^{-3}	1.6×10^{-2}	1.6×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.7×10^{-3}	9.1×10^{-3}	7.0×10^{-3}
Gall Bl Wall	0.0	6.7×10^{-8}	2.8×10^{-5}	1.1×10^{-3}	3.5×10^{-3}	3.8×10^{-3}	3.6×10^{-3}	3.5×10^{-3}	3.3×10^{-3}	3.2×10^{-3}	3.2×10^{-3}	2.8×10^{-3}
GI Tract:												
LLI Wall	0.0	0.0	7.0×10^{-10}	3.1×10^{-6}	6.3×10^{-5}	1.4×10^{-4}	2.0×10^{-4}	3.1×10^{-4}	3.8×10^{-4}	4.3×10^{-4}	4.7×10^{-4}	4.7×10^{-4}
SI Wall	0.0	0.0	1.3×10^{-8}	1.8×10^{-5}	3.0×10^{-4}	6.4×10^{-4}	7.2×10^{-4}	8.8×10^{-4}	1.1×10^{-3}	1.0×10^{-3}	9.8×10^{-4}	8.7×10^{-4}
Stomach Wall	1.1×10^{-4}	6.1×10^{-4}	2.1×10^{-3}	5.6×10^{-3}	7.2×10^{-3}	6.2×10^{-3}	5.5×10^{-3}	5.2×10^{-3}	5.1×10^{-3}	4.9×10^{-3}	4.6×10^{-3}	4.0×10^{-3}
ULI Wall	0.0	0.0	3.2×10^{-8}	4.7×10^{-5}	4.1×10^{-4}	8.6×10^{-4}	9.6×10^{-4}	1.1×10^{-3}	1.2×10^{-3}	1.1×10^{-3}	1.1×10^{-3}	1.0×10^{-3}
Heart Wall	9.1×10^{-5}	3.3×10^{-3}	1.6×10^{-2}	3.5×10^{-2}	3.3×10^{-2}	2.3×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.7×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.2×10^{-2}
Kidneys	0.0	1.3×10^{-7}	4.2×10^{-5}	1.1×10^{-3}	3.0×10^{-3}	3.4×10^{-3}	3.2×10^{-3}	3.2×10^{-3}	3.5×10^{-3}	3.3×10^{-3}	3.1×10^{-3}	2.7×19^{-3}
Liver	1.2×10^{-4}	3.0×10^{-3}	9.5×10^{-3}	1.6×10^{-2}	1.4×10^{-2}	1.0×10^{-2}	9.3×10^{-3}	8.7×10^{-3}	8.1×10^{-3}	7.6×10^{-3}	7.1×10^{-3}	5.7×10^{-3}
Lungs[(a)]	9.1×10^{-1}	7.2×10^{-1}	5.0×10^{-1}	2.4×10^{-1}	9.4×10^{-2}	5.3×10^{-2}	5.0×10^{-2}	5.2×10^{-2}	4.7×10^{-2}	4.3×10^{-2}	4.0×10^{-2}	3.1×10^{-2}
ET Airways[(b)]	0.0	2.5×10^{-8}	3.1×10^{-5}	1.5×10^{-3}	4.3×10^{-3}	4.6×10^{-3}	4.1×10^{-3}	4.2×10^{-3}	4.0×10^{-3}	3.9×10^{-3}	3.8×10^{-3}	3.0×10^{-3}
Muscle	1.7×10^{-3}	5.0×10^{-3}	8.0×10^{-3}	9.1×10^{-3}	6.6×10^{-3}	4.7×10^{-3}	4.4×10^{-3}	4.3×10^{-3}	4.1×10^{-3}	3.8×10^{-3}	3.5×10^{-3}	2.9×10^{-3}
Ovaries	0.0	0.0	0.0	1.4×10^{-6}	5.2×10^{-5}	2.0×10^{-4}	3.7×10^{-4}	4.8×10^{-4}	5.2×10^{-4}	5.4×10^{-4}	5.6×10^{-4}	5.6×10^{-4}
Pancreas	2.9×10^{-8}	1.2×10^{-5}	8.4×10^{-4}	6.2×10^{-3}	1.1×10^{-2}	9.3×10^{-3}	7.8×10^{-3}	7.8×10^{-3}	6.8×10^{-3}	6.2×10^{-3}	5.8×10^{-3}	4.8×10^{-3}
Skeleton:												
Active Marrow	1.8×10^{-5}	3.1×10^{-4}	1.5×10^{-3}	4.6×10^{-3}	6.1×10^{-3}	5.6×10^{-3}	5.4×10^{-3}	5.6×10^{-3}	5.1×10^{-3}	4.7×10^{-3}	4.5×10^{-3}	3.8×10^{-3}
Bone Surfaces	4.5×10^{-5}	9.0×10^{-4}	4.7×10^{-3}	1.6×10^{-2}	2.0×10^{-2}	1.0×10^{-2}	5.6×10^{-3}	4.2×10^{-3}	3.8×10^{-3}	3.6×10^{-3}	3.3×10^{-3}	2.8×10^{-3}
Skin	1.1×10^{-6}	3.9×10^{-5}	4.8×10^{-4}	1.9×10^{-3}	2.3×10^{-3}	2.0×10^{-3}	2.0×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	2.1×10^{-3}	1.8×10^{-3}
Spleen	8.5×10^{-5}	8.5×10^{-4}	4.4×10^{-3}	1.1×10^{-2}	1.1×10^{-2}	8.4×10^{-3}	7.7×10^{-3}	7.2×10^{-3}	7.0×10^{-3}	6.5×10^{-3}	6.1×10^{-3}	5.2×10^{-3}
Testes	0.0	0.0	0.0	2.5×10^{-9}	1.1×10^{-6}	1.1×10^{-5}	2.9×10^{-5}	6.4×10^{-5}	9.9×10^{-5}	1.2×10^{-4}	1.3×10^{-4}	1.6×10^{-4}
Thymus	0.0	8.7×10^{-6}	1.3×10^{-3}	1.2×10^{-2}	1.9×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	8.3×10^{-3}
Thyroid	0.0	2.5×10^{-8}	3.1×10^{-5}	1.5×10^{-3}	4.3×10^{-3}	4.6×10^{-3}	4.1×10^{-3}	4.2×10^{-3}	4.0×10^{-3}	3.9×10^{-3}	3.8×10^{-3}	3.0×10^{-3}
Urinary Bl Wall	0.0	0.0	0.0	1.3×10^{-7}	1.2×10^{-5}	4.5×10^{-5}	9.8×10^{-5}	1.7×10^{-4}	2.3×10^{-4}	2.6×10^{-4}	2.9×10^{-4}	3.5×10^{-4}
Uterus	0.0	0.0	0.0	9.9×10^{-7}	5.2×10^{-5}	1.6×10^{-4}	2.7×10^{-4}	3.7×10^{-4}	4.3×10^{-4}	4.6×10^{-4}	4.9×10^{-4}	5.3×10^{-4}
Whole Body	1.4×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	8.6×10^{-3}	5.7×10^{-3}	5.0×10^{-3}	4.9×10^{-3}	4.6×10^{-3}	4.3×10^{-3}	4.0×10^{-3}	3.3×10^{-3}

(a) Lungs include BB, bb, AI, and LN_{TH}.

(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.19. Specific absorbed fraction of photon energy (in kg^{-1}) for the newborn (3.4 kg) with the lungs as the target

Target	Energy, MeV											
	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	3.2×10^{-2}	2.8×10^{-1}	4.8×10^{-1}	3.9×10^{-1}	2.1×10^{-1}	1.2×10^{-1}	1.2×10^{-1}	1.1×10^{-1}	1.1×10^{-1}	9.4×10^{-2}	8.5×10^{-2}	7.2×10^{-2}
Brain	0.0	1.8×10^{-7}	1.3×10^{-4}	3.4×10^{-3}	6.9×10^{-3}	5.6×10^{-3}	5.6×10^{-3}	7.3×10^{-3}	7.9×10^{-3}	7.7×10^{-3}	7.3×10^{-3}	6.4×10^{-3}
Breasts	7.1×10^{-3}	1.4×10^{-1}	3.2×10^{-1}	2.9×10^{-1}	1.4×10^{-1}	8.1×10^{-2}	8.4×10^{-2}	8.5×10^{-2}	8.5×10^{-2}	8.4×10^{-2}	8.0×10^{-2}	6.0×10^{-2}
Gall Bl Cont	2.7×10^{-7}	2.9×10^{-3}	4.4×10^{-2}	1.3×10^{-1}	9.1×10^{-2}	5.7×10^{-2}	5.1×10^{-2}	5.0×10^{-2}	4.7×10^{-2}	4.4×10^{-2}	4.1×10^{-2}	3.4×10^{-2}
GI Tract:												
LLI Cont	0.0	2.8×10^{-6}	6.4×10^{-4}	9.5×10^{-3}	1.3×10^{-2}	1.2×10^{-2}	1.0×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	9.0×10^{-3}
SI Cont	0.0	2.7×10^{-5}	2.6×10^{-3}	2.6×10^{-2}	3.2×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.5×10^{-2}
Stomach Cont	1.3×10^{-4}	2.9×10^{-2}	8.2×10^{-2}	1.5×10^{-1}	9.8×10^{-2}	5.5×10^{-2}	5.3×10^{-2}	5.2×10^{-2}	4.9×10^{-2}	4.4×10^{-2}	4.0×10^{-2}	3.5×10^{-2}
ULI Cont	0.0	4.7×10^{-5}	4.1×10^{-3}	3.1×10^{-2}	3.6×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	2.4×10^{-2}	2.2×10^{-2}	1.9×10^{-2}	1.8×10^{-2}	1.6×10^{-2}
Heart Cont	3.1×10^{-2}	3.3×10^{-1}	7.2×10^{-1}	6.6×10^{-1}	2.9×10^{-1}	1.6×10^{-1}	1.6×10^{-1}	1.6×10^{-1}	1.5×10^{-1}	1.4×10^{-1}	1.3×10^{-1}	1.0×10^{-1}
Heart Wall	8.9×10^{-2}	4.3×10^{-1}	7.1×10^{-1}	5.9×10^{-1}	2.7×10^{-1}	1.5×10^{-1}	1.5×10^{-1}	1.5×10^{-1}	1.4×10^{-1}	1.3×10^{-1}	1.2×10^{-1}	9.1×10^{-2}
Kidneys	2.1×10^{-6}	6.2×10^{-3}	4.4×10^{-2}	1.0×10^{-1}	7.4×10^{-2}	4.6×10^{-2}	4.6×10^{-2}	5.0×10^{-2}	4.1×10^{-2}	4.0×10^{-2}	3.9×10^{-2}	3.1×10^{-2}
Liver	4.3×10^{-2}	2.1×10^{-1}	3.2×10^{-1}	2.8×10^{-1}	1.4×10^{-1}	7.8×10^{-2}	7.7×10^{-2}	8.1×10^{-2}	7.4×10^{-2}	6.6×10^{-2}	6.0×10^{-2}	5.3×10^{-2}
Lungs(a)	15	8.7	4.9	1.8	6.1×10^{-1}	3.4×10^{-1}	3.5×10^{-1}	3.9×10^{-1}	3.6×10^{-1}	3.3×10^{-1}	3.0×10^{-1}	2.3×10^{-1}
ET Airways(b)	1.1×10^{-7}	2.9×10^{-3}	5.1×10^{-2}	1.3×10^{-1}	9.2×10^{-2}	4.9×10^{-2}	4.7×10^{-2}	5.0×10^{-2}	4.6×10^{-2}	4.3×10^{-2}	4.0×10^{-2}	3.1×10^{-2}
Muscle	1.0×10^{-1}	1.9×10^{-1}	2.1×10^{-1}	1.5×10^{-1}	7.3×10^{-2}	4.2×10^{-2}	4.3×10^{-2}	4.5×10^{-2}	4.3×10^{-2}	4.0×10^{-2}	3.7×10^{-2}	2.9×10^{-2}
Ovaries	0.0	5.1×10^{-7}	4.5×10^{-4}	6.4×10^{-3}	1.7×10^{-2}	1.2×10^{-2}	1.3×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	9.6×10^{-3}
Pancreas	1.2×10^{-4}	5.0×10^{-2}	1.9×10^{-1}	2.8×10^{-1}	1.6×10^{-1}	9.1×10^{-2}	9.0×10^{-2}	8.7×10^{-2}	8.3×10^{-2}	7.8×10^{-2}	7.4×10^{-2}	6.4×10^{-2}
Skeleton:												
Active Marrow	3.7×10^{-3}	3.6×10^{-2}	7.9×10^{-2}	8.9×10^{-2}	5.3×10^{-2}	3.1×10^{-2}	3.3×10^{-2}	3.5×10^{-2}	3.2×10^{-2}	2.9×10^{-2}	2.7×10^{-2}	2.3×10^{-2}
Whole Skeleton	4.7×10^{-3}	4.5×10^{-2}	1.0×10^{-1}	1.1×10^{-1}	6.6×10^{-2}	3.9×10^{-2}	4.1×10^{-2}	4.4×10^{-2}	3.9×10^{-2}	3.6×10^{-2}	3.4×10^{-2}	2.9×10^{-2}
Spleen	2.1×10^{-2}	1.7×10^{-1}	3.4×10^{-1}	2.9×10^{-1}	1.5×10^{-1}	7.9×10^{-2}	7.7×10^{-2}	7.9×10^{-2}	7.3×10^{-2}	6.5×10^{-2}	5.8×10^{-2}	4.7×10^{-2}
Testes	0.0	0.0	5.3×10^{-6}	1.0×10^{-3}	2.4×10^{-3}	3.3×10^{-3}	3.7×10^{-3}	4.0×10^{-3}	4.2×10^{-3}	4.3×10^{-3}	4.3×10^{-3}	4.2×10^{-3}
Thymus	1.3×10^{-4}	4.0×10^{-2}	1.7×10^{-1}	2.6×10^{-1}	1.4×10^{-1}	8.1×10^{-2}	7.8×10^{-2}	7.8×10^{-2}	7.8×10^{-2}	6.9×10^{-2}	6.1×10^{-2}	4.9×10^{-2}
Thyroid	1.2×10^{-7}	3.1×10^{-3}	5.3×10^{-2}	1.3×10^{-1}	9.5×10^{-2}	4.9×10^{-2}	4.7×10^{-2}	5.0×10^{-2}	4.6×10^{-2}	4.3×10^{-2}	4.0×10^{-2}	3.1×10^{-2}
Urinary Bl Cont	0.0	1.4×10^{-8}	6.7×10^{-5}	4.7×10^{-3}	6.7×10^{-3}	7.2×10^{-3}	6.6×10^{-3}	6.9×10^{-3}	7.7×10^{-3}	7.7×10^{-3}	7.5×10^{-3}	6.5×10^{-3}
Uterus	0.0	2.7×10^{-7}	3.4×10^{-4}	6.9×10^{-3}	1.6×10^{-2}	1.0×10^{-2}	1.1×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.2×10^{-3}
Whole Body	2.9×10^{-1}	2.9×10^{-1}	2.6×10^{-1}	1.7×10^{-1}	7.9×10^{-2}	4.4×10^{-2}	4.6×10^{-2}	4.8×10^{-2}	4.5×10^{-2}	4.2×10^{-2}	3.9×10^{-2}	3.1×10^{-2}

(a) Lungs include BB, bb, AI, and LN_{TH}.

(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.20. Specific absorbed fraction of photon energy (in kg^{-1}) for the 1-y old (9.8 kg) with the lungs as the target

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	2.0×10^{-3}	5.4×10^{-2}	1.4×10^{-1}	1.6×10^{-1}	9.9×10^{-2}	5.9×10^{-2}	5.4×10^{-2}	5.7×10^{-2}	5.0×10^{-2}	4.6×10^{-2}	4.3×10^{-2}	3.3×10^{-2}
Brain	0.0	1.4×10^{-9}	8.2×10^{-6}	6.1×10^{-4}	2.1×10^{-3}	2.4×10^{-3}	2.4×10^{-3}	3.4×10^{-3}	3.7×10^{-3}	3.6×10^{-3}	3.4×10^{-3}	3.1×10^{-3}
Breasts	9.0×10^{-4}	3.1×10^{-2}	1.1×10^{-1}	1.3×10^{-1}	7.7×10^{-2}	4.5×10^{-2}	4.7×10^{-2}	4.8×10^{-2}	4.5×10^{-2}	4.2×10^{-2}	3.9×10^{-2}	3.3×10^{-2}
Gall Bl Cont	1.7×10^{-10}	1.4×10^{-4}	5.5×10^{-3}	3.0×10^{-2}	3.7×10^{-2}	2.5×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.8×10^{-2}	1.4×10^{-2}
GI Tract:												
LLI Cont	0.0	2.9×10^{-8}	4.9×10^{-5}	2.0×10^{-3}	3.9×10^{-3}	5.0×10^{-3}	4.9×10^{-3}	5.2×10^{-3}	5.3×10^{-3}	5.1×10^{-3}	4.9×10^{-3}	4.1×10^{-3}
SI Cont	0.0	4.1×10^{-7}	2.8×10^{-4}	5.2×10^{-3}	1.2×10^{-2}	9.1×10^{-3}	8.6×10^{-3}	8.6×10^{-3}	8.5×10^{-3}	8.8×10^{-3}	8.7×10^{-3}	6.7×10^{-3}
Stomach Cont	6.0×10^{-4}	5.7×10^{-3}	2.8×10^{-2}	6.4×10^{-2}	5.0×10^{-2}	3.1×10^{-2}	2.8×10^{-2}	2.7×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.2×10^{-2}	1.7×10^{-2}
ULI Cont	0.0	7.2×10^{-7}	4.4×10^{-4}	6.6×10^{-3}	1.4×10^{-2}	1.0×10^{-2}	9.5×10^{-3}	1.0×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.8×10^{-3}	6.9×10^{-3}
Heart Cont	3.9×10^{-3}	9.6×10^{-2}	2.6×10^{-1}	3.1×10^{-1}	1.7×10^{-1}	9.1×10^{-2}	8.7×10^{-2}	8.7×10^{-2}	7.8×10^{-2}	7.1×10^{-2}	6.6×10^{-2}	5.3×10^{-2}
Heart Wall	1.5×10^{-2}	1.2×10^{-1}	2.6×10^{-1}	2.8×10^{-1}	1.5×10^{-1}	8.2×10^{-2}	7.8×10^{-2}	8.2×10^{-2}	7.5×10^{-2}	6.8×10^{-2}	6.2×10^{-2}	4.9×10^{-2}
Kidneys	1.8×10^{-8}	6.7×10^{-4}	1.1×10^{-2}	3.7×10^{-2}	3.3×10^{-2}	2.2×10^{-2}	2.2×10^{-2}	2.1×10^{-2}	2.2×10^{-2}	2.1×10^{-2}	1.9×10^{-2}	1.5×10^{-2}
Liver	1.0×10^{-2}	6.7×10^{-2}	1.2×10^{-1}	1.3×10^{-1}	7.3×10^{-2}	4.3×10^{-2}	4.0×10^{-2}	4.1×10^{-2}	3.9×10^{-2}	3.5×10^{-2}	3.2×10^{-2}	2.6×10^{-2}
Lungs(a)	5.8	3.8	2.3	9.3×10^{-1}	3.2×10^{-1}	1.8×10^{-1}	1.8×10^{-1}	2.0×10^{-1}	1.8×10^{-1}	1.7×10^{-1}	1.5×10^{-1}	1.2×10^{-1}
ET Airways(b)	3.1×10^{-10}	1.9×10^{-4}	1.0×10^{-2}	4.5×10^{-2}	4.3×10^{-2}	2.9×10^{-2}	2.9×10^{-2}	2.3×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	1.6×10^{-2}
Muscle	2.9×10^{-2}	6.5×10^{-2}	8.0×10^{-2}	6.5×10^{-2}	3.6×10^{-2}	2.2×10^{-2}	2.1×10^{-2}	2.2×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.8×10^{-2}	1.4×10^{-2}
Ovaries	0.0	1.2×10^{-9}	2.0×10^{-5}	1.1×10^{-3}	4.6×10^{-3}	5.5×10^{-3}	4.8×10^{-3}	5.2×10^{-3}	4.8×10^{-3}	4.7×10^{-3}	4.6×10^{-3}	4.4×10^{-3}
Pancreas	3.8×10^{-6}	9.4×10^{-3}	5.8×10^{-2}	1.2×10^{-1}	8.0×10^{-2}	4.9×10^{-2}	4.5×10^{-2}	4.0×10^{-2}	3.8×10^{-2}	3.5×10^{-2}	3.3×10^{-2}	2.6×10^{-2}
Skeleton:												
Active Marrow	6.1×10^{-4}	8.0×10^{-3}	2.2×10^{-2}	3.3×10^{-2}	2.6×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.8×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.2×10^{-2}
Whole Skeleton	6.8×10^{-4}	8.8×10^{-3}	2.5×10^{-2}	3.8×10^{-2}	3.0×10^{-2}	1.8×10^{-2}	1.7×10^{-2}	2.0×10^{-2}	1.8×10^{-2}	1.8×10^{-2}	1.7×10^{-2}	1.3×10^{-2}
Spleen	2.7×10^{-5}	4.1×10^{-2}	1.1×10^{-1}	1.2×10^{-1}	7.3×10^{-2}	4.2×10^{-2}	4.1×10^{-2}	4.1×10^{-2}	3.7×10^{-2}	3.4×10^{-2}	3.1×10^{-2}	2.1×10^{-2}
Testes	0.0	0.0	5.2×10^{-8}	1.2×10^{-4}	5.7×10^{-4}	1.3×10^{-3}	1.4×10^{-3}	1.6×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}
Thymus	4.5×10^{-6}	7.0×10^{-3}	5.7×10^{-2}	1.2×10^{-1}	8.5×10^{-2}	4.8×10^{-2}	4.4×10^{-2}	4.4×10^{-2}	4.2×10^{-2}	4.0×10^{-2}	3.8×10^{-2}	2.9×10^{-2}
Thyroid	3.6×10^{-10}	2.1×10^{-4}	1.2×10^{-2}	5.0×10^{-2}	4.7×10^{-2}	2.9×10^{-2}	2.9×10^{-2}	2.3×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	1.6×10^{-2}
Urinary Bl Cont	0.0	0.0	1.6×10^{-6}	4.4×10^{-4}	1.9×10^{-3}	2.6×10^{-3}	2.4×10^{-3}	3.1×10^{-3}	2.9×10^{-3}	2.8×10^{-3}	2.8×10^{-3}	2.9×10^{-3}
Uterus	0.0	4.4×10^{-10}	1.3×10^{-5}	1.3×10^{-3}	4.3×10^{-3}	4.9×10^{-3}	4.5×10^{-3}	5.2×10^{-3}	5.2×10^{-3}	5.0×10^{-3}	4.8×10^{-3}	4.2×10^{-3}
Whole Body	1.2×10^{-1}	1.1×10^{-1}	1.1×10^{-1}	7.7×10^{-2}	4.1×10^{-2}	2.3×10^{-2}	2.3×10^{-2}	2.3×10^{-2}	2.2×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.5×10^{-2}

(a) Lungs include BB, bb, AI, and LN_{TH}.

(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.21. Specific absorbed fraction of photon energy (in kg^{-1}) for the 5-y old (19 kg) with the lungs as the target

Target	Energy, MeV 0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	1.8×10^{-4}	1.4×10^{-2}	5.3×10^{-2}	7.8×10^{-2}	5.6×10^{-2}	3.6×10^{-2}	3.3×10^{-2}	3.1×10^{-2}	3.1×10^{-2}	2.8×10^{-2}	2.5×10^{-2}	1.8×10^{-2}
Brain	0.0	0.0	1.1×10^{-6}	1.5×10^{-4}	8.7×10^{-4}	1.4×10^{-3}	1.5×10^{-3}	2.0×10^{-3}	2.1×10^{-3}	2.0×10^{-3}	1.9×10^{-3}	2.1×10^{-3}
Breasts	1.2×10^{-4}	1.3×10^{-2}	5.6×10^{-2}	8.2×10^{-2}	5.2×10^{-2}	3.2×10^{-2}	3.2×10^{-2}	3.3×10^{-2}	3.1×10^{-2}	2.8×10^{-2}	2.5×10^{-2}	2.2×10^{-2}
Gall Bl Cont	4.6×10^{-8}	2.0×10^{-5}	1.5×10^{-3}	1.2×10^{-2}	1.9×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	9.7×10^{-3}	7.9×10^{-3}
GI Tract:												
LLI Cont	0.0	1.2×10^{-10}	2.2×10^{-6}	3.2×10^{-4}	1.7×10^{-3}	1.9×10^{-3}	1.9×10^{-3}	2.0×10^{-3}	2.2×10^{-3}	2.3×10^{-3}	2.3×10^{-3}	2.1×10^{-3}
SI Cont	0.0	4.1×10^{-9}	1.8×10^{-5}	1.6×10^{-3}	4.0×10^{-3}	4.2×10^{-3}	4.1×10^{-3}	4.6×10^{-3}	4.3×10^{-3}	4.2×10^{-3}	4.1×10^{-3}	3.6×10^{-3}
Stomach Cont	2.8×10^{-6}	1.3×10^{-3}	8.8×10^{-3}	2.6×10^{-2}	2.7×10^{-2}	1.8×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.1×10^{-2}
ULI Cont	0.0	6.6×10^{-9}	3.1×10^{-5}	2.0×10^{-3}	4.2×10^{-3}	5.4×10^{-3}	4.8×10^{-3}	4.9×10^{-3}	4.9×10^{-3}	4.9×10^{-3}	4.7×10^{-3}	3.8×10^{-3}
Heart Cont	6.7×10^{-4}	3.0×10^{-2}	1.1×10^{-1}	1.7×10^{-1}	1.1×10^{-1}	6.1×10^{-2}	5.5×10^{-2}	5.4×10^{-2}	4.9×10^{-2}	4.5×10^{-2}	4.2×10^{-2}	3.3×10^{-2}
Heart Wall	3.4×10^{-3}	4.7×10^{-2}	1.2×10^{-1}	1.6×10^{-1}	9.8×10^{-2}	5.7×10^{-2}	5.2×10^{-2}	5.1×10^{-2}	4.6×10^{-2}	4.2×10^{-2}	3.9×10^{-2}	3.0×10^{-2}
Kidneys	1.7×10^{-7}	4.5×10^{-5}	2.4×10^{-3}	1.1×10^{-2}	1.7×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.8×10^{-3}	7.9×10^{-3}
Liver	2.6×10^{-3}	2.5×10^{-2}	5.2×10^{-2}	6.4×10^{-2}	4.3×10^{-2}	2.6×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.2×10^{-2}	2.0×10^{-2}	1.8×10^{-2}	1.4×10^{-2}
Lungs[(a)]	3.0	2.1	1.3	5.7×10^{-1}	2.1×10^{-1}	1.2×10^{-1}	1.2×10^{-1}	1.2×10^{-1}	1.2×10^{-1}	1.0×10^{-1}	9.5×10^{-2}	7.5×10^{-2}
ET Airways[(b)]	0.0	2.6×10^{-5}	2.2×10^{-3}	1.7×10^{-2}	2.3×10^{-2}	1.7×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.0×10^{-2}
Muscle	1.1×10^{-2}	2.8×10^{-2}	3.7×10^{-2}	3.3×10^{-2}	2.0×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.8×10^{-3}	8.2×10^{-3}
Ovaries	0.0	0.0	5.0×10^{-7}	3.0×10^{-4}	1.6×10^{-3}	2.3×10^{-3}	2.0×10^{-3}	2.6×10^{-3}	2.8×10^{-3}	2.7×10^{-3}	2.5×10^{-3}	2.3×10^{-3}
Pancreas	6.1×10^{-5}	1.6×10^{-3}	1.6×10^{-2}	5.2×10^{-2}	4.6×10^{-2}	2.8×10^{-2}	2.5×10^{-2}	2.4×10^{-2}	2.2×10^{-2}	2.1×10^{-2}	1.9×10^{-2}	1.5×10^{-2}
Skeleton:												
Active Marrow	2.3×10^{-4}	2.9×10^{-3}	9.4×10^{-3}	1.7×10^{-2}	1.6×10^{-2}	1.0×10^{-2}	9.9×10^{-3}	1.1×10^{-2}	1.0×10^{-2}	9.6×10^{-3}	9.1×10^{-3}	7.4×10^{-3}
Whole Skeleton	2.0×10^{-4}	2.5×10^{-3}	8.2×10^{-3}	1.5×10^{-2}	1.4×10^{-2}	9.3×10^{-3}	9.0×10^{-3}	1.0×10^{-2}	9.6×10^{-3}	8.9×10^{-3}	8.3×10^{-3}	6.8×10^{-3}
Spleen	5.5×10^{-4}	1.2×10^{-2}	4.0×10^{-2}	5.8×10^{-2}	4.0×10^{-2}	2.5×10^{-2}	2.4×10^{-2}	2.2×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.9×10^{-2}	1.4×10^{-2}
Testes	0.0	0.0	2.5×10^{-10}	7.2×10^{-6}	1.7×10^{-4}	2.5×10^{-4}	3.4×10^{-4}	4.8×10^{-4}	5.8×10^{-4}	6.5×10^{-4}	7.0×10^{-4}	8.2×10^{-4}
Thymus	1.7×10^{-7}	1.8×10^{-3}	2.3×10^{-2}	7.0×10^{-2}	5.6×10^{-2}	3.5×10^{-2}	3.2×10^{-2}	3.1×10^{-2}	2.9×10^{-2}	2.6×10^{-2}	2.4×10^{-2}	2.1×10^{-2}
Thyroid	0.0	3.0×10^{-5}	2.5×10^{-3}	1.9×10^{-2}	2.5×10^{-2}	1.7×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.0×10^{-2}
Urinary Bl Cont	0.0	0.0	2.1×10^{-8}	6.2×10^{-5}	6.0×10^{-4}	7.4×10^{-4}	9.0×10^{-4}	1.1×10^{-3}	1.3×10^{-3}	1.3×10^{-3}	1.4×10^{-3}	1.5×10^{-3}
Uterus	0.0	0.0	2.9×10^{-7}	2.4×10^{-4}	1.2×10^{-3}	1.8×10^{-3}	1.8×10^{-3}	2.4×10^{-3}	2.4×10^{-3}	2.4×10^{-3}	2.3×10^{-3}	2.2×10^{-3}
Whole Body	5.7×10^{-2}	5.6×10^{-2}	5.3×10^{-2}	4.0×10^{-2}	2.4×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	8.9×10^{-3}

(a) Lungs include BB, bb, AI, and LN_{TH}.
(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.22. Specific absorbed fraction of photon energy (in kg^{-1}) for the 10-y old (32 kg) with the lungs as the target

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	4.9×10^{-6}	4.7×10^{-3}	2.0×10^{-2}	4.2×10^{-2}	3.5×10^{-2}	2.4×10^{-2}	2.1×10^{-2}	2.1×10^{-2}	1.9×10^{-2}	1.7×10^{-2}	1.5×10^{-2}	1.1×10^{-2}
Brain	0.0	0.0	1.7×10^{-7}	8.7×10^{-5}	4.9×10^{-4}	8.7×10^{-4}	9.1×10^{-4}	1.2×10^{-3}	1.4×10^{-3}	1.5×10^{-3}	1.5×10^{-3}	1.4×10^{-3}
Breasts	3.2×10^{-5}	5.9×10^{-3}	3.2×10^{-2}	5.7×10^{-2}	3.7×10^{-2}	2.3×10^{-2}	2.3×10^{-2}	2.4×10^{-2}	2.2×10^{-2}	2.1×10^{-2}	2.0×10^{-2}	1.6×10^{-2}
Gall Bl Cont	1.3×10^{-9}	2.0×10^{-6}	3.6×10^{-4}	4.7×10^{-3}	1.0×10^{-2}	8.4×10^{-3}	7.6×10^{-3}	7.8×10^{-3}	7.4×10^{-3}	6.6×10^{-3}	6.1×10^{-3}	5.7×10^{-3}
GI Tract:												
LLI Cont	0.0	0.0	1.4×10^{-7}	7.9×10^{-5}	4.5×10^{-4}	1.0×10^{-3}	1.0×10^{-3}	1.2×10^{-3}	1.4×10^{-3}	1.5×10^{-3}	1.4×10^{-3}	1.3×10^{-3}
SI Cont	0.0	0.0	1.5×10^{-6}	3.5×10^{-4}	1.6×10^{-3}	2.2×10^{-3}	2.2×10^{-3}	2.5×10^{-3}	2.4×10^{-3}	2.4×10^{-3}	2.4×10^{-3}	2.0×10^{-3}
Stomach Cont	1.7×10^{-5}	3.8×10^{-4}	3.5×10^{-3}	1.3×10^{-2}	1.6×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	9.6×10^{-3}	8.8×10^{-3}	6.6×10^{-3}
ULI Cont	0.0	0.0	2.7×10^{-6}	5.0×10^{-4}	2.0×10^{-3}	2.7×10^{-3}	2.8×10^{-3}	2.8×10^{-3}	2.8×10^{-3}	2.7×10^{-3}	2.5×10^{-3}	2.0×10^{-3}
Heart Cont	2.0×10^{-4}	1.3×10^{-2}	5.7×10^{-2}	1.0×10^{-1}	7.5×10^{-2}	4.4×10^{-2}	3.9×10^{-2}	3.8×10^{-2}	3.5×10^{-2}	3.2×10^{-2}	2.9×10^{-2}	2.5×10^{-2}
Heart Wall	1.4×10^{-3}	2.2×10^{-2}	6.6×10^{-2}	9.6×10^{-2}	6.9×10^{-2}	4.1×10^{-2}	3.7×10^{-2}	3.5×10^{-2}	3.4×10^{-2}	3.0×10^{-2}	2.7×10^{-2}	2.2×10^{-2}
Kidneys	0.0	5.1×10^{-6}	6.0×10^{-4}	5.3×10^{-3}	9.1×10^{-3}	7.9×10^{-3}	7.3×10^{-3}	6.8×10^{-3}	7.1×10^{-3}	6.3×10^{-3}	5.7×10^{-3}	5.1×10^{-3}
Liver	8.7×10^{-4}	1.2×10^{-2}	2.9×10^{-2}	4.0×10^{-2}	2.9×10^{-2}	1.8×10^{-2}	1.7×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.1×10^{-2}
Lungs(a)	2.0	1.4	9.4×10^{-1}	4.2×10^{-1}	1.6×10^{-1}	8.7×10^{-2}	8.5×10^{-2}	8.9×10^{-2}	8.2×10^{-2}	7.4×10^{-2}	6.8×10^{-2}	5.5×10^{-2}
ET Airways(b)	0.0	2.5×10^{-6}	4.6×10^{-4}	7.1×10^{-3}	1.3×10^{-2}	1.1×10^{-2}	9.4×10^{-3}	8.8×10^{-3}	8.2×10^{-3}	8.0×10^{-3}	7.9×10^{-3}	6.8×10^{-3}
Muscle	5.6×10^{-3}	1.5×10^{-2}	2.2×10^{-2}	2.1×10^{-2}	1.3×10^{-2}	8.3×10^{-3}	8.1×10^{-3}	8.0×10^{-3}	7.5×10^{-3}	7.0×10^{-3}	6.5×10^{-3}	5.4×10^{-3}
Ovaries	0.0	0.0	1.5×10^{-8}	4.8×10^{-5}	4.2×10^{-4}	9.4×10^{-4}	1.1×10^{-3}	1.2×10^{-3}	1.5×10^{-3}	1.5×10^{-3}	1.5×10^{-3}	1.3×10^{-3}
Pancreas	1.8×10^{-6}	1.9×10^{-4}	5.5×10^{-3}	2.4×10^{-2}	2.6×10^{-2}	1.9×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.0×10^{-2}
Skeleton:												
Active Marrow	7.5×10^{-5}	1.2×10^{-3}	4.8×10^{-3}	1.1×10^{-2}	1.1×10^{-2}	8.1×10^{-3}	7.8×10^{-3}	8.2×10^{-3}	7.8×10^{-3}	7.0×10^{-3}	6.5×10^{-3}	5.7×10^{-3}
Whole Skeleton	5.6×10^{-5}	8.4×10^{-4}	3.4×10^{-3}	8.0×10^{-3}	8.5×10^{-3}	6.2×10^{-3}	6.0×10^{-3}	6.4×10^{-3}	6.1×10^{-3}	5.5×10^{-3}	5.0×10^{-3}	4.5×10^{-3}
Spleen	7.8×10^{-4}	4.7×10^{-3}	1.7×10^{-2}	3.1×10^{-2}	2.6×10^{-2}	1.7×10^{-2}	1.5×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	9.4×10^{-3}
Testes	0.0	0.0	0.0	5.5×10^{-7}	3.3×10^{-5}	1.2×10^{-4}	2.4×10^{-4}	3.3×10^{-4}	4.2×10^{-4}	4.7×10^{-4}	4.8×10^{-4}	4.5×10^{-4}
Thymus	2.1×10^{-9}	4.0×10^{-4}	9.7×10^{-3}	4.4×10^{-2}	4.0×10^{-2}	2.6×10^{-2}	2.4×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	1.9×10^{-2}	1.8×10^{-2}	1.4×10^{-2}
Thyroid	0.0	2.8×10^{-6}	5.2×10^{-4}	8.0×10^{-3}	1.4×10^{-2}	1.1×10^{-2}	9.4×10^{-3}	8.8×10^{-3}	8.2×10^{-3}	8.0×10^{-3}	7.9×10^{-3}	6.8×10^{-3}
Urinary Bl Cont	0.0	0.0	3.4×10^{-10}	7.2×10^{-6}	1.7×10^{-4}	3.0×10^{-4}	4.0×10^{-4}	5.2×10^{-4}	6.4×10^{-4}	7.2×10^{-4}	7.8×10^{-4}	8.5×10^{-4}
Uterus	0.0	0.0	7.6×10^{-9}	3.6×10^{-5}	4.9×10^{-4}	7.5×10^{-4}	9.2×10^{-4}	1.0×10^{-3}	1.1×10^{-3}	1.1×10^{-3}	1.2×10^{-3}	1.3×10^{-3}
Whole Body	3.4×10^{-2}	3.4×10^{-2}	3.2×10^{-2}	2.5×10^{-2}	1.6×10^{-2}	9.6×10^{-3}	9.0×10^{-3}	8.9×10^{-3}	8.4×10^{-3}	7.7×10^{-3}	7.2×10^{-3}	6.0×10^{-3}

(a) Lungs include BB, bb, AI, and LN_{TH}.

(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.23. Specific absorbed fraction of photon energy (in kg^{-1}) for the 15-y old or adult female (55–58 kg) with the lungs as the target

	Energy, MeV											
Target	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	2.9×10^{-8}	8.2×10^{-4}	6.7×10^{-3}	2.1×10^{-2}	2.2×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	8.6×10^{-3}
Brain	0.0	0.0	1.6×10^{-8}	1.9×10^{-5}	2.1×10^{-4}	4.4×10^{-4}	6.2×10^{-4}	7.7×10^{-4}	8.9×10^{-4}	9.6×10^{-4}	9.8×10^{-4}	9.6×10^{-4}
Breasts	5.4×10^{-6}	2.7×10^{-4}	4.4×10^{-3}	1.8×10^{-2}	1.9×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	8.2×10^{-3}
Gall Bl Cont	0.0	8.8×10^{-8}	4.5×10^{-5}	1.6×10^{-3}	4.9×10^{-3}	5.0×10^{-3}	4.7×10^{-3}	4.4×10^{-3}	4.0×10^{-3}	3.8×10^{-3}	3.7×10^{-3}	3.5×10^{-3}
GI Tract:												
LLI Cont	0.0	0.0	6.5×10^{-9}	1.3×10^{-5}	2.1×10^{-4}	4.9×10^{-4}	4.7×10^{-4}	5.4×10^{-4}	7.3×10^{-4}	7.8×10^{-4}	7.7×10^{-4}	7.3×10^{-4}
SI Cont	0.0	0.0	8.2×10^{-8}	7.2×10^{-5}	7.5×10^{-4}	1.1×10^{-3}	1.2×10^{-3}	1.2×10^{-3}	1.4×10^{-3}	1.5×10^{-3}	1.5×10^{-3}	1.4×10^{-3}
Stomach Cont	5.8×10^{-6}	1.7×10^{-4}	1.8×10^{-3}	7.8×10^{-3}	1.0×10^{-2}	8.0×10^{-3}	6.8×10^{-3}	7.1×10^{-3}	6.8×10^{-3}	6.3×10^{-3}	5.8×10^{-3}	4.7×10^{-3}
ULI Cont	0.0	0.0	1.6×10^{-7}	9.7×10^{-5}	8.2×10^{-4}	1.5×10^{-3}	1.5×10^{-3}	1.7×10^{-3}	1.8×10^{-3}	1.9×10^{-3}	1.9×10^{-3}	1.6×10^{-3}
Heart Cont	3.6×10^{-4}	4.0×10^{-3}	2.2×10^{-2}	5.7×10^{-2}	5.0×10^{-2}	3.3×10^{-2}	2.8×10^{-2}	2.6×10^{-2}	2.4×10^{-2}	2.1×10^{-2}	1.9×10^{-2}	1.7×10^{-2}
Heart Wall	2.7×10^{-4}	7.7×10^{-3}	2.9×10^{-2}	5.7×10^{-2}	4.8×10^{-2}	3.0×10^{-2}	2.6×10^{-2}	2.5×10^{-2}	2.3×10^{-2}	2.1×10^{-2}	2.0×10^{-2}	1.6×10^{-2}
Kidneys	3.4×10^{-10}	5.8×10^{-7}	1.1×10^{-4}	2.2×10^{-3}	4.7×10^{-3}	5.0×10^{-3}	4.9×10^{-3}	4.7×10^{-3}	4.5×10^{-3}	4.2×10^{-3}	4.0×10^{-3}	3.6×10^{-3}
Liver	2.5×10^{-4}	5.5×10^{-3}	1.6×10^{-2}	2.6×10^{-2}	2.1×10^{-2}	1.4×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.5×10^{-3}	7.7×10^{-3}
Lungs[(a)]	1.4	1.1	7.0×10^{-1}	3.2×10^{-1}	1.2×10^{-1}	6.9×10^{-2}	6.7×10^{-2}	7.0×10^{-2}	6.4×10^{-2}	5.8×10^{-2}	5.4×10^{-2}	4.3×10^{-2}
ET Airways[(b)]	0.0	5.6×10^{-8}	6.1×10^{-5}	2.1×10^{-3}	6.2×10^{-3}	6.1×10^{-3}	5.4×10^{-3}	5.1×10^{-3}	5.1×10^{-3}	4.7×10^{-3}	4.4×10^{-3}	4.1×10^{-3}
Muscle	2.9×10^{-3}	8.2×10^{-3}	1.3×10^{-2}	1.4×10^{-2}	9.4×10^{-3}	6.2×10^{-3}	5.8×10^{-3}	5.7×10^{-3}	5.3×10^{-3}	4.9×10^{-3}	4.6×10^{-3}	3.8×10^{-3}
Ovaries	0.0	0.0	2.8×10^{-10}	5.7×10^{-6}	1.7×10^{-4}	3.7×10^{-4}	4.5×10^{-4}	6.2×10^{-4}	7.2×10^{-4}	7.5×10^{-4}	7.6×10^{-4}	7.7×10^{-4}
Pancreas	1.7×10^{-7}	3.7×10^{-5}	1.7×10^{-3}	1.2×10^{-2}	1.7×10^{-2}	1.3×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	9.0×10^{-3}	8.0×10^{-3}	6.1×10^{-3}
Skeleton:												
Active Marrow	1.8×10^{-5}	2.7×10^{-4}	1.8×10^{-3}	5.9×10^{-3}	7.8×10^{-3}	6.4×10^{-3}	6.1×10^{-3}	6.4×10^{-3}	5.7×10^{-3}	5.3×10^{-3}	4.9×10^{-3}	4.2×10^{-3}
Whole Skeleton	9.9×10^{-6}	1.6×10^{-4}	1.1×10^{-3}	3.9×10^{-3}	5.3×10^{-3}	4.3×10^{-3}	4.1×10^{-3}	4.4×10^{-3}	3.9×10^{-3}	3.7×10^{-3}	3.5×10^{-3}	2.9×10^{-3}
Spleen	1.4×10^{-4}	1.4×10^{-3}	6.8×10^{-3}	1.7×10^{-2}	1.6×10^{-2}	1.2×10^{-2}	1.0×10^{-2}	9.7×10^{-3}	9.3×10^{-3}	8.5×10^{-3}	7.9×10^{-3}	6.7×10^{-3}
Testes	0.0	0.0	0.0	2.0×10^{-8}	4.4×10^{-6}	2.7×10^{-5}	6.2×10^{-5}	1.3×10^{-4}	1.7×10^{-4}	1.9×10^{-4}	2.1×10^{-4}	2.4×10^{-4}
Thymus	0.0	3.0×10^{-5}	2.4×10^{-3}	2.0×10^{-2}	2.7×10^{-2}	1.9×10^{-2}	1.6×10^{-2}	1.6×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.0×10^{-2}
Thyroid	0.0	6.3×10^{-8}	6.9×10^{-5}	2.3×10^{-3}	6.7×10^{-3}	6.2×10^{-3}	5.4×10^{-3}	5.1×10^{-3}	5.1×10^{-3}	4.7×10^{-3}	4.4×10^{-3}	4.1×10^{-3}
Urinary Bl Cont	0.0	0.0	0.0	5.8×10^{-7}	3.3×10^{-5}	1.0×10^{-4}	1.9×10^{-4}	3.0×10^{-4}	4.2×10^{-4}	4.6×10^{-4}	4.7×10^{-4}	4.8×10^{-4}
Uterus	0.0	0.0	1.1×10^{-10}	4.1×10^{-6}	1.2×10^{-4}	3.3×10^{-4}	4.7×10^{-4}	5.4×10^{-4}	6.1×10^{-4}	6.4×10^{-4}	6.6×10^{-4}	7.3×10^{-4}
Whole Body	2.0×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.6×10^{-2}	1.1×10^{-2}	6.9×10^{-3}	6.4×10^{-3}	6.3×10^{-3}	5.9×10^{-3}	5.4×10^{-3}	5.1×10^{-3}	4.2×10^{-3}

(a) Lungs include BB, bb, AI, and LN_{TH}.

(b) ET airways include ET_1, ET_2, and LN_{ET}.

Table G.24. Specific absorbed fraction of photon energy (in kg^{-1}) for the adult male (70 kg) with the lungs as the target

Target	Energy, MeV											
	0.010	0.015	0.020	0.030	0.050	0.100	0.200	0.500	1.000	1.500	2.000	4.000
Adrenals	4.1×10^{-5}	6.5×10^{-4}	4.6×10^{-3}	1.5×10^{-2}	1.5×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	9.5×10^{-3}	8.6×10^{-3}	8.1×10^{-3}	7.1×10^{-3}
Brain	0.0	0.0	8.4×10^{-9}	1.2×10^{-5}	1.8×10^{-4}	3.4×10^{-4}	4.4×10^{-4}	6.1×10^{-4}	7.3×10^{-4}	7.8×10^{-4}	8.1×10^{-4}	8.2×10^{-4}
Breasts	3.3×10^{-8}	5.3×10^{-4}	5.0×10^{-3}	1.8×10^{-2}	1.7×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	9.7×10^{-3}	9.1×10^{-3}	7.0×10^{-3}
Gall Bl Cont	0.0	1.1×10^{-8}	1.4×10^{-5}	9.9×10^{-4}	2.9×10^{-3}	3.7×10^{-3}	3.3×10^{-3}	3.1×10^{-3}	3.0×10^{-3}	3.0×10^{-3}	2.9×10^{-3}	2.5×10^{-3}
GI Tract:												
LLI Cont	0.0	0.0	8.5×10^{-10}	4.2×10^{-6}	7.2×10^{-5}	1.8×10^{-4}	2.9×10^{-4}	4.0×10^{-4}	4.6×10^{-4}	4.9×10^{-4}	5.0×10^{-4}	5.3×10^{-4}
SI Cont	0.0	0.0	1.5×10^{-6}	2.0×10^{-5}	3.2×10^{-4}	6.4×10^{-4}	7.2×10^{-4}	8.8×10^{-4}	1.1×10^{-3}	1.0×10^{-3}	9.8×10^{-4}	8.7×10^{-4}
Stomach Cont	9.0×10^{-8}	2.2×10^{-5}	1.1×10^{-3}	5.1×10^{-3}	7.0×10^{-3}	5.8×10^{-3}	5.0×10^{-3}	5.0×10^{-3}	5.0×10^{-3}	4.7×10^{-3}	4.4×10^{-3}	3.6×10^{-3}
ULI Cont	0.0	0.0	3.0×10^{-8}	3.8×10^{-5}	4.0×10^{-4}	8.9×10^{-4}	8.7×10^{-4}	1.1×10^{-3}	1.1×10^{-3}	1.2×10^{-3}	1.3×10^{-3}	1.1×10^{-3}
Heart Cont	1.2×10^{-4}	1.7×10^{-3}	1.2×10^{-2}	3.7×10^{-2}	3.7×10^{-2}	2.4×10^{-2}	2.1×10^{-2}	2.0×10^{-2}	1.8×10^{-2}	1.7×10^{-2}	1.5×10^{-2}	1.2×10^{-2}
Heart Wall	1.0×10^{-4}	3.7×10^{-3}	1.8×10^{-2}	3.9×10^{-2}	3.5×10^{-2}	2.3×10^{-2}	2.0×10^{-2}	1.9×10^{-2}	1.7×10^{-2}	1.6×10^{-2}	1.5×10^{-2}	1.2×10^{-2}
Kidneys	0.0	1.5×10^{-7}	4.8×10^{-5}	1.2×10^{-3}	3.2×10^{-3}	3.4×10^{-3}	3.2×10^{-3}	3.2×10^{-3}	3.5×10^{-3}	3.3×10^{-3}	3.1×10^{-3}	2.7×10^{-3}
Liver	1.3×10^{-4}	3.3×10^{-3}	1.1×10^{-2}	1.8×10^{-2}	1.5×10^{-2}	1.1×10^{-2}	9.3×10^{-3}	8.7×10^{-3}	8.1×10^{-3}	7.6×10^{-3}	7.1×10^{-3}	5.7×10^{-3}
Lungs$^{(a)}$	9.1×10^{-1}	7.2×10^{-1}	5.0×10^{-1}	2.4×10^{-1}	9.4×10^{-2}	5.3×10^{-2}	5.0×10^{-2}	5.2×10^{-2}	4.7×10^{-2}	4.3×10^{-2}	4.0×10^{-2}	3.1×10^{-2}
ET Airways$^{(b)}$	0.0	2.5×10^{-8}	3.1×10^{-5}	1.5×10^{-3}	4.3×10^{-3}	4.6×10^{-3}	4.1×10^{-3}	4.2×10^{-3}	4.0×10^{-3}	3.9×10^{-3}	3.8×10^{-3}	3.0×10^{-3}
Muscle	1.9×10^{-3}	5.6×10^{-3}	9.0×10^{-3}	1.0×10^{-2}	7.1×10^{-3}	4.7×10^{-3}	4.4×10^{-3}	4.3×10^{-3}	4.1×10^{-3}	3.8×10^{-3}	3.5×10^{-3}	2.9×10^{-3}
Ovaries	0.0	0.0	0.0	1.6×10^{-6}	5.6×10^{-5}	2.0×10^{-4}	3.7×10^{-4}	4.8×10^{-4}	5.2×10^{-4}	5.4×10^{-4}	5.6×10^{-4}	5.6×10^{-4}
Pancreas	3.3×10^{-8}	1.3×10^{-5}	9.4×10^{-4}	7.0×10^{-3}	1.1×10^{-2}	9.4×10^{-3}	7.8×10^{-3}	7.8×10^{-3}	6.8×10^{-3}	6.2×10^{-3}	5.8×10^{-3}	4.8×10^{-3}
Skeleton:												
Active Marrow	1.9×10^{-5}	3.9×10^{-4}	1.8×10^{-3}	5.1×10^{-3}	6.7×10^{-3}	5.5×10^{-3}	5.3×10^{-3}	5.6×10^{-3}	5.1×10^{-3}	4.7×10^{-3}	4.5×10^{-3}	3.8×10^{-3}
Whole Skeleton	9.4×10^{-6}	2.0×10^{-4}	9.6×10^{-4}	2.9×10^{-3}	4.0×10^{-3}	3.4×10^{-3}	3.2×10^{-3}	3.5×10^{-3}	3.2×10^{-3}	3.0×10^{-3}	2.8×10^{-3}	2.4×10^{-3}
Spleen	9.5×10^{-5}	9.5×10^{-4}	4.9×10^{-3}	1.2×10^{-2}	1.2×10^{-2}	8.5×10^{-3}	7.7×10^{-3}	7.2×10^{-3}	7.0×10^{-3}	6.5×10^{-3}	6.1×10^{-3}	5.2×10^{-3}
Testes	0.0	0.0	0.0	2.8×10^{-9}	1.2×10^{-6}	1.1×10^{-5}	2.9×10^{-5}	6.4×10^{-5}	9.9×10^{-5}	1.2×10^{-4}	1.3×10^{-4}	1.6×10^{-4}
Thymus	0.0	9.8×10^{-6}	1.4×10^{-3}	1.4×10^{-2}	2.1×10^{-2}	1.6×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.2×10^{-2}	1.1×10^{-2}	1.0×10^{-2}	8.3×10^{-3}
Thyroid	0.0	2.8×10^{-8}	3.5×10^{-5}	1.7×10^{-3}	4.6×10^{-3}	4.6×10^{-3}	4.1×10^{-3}	4.2×10^{-3}	4.0×10^{-3}	3.9×10^{-3}	3.8×10^{-3}	3.0×10^{-3}
Urinary Bl Cont	0.0	0.0	0.0	1.3×10^{-7}	1.3×10^{-5}	4.2×10^{-5}	6.6×10^{-5}	1.2×10^{-4}	1.8×10^{-4}	2.2×10^{-4}	2.5×10^{-4}	3.5×10^{-4}
Uterus	0.0	0.0	0.0	1.1×10^{-6}	5.7×10^{-5}	1.6×10^{-4}	2.7×10^{-4}	3.7×10^{-4}	4.3×10^{-4}	4.6×10^{-4}	4.9×10^{-4}	5.3×10^{-4}
Whole Body	1.5×10^{-2}	1.5×10^{-2}	1.4×10^{-2}	1.2×10^{-2}	8.2×10^{-3}	5.4×10^{-3}	5.0×10^{-3}	4.9×10^{-3}	4.6×10^{-3}	4.3×10^{-3}	4.0×10^{-3}	3.3×10^{-3}

(a) Lungs include BB, bb, AI, and LN_{TH}.
(b) ET airways include ET_1, ET_2, and LN_{ET}.

ANNEXE H. ABSORBED FRACTIONS FOR ALPHA, ELECTRON, AND BETA EMISSIONS

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Contents

H.1. Introduction

(H1) In this annexe, the methods used in this report to calculate absorbed fractions for sources of short-range radiations within the respiratory tract are briefly described. The resulting values of AF(T←S) that are recommended for substitution in the dosimetric model are shown graphically as functions of radiation energy in Chapter 8. Tables H.1–H.6 give the values of AF(T←S) calculated for discrete values of the mean energy of short-range particulate radiations of each type. Algebraic formulae derived to approximate these calculated absorbed fractions and to interpolate between them are given in Tables H.7–H.10. These formulae are provided for ease of calculation to evaluate AF(T←S) adequately for any radionuclide that emits alpha particles, electrons, or beta particles (negatrons or positrons). Other approximations may also be appropriate.

(H2) The average fraction of energy absorbed in target tissue T per emission of radiation R in source S is given by:

$$\mathrm{AF}(\mathrm{T} \leftarrow \mathrm{S})_\mathrm{R} = \frac{\mathrm{E}(\mathrm{T} \leftarrow \mathrm{S})_\mathrm{R}}{\mathrm{E}_\mathrm{R}} \qquad \text{(H1)}$$

where $\mathrm{E}(\mathrm{T} \leftarrow \mathrm{S})_\mathrm{R}$ is the average energy (in MeV) absorbed by the target tissue in T per emission of radiation R in source S, and E_R is the energy (in MeV) of the radiation.

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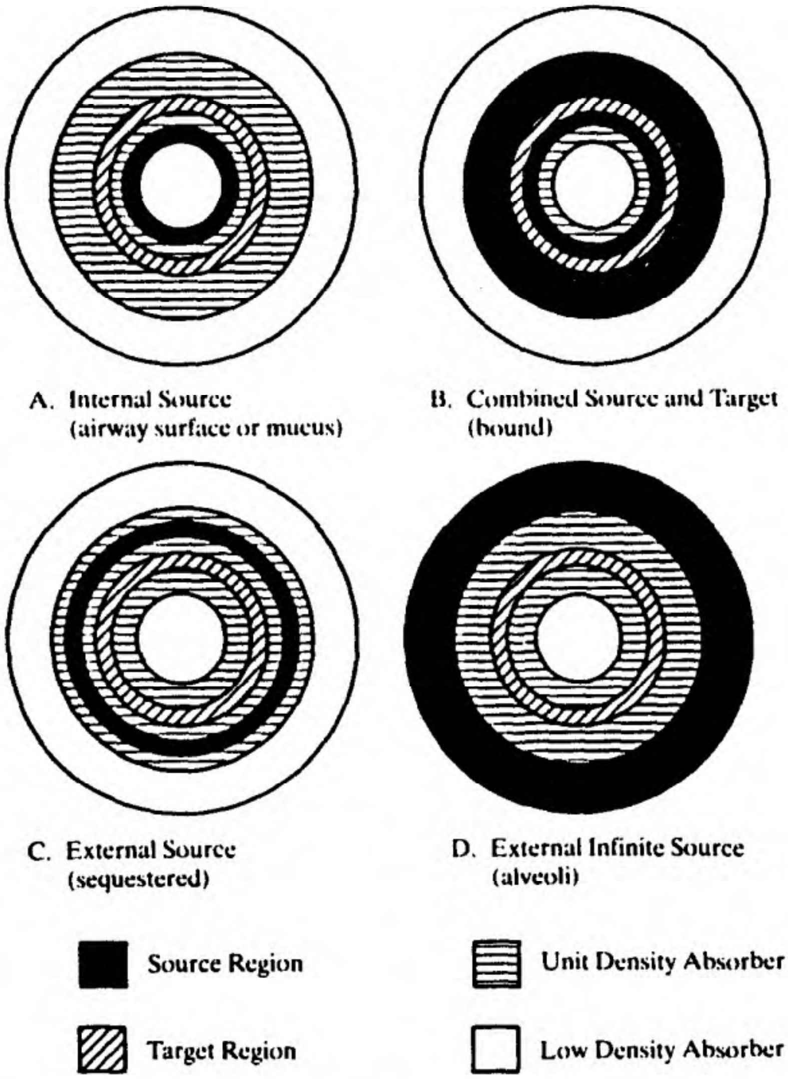
(H3) All of the absorbed fractions required to evaluate the respiratory tract dosimetry model as a function of the emitted radiation energy were calculated by a three-dimensional, Monte Carlo radiation transport method. This provided substantially improved accuracy in the absorbed fractions calculated for alpha emissions at high energies compared to the approximation method used earlier by the Task Group (James *et al.*, 1991). The Monte Carlo radiation transport code used here also increased the accuracy of absorbed fractions calculated for electron emissions over that possible with the point-kernel method used earlier (James *et al.*, 1991), by taking realistic account of multiple electron-scattering and the effects of air–tissue interfaces.

H.2. Implementation of Source and Target Configurations

(H4) Figure H.1 shows in cross-section the four different arrangements of cylindrical radiation source and target that apply to the various regions of the respiratory tract. For each case, Chapter 2 defines the radius of the inner surface of the airway, and the radial extent of the underlying source, target, and absorbing tissue layers.



A. Internal Source (airway surface or mucus)

B. Combined Source and Target (bound)

C. External Source (sequestered)

D. External Infinite Source (alveoli)

Fig. H.1. Cross-sectional diagrams of source and target configurations used to calculate absorbed fractions for the respiratory tract dosimetry model.

(H5) Figure H.1A represents the geometry used to calculate absorbed fractions for radiation sources at the airway surface, i.e. AF($ET_1 \leftarrow$ surface), or in a layer of fluid at the airway surface, i.e. AF($ET_2 \leftarrow$ fast mucus), AF(BB ← fast mucus), or AF(bb ← fast mucus). To calculate the absorbed fractions AF(BB ← slow mucus) and AF(bb ← slow mucus), the layer of shielding at the airway surface provided by the overlying "fast mucus" was added.

(H6) Figure H.1B represents the arrangement of source, target, and shielding layers used to calculate absorbed fractions for radionuclides that are "bound" in the epithelial tissue, i.e. for AF($ET_2 \leftarrow$ bound), AF(BB ← bound), and AF(bb ← bound), where the target layer comprises part of the source.

(H7) Figures H.1C and H.1D represent the two classes of source–target geometry where the source is entirely external to the target layer. Figure H.1C represents the geometrical arrangement used to calculate AF($ET_2 \leftarrow$ sequestered), AF(BB ← sequestered), and AF(bb ← sequestered), where the source is composed of a thin "macrophage" layer of unit-density tissue. Figure H.1D represents all cases where the source is assumed to be distributed through "alveolar" tissue, of density 0.2 g cm^{-3}, and infinite extent, i.e. AF(BB ← AI) and AF(bb ← AI).

(H8) In order to carry out the Monte Carlo calculations of AF(BB ← AI) and AF(bb ← AI), the "infinite" alveolar-interstitial source was replaced by a finite volume bounded by the radius, $R_{csda} + R_0$, where R_{csda} is the "continuous slowing down approximation" to the maximum range of the radiation considered, and R_0 is the outer radius of the airway wall. The appropriate values of R_{csda} were obtained for alpha particles from ICRU Report 49 (ICRU, 1993), and for electrons from ICRU Report 37 (ICRU, 1984). Under these conditions, the absorbed fractions for an "infinite" source were obtained by normalizing the calculated absorbed fraction, AF*(T ← AI), as follows:

$$\mathrm{AF(T \leftarrow AI)} = \mathrm{AF^*(T \leftarrow AI)}\,\frac{\pi[(R_{csda}+R_0)^2 - R_0^2]}{k} \tag{H2}$$

where AF*(T ← AI) is the absorbed fraction calculated for the source uniformly distributed in a cylindrical volume of material of density 0.2 g cm^{-3}, extending between radii R_0 and $R_0 + R_{csda}$ (in cm), and k is the proportional volume of the whole AI source that corresponds to unit length of target airways. For the reference adult male, the total length of target airways in the BB region is modelled as 183.5 cm, and that of the bb region is 7756 cm. Thus the values of the normalizing constant, k, are $5500\ cm^3 \div 183.5\ cm = 29.97\ cm^2$ for the BB region, and $5500\ cm^3 \div 7756\ cm = 0.709\ cm^2$ for the bb region.

(H9) Monte Carlo sampling of the points of origin and direction of transport of the emitted radiation was carried out uniformly within each source. For each calculation, the number of radiation transport cases followed was chosen to achieve a standard error in the calculated mean absorbed fraction, if possible, of less than 1%. The number of radiation transport histories required to achieve this precision depends rather critically on the spatial extent of the source, and the nature of the radiation (alpha particle or electron).

H.3. Absorbed Fractions for Alpha Particles

(H10) The Monte Carlo code used to calculate absorbed fractions for alpha particles (developed by G. Akabani, Pacific Northwest Laboratory) incorporated the stopping power and range values for liquid water and air given on pp. 256 and 213, respectively, of ICRU Report 49 (ICRU, 1993).

(H11) The trajectory of each alpha particle was followed in the code until all of its energy had been deposited, and the total amount of energy deposited in each target region from many alpha particles emitted from each source was determined. For internal, bound and sequestered sources (Figs H.1A–H.1C), 200,000 alpha particle histories were followed. For AF(bb←AI), where the alpha particle source is in the alveolar-interstitial region and the target is bronchiolar secretory cells, up to 2,000,000 histories were followed.

(H12) Table H.1 gives the values of absorbed fraction calculated for alpha particles of energy between 2.0 and 11.0 MeV. The table also shows the "cut-off" energy for each source–target combination, which corresponds to the minimum distance between points in the source and target.

(H13) For "bound" sources, there is no "cut-off" energy. At low energies, the absorbed fraction approaches asymptotically a constant value. This maximum value is determined by the volumetric proportion of the source that is occupied by the target.

(H14) For alpha particle sources in the AI region with the bronchial basal or secretory cells as target, the absorbed fractions $AF(BB_{bas}\leftarrow AI)$ and $AF(BB_{sec}\leftarrow AI)$ are always zero, because the thickness of absorbing tissue between the source and target exceeds the alpha-particle range.

H.4. Absorbed Fractions for Mono-energetic Electrons

(H15) The Monte Carlo code used to calculate absorbed fractions for mono-energetic electrons (also developed by G. Akabani, Pacific Northwest Laboratory) incorporated the "Electron Gamma Shower" transport code EGS4 (Nelson *et al.*, 1985; Bielajew *et al.*, 1991). The materials used in the code were air, and water to simulate tissue.

(H16) The EGS4 code accurately represents radiation transport phenomena for electrons and photons down to 1 keV. The code models the production of both knock-on electrons and bremsstrahlung above a certain energy threshold (taken to be 1 keV for these calculations). Transport of the electrons themselves is governed in the code by the Multiple Scattering theory. For these calculations, a practical upper limit for energy loss in each scattering event was set at 6% of the current electron energy, i.e. the variable ESTEPE in the EGS4 code was set at 0.06. This value of ESTEPE is consistent with the small linear dimensions of tissue targets in which electron energy loss is to be followed, and allows accurate simulation of the electron's curved path.

(H17) The energy deposited along an electron's path was scored in each cylindrical shell of absorber for each of the source–target arrangements shown in Figs H.1A–H.1D. Electrons and photons were transported until their energy dropped to 1 keV, which was assumed to be deposited locally. Thus, the history of all secondary electrons and photons (bremsstrahlung) produced by each electron emitted in the source was followed completely.

(H18) For internal, bound and sequestered sources (Figs H.1A–H.1C), the histories of 100,000 electrons of a given energy emitted in the source were followed. For AF(BB←AI) and AF(bb←AI), where the electron source is in the alveolar-interstitial region, up to 4,000,000 histories were followed for electrons emitted with high energy.

Table H.1. Values of absorbed fraction, $AF(T \leftarrow S)_\alpha$, for alpha particles

Target (T)	ET_1	ET_2	ET_2	ET_2	BB_{bas}	BB_{bas}	BB_{bas}	BB_{bas}	BB_{bas}
Source (S)	Surface	Surface	Bound	Sequestered	Fast Mucus	Slow Mucus	Bound	Sequestered	AI
Energy, MeV									
2.00	0	0	0.179	0.0131	0	0	0.250	0.000035	0
2.50	0	0	0.175	0.0374	0	0	0.251	0.00228	0
3.00	0	0	0.167	0.0739	0	0	0.249	0.0140	0
3.50	0	0	0.161	0.112	0	0	0.244	0.0393	0
4.00	0	0	0.153	0.135	0	0	0.239	0.0747	0
4.19	0	0	0.151	0.139	0	0	0.235	0.0885	0
4.39	0	0	0.147	0.141	0	0	0.232	0.102	0
4.50	0	0	0.147	0.142	0	0	0.230	0.109	0
4.76	0	0	0.143	0.142	0	0	0.227	0.123	0
5.00	0	0	0.140	0.141	0	0.000088	0.221	0.132	0
5.15	0	0	0.139	0.138	0	0.00054	0.219	0.135	0
5.50	0.00127	0.000076	0.135	0.135	0.000063	0.00506	0.213	0.141	0
6.00	0.0162	0.00251	0.131	0.128	0.00506	0.0217	0.202	0.141	0
6.50	0.0478	0.0112	0.125	0.121	0.0218	0.0435	0.191	0.139	0
7.00	0.0718	0.0234	0.118	0.114	0.0509	0.0600	0.182	0.134	0
7.50	0.0845	0.0321	0.111	0.107	0.0802	0.0778	0.172	0.128	0
7.69	0.0873	0.0345	0.109	0.104	0.0893	0.0857	0.167	0.127	0
8.00	0.0910	0.0368	0.104	0.101	0.101	0.0988	0.163	0.123	0
8.50	0.0931	0.0393	0.0984	0.0948	0.112	0.110	0.156	0.117	0
8.78	0.0939	0.0399	0.0949	0.0926	0.114	0.115	0.154	0.114	0
9.00	0.0942	0.0415	0.0926	0.0897	0.116	0.115	0.150	0.112	0
10.00	0.0917	0.0578	0.0835	0.0802	0.119	0.119	0.144	0.102	0
11.00	0.0871	0.0647	0.0797	0.0716	0.116	0.116	0.140	0.0930	0
Cut-off Energy, MeV	5.21	5.21	-	0.79	5.29	4.76	-	1.79	-

Table H.1. (*continued*)

Target (T)	BB_{sec}	BB_{sec}	BB_{sec}	BB_{sec}	BB_{sec}	bb_{sec}	bb_{sec}	bb_{sec}	bb_{sec}	bb_{sec}
Source (S)	Fast Mucus	Slow Mucus	Bound	Sequestered	AI	Fast Mucus	Slow Mucus	Bound	Sequestered	AI
Energy, MeV										
2.00	0	0	0.500	0	0	0.00526	0.0562	0.387	0.00209	0
2.50	0	0.00388	0.499	0	0	0.0387	0.110	0.367	0.0181	0
3.00	0.00022	0.0227	0.497	0	0	0.115	0.162	0.338	0.0544	0
3.50	0.00775	0.0599	0.493	0.00011	0	0.192	0.203	0.305	0.0918	0
4.00	0.0327	0.101	0.485	0.00373	0	0.231	0.235	0.278	0.111	1.22×10^{-6}
4.19	0.0455	0.116	0.481	0.00759	0	0.237	0.241	0.270	0.113	4.23×10^{-6}
4.39	0.0609	0.132	0.477	0.0136	0	0.239	0.243	0.263	0.114	1.07×10^{-5}
4.50	0.0708	0.140	0.474	0.0182	0	0.240	0.245	0.261	0.115	1.61×10^{-5}
4.76	0.0965	0.159	0.467	0.0304	0	0.238	0.243	0.253	0.114	3.40×10^{-5}
5.00	0.125	0.179	0.459	0.0432	0	0.236	0.240	0.247	0.113	5.55×10^{-5}
5.15	0.144	0.192	0.454	0.0515	0	0.233	0.237	0.244	0.111	7.06×10^{-5}
5.50	0.189	0.227	0.439	0.0726	0	0.225	0.229	0.239	0.110	1.08×10^{-4}
6.00	0.249	0.272	0.420	0.102	0	0.214	0.217	0.227	0.117	1.63×10^{-4}
6.50	0.301	0.309	0.398	0.130	0	0.200	0.202	0.214	0.123	2.17×10^{-4}
7.00	0.334	0.333	0.381	0.148	0	0.188	0.190	0.202	0.124	2.76×10^{-4}
7.50	0.348	0.350	0.370	0.156	0	0.177	0.178	0.188	0.121	3.47×10^{-4}
7.69	0.353	0.355	0.362	0.159	0	0.172	0.173	0.183	0.120	3.76×10^{-4}
8.00	0.353	0.356	0.354	0.160	0	0.166	0.166	0.175	0.118	4.23×10^{-4}
8.50	0.349	0.354	0.346	0.159	0	0.155	0.155	0.165	0.113	4.99×10^{-4}
8.78	0.346	0.350	0.341	0.159	0	0.150	0.151	0.160	0.111	5.42×10^{-4}
9.00	0.342	0.345	0.339	0.157	0	0.146	0.146	0.154	0.108	5.71×10^{-4}
10.00	0.323	0.325	0.324	0.155	0	0.128	0.128	0.135	0.0990	7.04×10^{-4}
11.00	0.300	0.303	0.307	0.167	0	0.113	0.113	0.121	0.0894	8.23×10^{-4}
Cut-off Energy,	2.70	1.79	-	3.20	-	1.43	0.57	-	1.43	3.56

(H19) Table H.2 gives the values of absorbed fraction calculated for mono-energetic electrons of energy between 0.01 and 9.0 MeV. For each source–target combination, the absorbed fractions were calculated for at least 14, and generally more than 20, values of electron energy. Additional values shown in Table H.2 were obtained by cubic-spline interpolation between the calculated nodes.

(H20) In contrast to the transport of alpha particles, where the highest range in unit density tissue that needs to be considered is about 130 μm (for an 11-MeV alpha particle), high-energy electrons travel many centimetres. The csda range for a 9-MeV electron is about 4.5 cm in unit density tissue, and up to 22.5 cm in alveolated tissue. Therefore, a high-energy electron emitted in the wall of one airway can traverse many other airways in its path through the AI region.

(H21) However, the Monte Carlo calculation of absorbed fractions for all sources associated with the airway internal surface or airway wall (Figs H.1A–H.1C) represents only the "local" absorption of energy in a single airway, which is assumed to be surrounded by an "infinite" cylinder of AI tissue. Additional energy deposition in each regional target tissue that results from cross-irradiation of remote airways is not represented explicitly in the calculation. However, this additional contribution can be adequately approximated by adding the surrogate calculated value of AF(T←AI) to each calculated value of the "locally" absorbed fraction, AF(T←S_{airway}). The values of AF(BB←mucus), AF(BB←bound), AF(BB←sequestered), and of AF(bb←mucus), AF(bb←bound), AF(bb←sequestered) given in Table H.2, therefore include the respective components from AF(BB←AI) and AF(bb←AI).

(H22) This use of AF(T←AI) as a surrogate for the additive effect of a local airway source also irradiating remote airways at high electron energies will, in fact, tend to overestimate the contribution of airway "cross-fire" within the BB and bb regions when these are considered as discrete sources and targets. In reality, there will also be cross-fire at high energies between the bb and BB regions, and *vice versa*. This additional cross-fire will tend to off-set the overestimation of absorbed fractions at high energies that results from using AF(T←AI) to represent remote airway sources within each region. Consequently, it is not necessary to add in explicitly the relatively small fractions of emitted electron energy absorbed by cross-fire between the BB and bb regions.

(H23) As for alpha particles, Table H.2 also shows the "cut-off" electron energy for each source–target combination. This corresponds to the minimum distance between points in the source and target. Again, for "bound" sources, there is no "cut-off" energy, and at low energies the absorbed fraction approaches asymptotically the constant value determined by the volumetric proportion of the source that is occuped by the target.

H.5. Absorbed Fractions for β^- and β^+ Particles

(H24) Absorbed fractions for beta particles (negatrons and positrons) were calculated from the absorbed fraction data for mono-energetic electrons and the beta spectra for a series of radionuclides. The spectral-average absorbed fraction for a beta emitter is:

$$\mathrm{AF}_\beta = \frac{\int Y(E)E\,\mathrm{AF}(\mathrm{T}\leftarrow \mathrm{S};E)\,\mathrm{d}E}{\int Y(E)E\,\mathrm{d}E} \tag{H3}$$

where $Y(E)$ is the spectral yield at energy E.

Table H.2. Values of absorbed fraction, $AF(T \leftarrow S)_e$, for electrons

Target (T)	ET_1	ET_2	ET_2	ET_2	BB_{bas}	BB_{bas}	BB_{bas}	BB_{bas}	BB_{bas}
Source (S)	Surface	Surface	Bound	Sequestered	Fast Mucus	Slow Mucus	Bound	Sequestered	AI
Energy, MeV									
0.010	0	0	1.82×10^{-1}	0	0	0	2.50×10^{-1}	0	0
0.015	0	0	1.82×10^{-1}	3.69×10^{-5}	0	0	2.50×10^{-1}	0	0
0.020	0	0	1.82×10^{-1}	8.33×10^{-4}	0	0	2.50×10^{-1}	0	0
0.025	0	0	1.80×10^{-1}	1.22×10^{-2}	0	0	2.50×10^{-1}	3.24×10^{-4}	0
0.030	0	0	1.75×10^{-1}	4.05×10^{-2}	0	0	2.50×10^{-1}	2.61×10^{-3}	0
0.035	0	0	1.66×10^{-1}	8.11×10^{-2}	0	0	2.47×10^{-1}	1.69×10^{-2}	0
0.040	0	0	1.56×10^{-1}	1.19×10^{-1}	0	0	2.42×10^{-1}	4.58×10^{-2}	0
0.045	0	0	1.49×10^{-1}	1.42×10^{-1}	0	1.15×10^{-5}	2.36×10^{-1}	8.11×10^{-2}	0
0.050	4.05×10^{-4}	4.42×10^{-7}	1.43×10^{-1}	1.49×10^{-1}	2.22×10^{-5}	1.31×10^{-4}	2.28×10^{-1}	1.15×10^{-1}	0
0.055	8.65×10^{-4}	7.59×10^{-5}	1.38×10^{-1}	1.49×10^{-1}	2.06×10^{-4}	2.53×10^{-3}	2.18×10^{-1}	1.35×10^{-1}	0
0.060	8.13×10^{-3}	1.39×10^{-3}	1.33×10^{-1}	1.42×10^{-1}	3.03×10^{-3}	1.13×10^{-2}	2.07×10^{-1}	1.45×10^{-1}	0
0.065	2.57×10^{-2}	6.09×10^{-3}	1.27×10^{-1}	1.34×10^{-1}	1.36×10^{-2}	2.62×10^{-2}	1.96×10^{-1}	1.49×10^{-1}	0
0.070	4.84×10^{-2}	1.34×10^{-2}	1.20×10^{-1}	1.24×10^{-1}	3.16×10^{-2}	4.49×10^{-2}	1.86×10^{-1}	1.45×10^{-1}	0
0.075	6.65×10^{-2}	2.20×10^{-2}	1.13×10^{-1}	1.17×10^{-1}	5.45×10^{-2}	6.46×10^{-2}	1.76×10^{-1}	1.39×10^{-1}	0
0.080	8.02×10^{-2}	3.03×10^{-2}	1.07×10^{-1}	1.08×10^{-1}	7.76×10^{-2}	8.32×10^{-2}	1.67×10^{-1}	1.33×10^{-1}	0
0.085	8.91×10^{-2}	3.69×10^{-2}	1.01×10^{-1}	1.01×10^{-1}	9.62×10^{-2}	9.87×10^{-2}	1.58×10^{-1}	1.27×10^{-1}	0

0.090	9.36×10^{-2}	4.26×10^{-2}	9.48×10^{-2}	9.36×10^{-2}	1.09×10^{-1}	1.10×10^{-1}	1.50×10^{-1}	1.21×10^{-1}	0
0.095	9.54×10^{-2}	4.83×10^{-2}	9.00×10^{-2}	8.83×10^{-2}	1.16×10^{-1}	1.17×10^{-1}	1.46×10^{-1}	1.14×10^{-1}	0
0.100	9.57×10^{-2}	5.36×10^{-2}	8.60×10^{-2}	8.32×10^{-2}	1.19×10^{-1}	1.20×10^{-1}	1.43×10^{-1}	1.07×10^{-1}	0
0.1125	9.04×10^{-2}	6.19×10^{-2}	7.86×10^{-2}	7.11×10^{-2}	1.19×10^{-1}	1.20×10^{-1}	1.36×10^{-1}	9.71×10^{-2}	0
0.125	8.40×10^{-2}	6.36×10^{-2}	7.39×10^{-2}	6.38×10^{-2}	1.13×10^{-1}	1.14×10^{-1}	1.27×10^{-1}	9.36×10^{-2}	0
0.150	7.03×10^{-2}	5.59×10^{-2}	6.78×10^{-2}	5.84×10^{-2}	9.66×10^{-2}	9.71×10^{-2}	1.09×10^{-1}	8.77×10^{-2}	0
0.175	5.90×10^{-2}	4.69×10^{-2}	6.07×10^{-2}	5.35×10^{-2}	8.24×10^{-2}	8.27×10^{-2}	9.32×10^{-2}	7.85×10^{-2}	0
0.200	5.12×10^{-2}	3.97×10^{-2}	5.30×10^{-2}	4.75×10^{-2}	7.12×10^{-2}	7.15×10^{-2}	8.01×10^{-2}	6.83×10^{-2}	0
0.300	3.14×10^{-2}	2.25×10^{-2}	3.34×10^{-2}	3.09×10^{-2}	4.37×10^{-2}	4.39×10^{-2}	4.90×10^{-2}	4.34×10^{-2}	1.57×10^{-5}
0.400	2.19×10^{-2}	1.50×10^{-2}	2.40×10^{-2}	2.26×10^{-2}	3.07×10^{-2}	3.09×10^{-2}	3.42×10^{-2}	3.13×10^{-2}	7.66×10^{-5}
0.500	1.66×10^{-2}	1.12×10^{-2}	1.87×10^{-2}	1.77×10^{-2}	2.35×10^{-2}	2.35×10^{-2}	2.62×10^{-2}	2.37×10^{-2}	1.39×10^{-4}
0.600	1.33×10^{-2}	9.06×10^{-3}	1.54×10^{-2}	1.46×10^{-2}	1.89×10^{-2}	1.89×10^{-2}	2.12×10^{-2}	1.90×10^{-2}	1.85×10^{-4}
0.700	1.10×10^{-2}	7.63×10^{-3}	1.31×10^{-2}	1.23×10^{-2}	1.56×10^{-2}	1.56×10^{-2}	1.76×10^{-2}	1.58×10^{-2}	2.21×10^{-4}
0.800	9.34×10^{-3}	6.61×10^{-3}	1.13×10^{-2}	1.07×10^{-2}	1.32×10^{-2}	1.32×10^{-2}	1.47×10^{-2}	1.34×10^{-2}	2.49×10^{-4}
0.900	8.15×10^{-3}	5.83×10^{-3}	9.95×10^{-3}	9.50×10^{-3}	1.14×10^{-2}	1.14×10^{-2}	1.28×10^{-2}	1.15×10^{-2}	2.70×10^{-4}
1.000	7.25×10^{-3}	5.22×10^{-3}	8.88×10^{-3}	8.54×10^{-3}	9.86×10^{-3}	1.01×10^{-2}	1.13×10^{-2}	1.02×10^{-2}	2.85×10^{-4}
1.500	4.36×10^{-3}	3.50×10^{-3}	5.72×10^{-3}	5.78×10^{-3}	5.65×10^{-3}	6.11×10^{-3}	7.10×10^{-3}	6.44×10^{-3}	3.23×10^{-4}
2.000	3.07×10^{-3}	2.67×10^{-3}	4.21×10^{-3}	4.31×10^{-3}	4.56×10^{-3}	4.58×10^{-3}	5.22×10^{-3}	4.78×10^{-3}	3.34×10^{-4}
3.000	1.93×10^{-3}	1.85×10^{-3}	2.80×10^{-3}	2.90×10^{-3}	3.08×10^{-3}	3.08×10^{-3}	3.51×10^{-3}	3.28×10^{-3}	3.66×10^{-4}
4.000	1.41×10^{-3}	1.42×10^{-3}	2.02×10^{-3}	2.15×10^{-3}	2.39×10^{-3}	2.41×10^{-3}	2.72×10^{-3}	2.54×10^{-3}	3.93×10^{-4}
9.000	5.50×10^{-4}	6.61×10^{-4}	8.69×10^{-4}	9.65×10^{-4}	1.18×10^{-3}	1.17×10^{-3}	1.35×10^{-3}	1.30×10^{-3}	3.93×10^{-4}
Cut-off Energy, MeV	0.0478	0.0478	-	0.0147	0.0485	0.0443	-	0.0217	0.215

Table H.2. *(continued)*

Target (T)	BB_{sec}	BB_{sec}	BB_{sec}	BB_{sec}	BB_{sec}	bb_{sec}	bb_{sec}	bb_{sec}	bb_{sec}	bb_{sec}
Source (S)	Fast Mucus	Slow Mucus	Bound	Sequestered	AI	Fast Mucus	Slow Mucus	Bound	Sequestered	AI
Energy, MeV										
0.010	0	0	5.00×10^{-1}	0	0	0	0	3.98×10^{-1}	0	0
0.015	0	0	4.99×10^{-1}	0	0	0	2.08×10^{-4}	3.97×10^{-1}	0	0
0.020	0	0	4.97×10^{-1}	0	0	3.40×10^{-4}	9.72×10^{-3}	3.95×10^{-1}	0	0
0.025	0	6.43×10^{-4}	4.96×10^{-1}	0	0	3.45×10^{-3}	5.60×10^{-2}	3.88×10^{-1}	1.40×10^{-3}	0
0.030	3.56×10^{-6}	4.13×10^{-3}	4.96×10^{-1}	0	0	4.30×10^{-2}	1.22×10^{-1}	3.66×10^{-1}	1.90×10^{-2}	0
0.035	9.12×10^{-4}	2.65×10^{-2}	4.95×10^{-1}	4.40×10^{-6}	0	1.28×10^{-1}	1.79×10^{-1}	3.30×10^{-1}	5.82×10^{-2}	0
0.040	1.22×10^{-2}	6.50×10^{-2}	4.92×10^{-1}	7.96×10^{-4}	0	2.06×10^{-1}	2.22×10^{-1}	2.97×10^{-1}	9.69×10^{-2}	1.73×10^{-6}
0.045	4.00×10^{-2}	1.08×10^{-1}	4.85×10^{-1}	7.34×10^{-3}	0	2.45×10^{-1}	2.49×10^{-1}	2.70×10^{-1}	1.17×10^{-1}	1.84×10^{-5}
0.050	8.50×10^{-2}	1.55×10^{-1}	4.73×10^{-1}	2.39×10^{-2}	0	2.54×10^{-1}	2.55×10^{-1}	2.53×10^{-1}	1.22×10^{-1}	5.25×10^{-5}
0.055	1.42×10^{-1}	1.99×10^{-1}	4.56×10^{-1}	4.98×10^{-2}	0	2.44×10^{-1}	2.49×10^{-1}	2.39×10^{-1}	1.20×10^{-1}	1.02×10^{-4}
0.060	2.06×10^{-1}	2.45×10^{-1}	4.35×10^{-1}	7.88×10^{-2}	0	2.33×10^{-1}	2.35×10^{-1}	2.27×10^{-1}	1.22×10^{-1}	1.62×10^{-4}
0.065	2.64×10^{-1}	2.88×10^{-1}	4.14×10^{-1}	1.09×10^{-1}	0	2.18×10^{-1}	2.20×10^{-1}	2.15×10^{-1}	1.24×10^{-1}	2.28×10^{-4}
0.070	3.09×10^{-1}	3.22×10^{-1}	3.94×10^{-1}	1.34×10^{-1}	0	2.02×10^{-1}	2.04×10^{-1}	2.05×10^{-1}	1.25×10^{-1}	2.98×10^{-4}
0.075	3.39×10^{-1}	3.46×10^{-1}	3.77×10^{-1}	1.51×10^{-1}	0	1.87×10^{-1}	1.88×10^{-1}	1.92×10^{-1}	1.25×10^{-1}	3.71×10^{-4}
0.080	3.56×10^{-1}	3.59×10^{-1}	3.63×10^{-1}	1.61×10^{-1}	0	1.74×10^{-1}	1.75×10^{-1}	1.80×10^{-1}	1.21×10^{-1}	4.44×10^{-4}
0.085	3.61×10^{-1}	3.64×10^{-1}	3.51×10^{-1}	1.65×10^{-1}	0	1.63×10^{-1}	1.63×10^{-1}	1.69×10^{-1}	1.18×10^{-1}	5.17×10^{-4}

0.090	3.59×10^{-1}	3.62×10^{-1}	3.40×10^{-1}	1.66×10^{-1}	0	1.51×10^{-1}	1.52×10^{-1}	1.57×10^{-1}	1.15×10^{-1}	5.89×10^{-4}
0.095	3.53×10^{-1}	3.55×10^{-1}	3.31×10^{-1}	1.66×10^{-1}	0	1.40×10^{-1}	1.42×10^{-1}	1.47×10^{-1}	1.09×10^{-1}	6.59×10^{-4}
0.100	3.44×10^{-1}	3.44×10^{-1}	3.23×10^{-1}	1.66×10^{-1}	0	1.31×10^{-1}	1.31×10^{-1}	1.37×10^{-1}	1.04×10^{-1}	7.25×10^{-4}
0.1125	3.15×10^{-1}	3.15×10^{-1}	3.03×10^{-1}	1.70×10^{-1}	0	1.11×10^{-1}	1.11×10^{-1}	1.18×10^{-1}	9.02×10^{-2}	8.74×10^{-4}
0.125	2.84×10^{-1}	2.86×10^{-1}	2.81×10^{-1}	1.74×10^{-1}	0	9.57×10^{-2}	9.47×10^{-2}	1.01×10^{-1}	7.89×10^{-2}	9.99×10^{-4}
0.150	2.33×10^{-1}	2.34×10^{-1}	2.36×10^{-1}	1.66×10^{-1}	0	7.19×10^{-2}	7.13×10^{-2}	7.60×10^{-2}	6.12×10^{-2}	1.19×10^{-3}
0.175	1.94×10^{-1}	1.94×10^{-1}	1.98×10^{-1}	1.49×10^{-1}	0	5.58×10^{-2}	5.55×10^{-2}	5.94×10^{-2}	4.83×10^{-2}	1.32×10^{-3}
0.200	1.64×10^{-1}	1.65×10^{-1}	1.69×10^{-1}	1.30×10^{-1}	0	4.51×10^{-2}	4.46×10^{-2}	4.86×10^{-2}	3.91×10^{-2}	1.41×10^{-3}
0.300	9.87×10^{-2}	9.84×10^{-2}	1.02×10^{-1}	8.28×10^{-2}	2.85×10^{-5}	2.34×10^{-2}	2.33×10^{-2}	2.57×10^{-2}	2.10×10^{-2}	1.59×10^{-3}
0.400	6.85×10^{-2}	6.79×10^{-2}	7.10×10^{-2}	5.91×10^{-2}	1.52×10^{-4}	1.54×10^{-2}	1.54×10^{-2}	1.71×10^{-2}	1.40×10^{-2}	1.65×10^{-3}
0.500	5.18×10^{-2}	5.14×10^{-2}	5.40×10^{-2}	4.48×10^{-2}	2.78×10^{-4}	1.15×10^{-2}	1.15×10^{-2}	1.28×10^{-2}	1.05×10^{-2}	1.67×10^{-3}
0.600	4.11×10^{-2}	4.11×10^{-2}	4.36×10^{-2}	3.57×10^{-2}	3.67×10^{-4}	9.23×10^{-3}	9.33×10^{-3}	1.03×10^{-2}	8.50×10^{-3}	1.69×10^{-3}
0.700	3.37×10^{-2}	3.38×10^{-2}	3.58×10^{-2}	2.96×10^{-2}	4.37×10^{-4}	7.91×10^{-3}	7.95×10^{-3}	8.67×10^{-3}	7.28×10^{-3}	1.71×10^{-3}
0.800	2.85×10^{-2}	2.84×10^{-2}	3.01×10^{-2}	2.51×10^{-2}	4.93×10^{-4}	6.91×10^{-3}	6.95×10^{-3}	7.66×10^{-3}	6.41×10^{-3}	1.72×10^{-3}
0.900	2.45×10^{-2}	2.45×10^{-2}	2.61×10^{-2}	2.16×10^{-2}	5.34×10^{-4}	6.20×10^{-3}	6.33×10^{-3}	6.92×10^{-3}	5.82×10^{-3}	1.73×10^{-3}
1.000	2.14×10^{-2}	2.47×10^{-2}	2.30×10^{-2}	1.91×10^{-2}	5.64×10^{-4}	5.73×10^{-3}	5.82×10^{-3}	6.26×10^{-3}	5.39×10^{-3}	1.74×10^{-3}
1.500	1.32×10^{-2}	1.33×10^{-2}	1.43×10^{-2}	1.20×10^{-2}	6.44×10^{-4}	4.26×10^{-3}	4.33×10^{-3}	4.65×10^{-3}	4.04×10^{-3}	1.76×10^{-3}
2.000	9.77×10^{-3}	9.76×10^{-3}	1.06×10^{-2}	8.91×10^{-3}	6.65×10^{-4}	3.63×10^{-3}	3.68×10^{-3}	3.91×10^{-3}	3.49×10^{-3}	1.77×10^{-3}
3.000	6.55×10^{-3}	6.58×10^{-3}	7.02×10^{-3}	6.08×10^{-3}	7.20×10^{-4}	2.98×10^{-3}	3.03×10^{-3}	3.18×10^{-3}	2.92×10^{-3}	1.77×10^{-3}
4.000	5.08×10^{-3}	5.14×10^{-3}	5.45×10^{-3}	4.76×10^{-3}	7.86×10^{-4}	2.69×10^{-3}	2.71×10^{-3}	2.83×10^{-3}	2.63×10^{-3}	1.77×10^{-3}
9.000	2.49×10^{-3}	2.55×10^{-3}	2.70×10^{-3}	2.44×10^{-3}	7.86×10^{-4}	2.17×10^{-3}	2.18×10^{-3}	2.23×10^{-3}	2.15×10^{-3}	1.77×10^{-3}
Cut-off Energy, MeV	0.0284	0.0217	-	0.0322	0.218	0.0192	0.013	-	0.0192	0.035

(H25) The energy spectra of each of the beta particle emissions listed in Table H.3 for negatrons, and Table H.4 for positrons, were obtained from the National Nuclear Data Center (Brookhaven National Laboratory). Each spectrum was calculated from the Evaluated Nuclear Structure Data Files (ENSDF), using the computer code RADLST (Burrows, 1988). In order to evaluate the above integral, at least 150 energy bins were used to represent each energy spectrum.

(H26) Table H.5 gives the spectral-average absorbed fractions, as a function of mean spectral energy, for each of the negatron emissions listed in Table H.3.

(H27) Table H.6 gives the absorbed fractions calculated in the same manner for the positron emissions listed in Table H.4. For positron emissions of energy higher than the maximum listed value of 0.7353 MeV (from ^{15}O), the absorbed fractions are identical to the values calculated for negatrons.

Table H.3. Beta-emitting isotopes with their average emitted energy used to evaluate $AF(T \leftarrow S)_{\beta^-}$ for β^- emissions

Isotope name	Average energy (MeV)
^{3}H	0.0056
^{106}Ru	0.0100
^{63}Ni	0.0174
^{103}Ru	0.0315[a]
^{35}S	0.0487
^{14}C	0.0498
^{147}Pm	0.0617
^{45}Ca	0.0773
^{99}Tc	0.0845
^{60}Co	0.0958
^{127}Sn	0.1354[a]
^{127}Sn	0.1581[a]
^{127}Sn	0.1694[a]
^{90}Sr	0.2010
^{204}Tl	0.2394
^{36}Cl	0.2507
^{85}Kr	0.2562
^{210}Bi	0.3888
^{24}Na	0.5516
^{89}Sr	0.5672
^{91}Y	0.5886
^{32}P	0.6918
^{49}Sc	0.8153
^{90}Y	0.9258
^{28}Al	1.2350
^{87}Kr	1.6938
^{78}As	1.8570

[a] Branch-energy selected from complex spectrum.

Table H.4. Beta-emitting isotopes with their average emitted energy used to evaluate $AF(T \leftarrow S)_{\beta^+}$ for β^+ emissions

Isotope name	Average energy (MeV)
^{34}Cl	0.0502[a]
^{48}Cr	0.0914[a]
^{118}Sb	0.1300[a]
^{107}Cd	0.1418[a]
^{58}Co	0.2013
^{22}Na	0.2155
^{52}Mn	0.2416
^{18}F	0.2498
^{88}Y	0.3595
^{13}N	0.4918
^{15}O	0.7353

[a] Branch energy selected from complex spectrum.

H.6. Algebraic Approximations

(H28) To facilitate the evaluation of $AF(T \leftarrow S)_R$ for emissions of intermediate energy, and for complex emission spectra involving multiple radiation energies, the calculated values of $AF(T \leftarrow S)_R$ are conveniently represented as functions of radiation energy by fitted algebraic expressions. Appriopriate expressions, which were developed by A. Birchall and N. S. Jarvis (National Radiological Protection Board), are given in Table H.7. Values of the parameters to be substituted in these expressions, in order to evaluate absorbed fractions for emissions of alpha particles, electrons, negatrons, and positrons, respectively, are listed in Tables H.8–H.11. The approximate values so obtained represent the calculated values of absorbed fraction to within about ± 1% relative error. As noted above, however, other approximations to the calculated values of $AF(T \leftarrow S)_R$ may also be appropriate.

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Table H.5. Values of absorbed fraction, $AF(T \leftarrow S)_{\beta^-}$, for negatrons

Source (S)	ET_1	ET_2	ET_2	ET_2	BB_{bas}	BB_{bas}	BB_{bas}	BB_{bas}	BB_{bas}
Target (T)	Surface	Surface	Bound	Sequestered	Fast Mucus	Slow Mucus	Bound	Sequestered	AI
Average Energy, MeV									
0.0056	0	0	1.82×10^{-1}	2.81×10^{-5}	0	0	2.50×10^{-1}	1.01×10^{-6}	0
0.0100	0	0	1.81×10^{-1}	5.91×10^{-3}	0	0	2.50×10^{-1}	4.96×10^{-4}	0
0.0174	1.17×10^{-4}	1.94×10^{-5}	1.71×10^{-1}	4.87×10^{-2}	4.42×10^{-5}	1.97×10^{-4}	2.46×10^{-1}	2.24×10^{-2}	0
0.0315	1.76×10^{-2}	6.60×10^{-3}	1.48×10^{-1}	9.07×10^{-2}	1.62×10^{-2}	1.91×10^{-2}	2.21×10^{-1}	7.49×10^{-2}	0
0.0487	4.70×10^{-2}	2.48×10^{-2}	1.20×10^{-1}	9.41×10^{-2}	5.33×10^{-2}	5.64×10^{-2}	1.86×10^{-1}	9.67×10^{-2}	0
0.0498	4.56×10^{-2}	2.32×10^{-2}	1.22×10^{-1}	9.71×10^{-2}	5.08×10^{-2}	5.42×10^{-2}	1.89×10^{-1}	9.85×10^{-2}	0
0.0617	5.60×10^{-2}	3.43×10^{-2}	1.04×10^{-1}	8.44×10^{-2}	6.82×10^{-2}	7.06×10^{-2}	1.63×10^{-1}	9.53×10^{-2}	0
0.0773	6.00×10^{-2}	3.90×10^{-2}	9.23×10^{-2}	7.78×10^{-2}	7.54×10^{-2}	7.74×10^{-2}	1.46×10^{-1}	9.34×10^{-2}	0
0.0849	5.86×10^{-2}	3.91×10^{-2}	8.62×10^{-2}	7.27×10^{-2}	7.47×10^{-2}	7.64×10^{-2}	1.36×10^{-1}	8.90×10^{-2}	0

0.0958	5.83×10^{-2}	3.96×10^{-2}	7.99×10^{-2}	6.85×10^{-2}	7.51×10^{-2}	7.66×10^{-2}	1.26×10^{-1}	8.60×10^{-2}	0
0.1354	5.02×10^{-2}	3.53×10^{-2}	6.25×10^{-2}	5.47×10^{-2}	6.64×10^{-2}	6.74×10^{-2}	9.71×10^{-2}	7.15×10^{-2}	6.56×10^{-6}
0.1581	4.56×10^{-2}	3.22×10^{-2}	5.49×10^{-2}	4.85×10^{-2}	6.09×10^{-2}	6.16×10^{-2}	8.47×10^{-2}	6.43×10^{-2}	1.48×10^{-5}
0.1694	4.35×10^{-2}	3.07×10^{-2}	5.18×10^{-2}	4.59×10^{-2}	5.82×10^{-2}	5.89×10^{-2}	7.95×10^{-2}	6.12×10^{-2}	1.99×10^{-5}
0.2010	3.89×10^{-2}	2.76×10^{-2}	4.47×10^{-2}	4.01×10^{-2}	5.26×10^{-2}	5.32×10^{-2}	6.80×10^{-2}	5.43×10^{-2}	2.97×10^{-5}
0.2394	3.24×10^{-2}	2.29×10^{-2}	3.75×10^{-2}	3.38×10^{-2}	4.41×10^{-2}	4.45×10^{-2}	5.64×10^{-2}	4.56×10^{-2}	6.38×10^{-5}
0.2507	3.26×10^{-2}	2.31×10^{-2}	3.68×10^{-2}	3.34×10^{-2}	4.46×10^{-2}	4.49×10^{-2}	5.53×10^{-2}	4.54×10^{-2}	5.91×10^{-5}
0.2562	3.12×10^{-2}	2.20×10^{-2}	3.56×10^{-2}	3.23×10^{-2}	4.27×10^{-2}	4.30×10^{-2}	5.33×10^{-2}	4.37×10^{-2}	6.43×10^{-5}
0.3888	2.05×10^{-2}	1.44×10^{-2}	2.36×10^{-2}	2.17×10^{-2}	2.84×10^{-2}	2.85×10^{-2}	3.42×10^{-2}	2.89×10^{-2}	1.46×10^{-4}
0.5516	1.46×10^{-2}	1.03×10^{-2}	1.68×10^{-2}	1.57×10^{-2}	2.03×10^{-2}	2.05×10^{-2}	2.35×10^{-2}	2.06×10^{-2}	1.98×10^{-4}
0.5672	1.40×10^{-2}	9.85×10^{-3}	1.62×10^{-2}	1.51×10^{-2}	1.94×10^{-2}	1.95×10^{-2}	2.26×10^{-2}	1.97×10^{-2}	2.07×10^{-4}
0.5886	1.34×10^{-2}	9.46×10^{-3}	1.56×10^{-2}	1.46×10^{-2}	1.85×10^{-2}	1.87×10^{-2}	2.17×10^{-2}	1.89×10^{-2}	2.14×10^{-4}
0.6918	1.13×10^{-2}	8.03×10^{-3}	1.32×10^{-2}	1.25×10^{-2}	1.56×10^{-2}	1.58×10^{-2}	1.81×10^{-2}	1.60×10^{-2}	2.37×10^{-4}
0.8153	9.34×10^{-3}	6.72×10^{-3}	1.11×10^{-2}	1.06×10^{-2}	1.28×10^{-2}	1.31×10^{-2}	1.49×10^{-2}	1.33×10^{-2}	2.61×10^{-4}
0.9258	8.02×10^{-3}	5.87×10^{-3}	9.68×10^{-3}	9.30×10^{-3}	1.10×10^{-2}	1.13×10^{-2}	1.29×10^{-2}	1.15×10^{-2}	2.77×10^{-4}
1.2350	5.72×10^{-3}	4.36×10^{-3}	7.14×10^{-3}	6.99×10^{-3}	7.90×10^{-3}	8.12×10^{-3}	9.25×10^{-3}	8.34×10^{-3}	3.04×10^{-4}
1.6938	3.89×10^{-3}	3.16×10^{-3}	5.08×10^{-3}	5.06×10^{-3}	5.58×10^{-3}	5.69×10^{-3}	6.47×10^{-3}	5.89×10^{-3}	3.30×10^{-4}
1.8570	3.49×10^{-3}	2.89×10^{-3}	4.61×10^{-3}	4.62×10^{-3}	5.07×10^{-3}	5.15×10^{-3}	5.86×10^{-3}	5.35×10^{-3}	3.38×10^{-4}

Table H.5. (*continued*)

Target (T)	BB$_{sec}$	BB$_{sec}$	BB$_{sec}$	BB$_{sec}$	BB$_{sec}$	bb$_{sec}$	bb$_{sec}$	bb$_{sec}$	bb$_{sec}$	bb$_{sec}$
Source (S)	Fast Mucus	Slow Mucus	Bound	Sequestered	AI	Fast Mucus	Slow Mucus	Bound	Sequestered	AI
Average Energy, MeV										
0.0056	0	2.18×10^{-6}	5.00×10^{-1}	0	0	0	0	3.98×10^{-1}	0	0
0.0100	1.21×10^{-5}	7.97×10^{-4}	4.98×10^{-1}	0	0	5.55×10^{-3}	2.06×10^{-2}	3.93×10^{-1}	2.45×10^{-3}	0
0.0174	1.38×10^{-2}	3.19×10^{-2}	4.93×10^{-1}	3.81×10^{-3}	0	7.64×10^{-2}	1.02×10^{-1}	3.54×10^{-1}	3.60×10^{-2}	7.08×10^{-6}
0.0315	1.21×10^{-1}	1.46×10^{-1}	4.54×10^{-1}	4.97×10^{-2}	0	1.47×10^{-1}	1.63×10^{-1}	2.83×10^{-1}	7.96×10^{-2}	1.30×10^{-4}
0.0487	2.16×10^{-1}	2.34×10^{-1}	3.94×10^{-1}	1.03×10^{-1}	0	1.51×10^{-1}	1.59×10^{-1}	2.13×10^{-1}	9.39×10^{-2}	3.97×10^{-4}
0.0498	2.16×10^{-1}	2.35×10^{-1}	3.99×10^{-1}	1.01×10^{-1}	0	1.57×10^{-1}	1.65×10^{-1}	2.17×10^{-1}	9.62×10^{-2}	3.68×10^{-4}
0.0617	2.30×10^{-1}	2.42×10^{-1}	3.48×10^{-1}	1.23×10^{-1}	0	1.30×10^{-1}	1.35×10^{-1}	1.73×10^{-1}	8.65×10^{-2}	6.20×10^{-4}
0.0773	2.33×10^{-1}	2.42×10^{-1}	3.12×10^{-1}	1.33×10^{-1}	0	1.15×10^{-1}	1.18×10^{-1}	1.44×10^{-1}	8.02×10^{-2}	7.87×10^{-4}
0.0849	2.22×10^{-1}	2.29×10^{-1}	2.90×10^{-1}	1.32×10^{-1}	0	1.04×10^{-1}	1.07×10^{-1}	1.30×10^{-1}	7.36×10^{-2}	8.82×10^{-4}

0.0958	2.15×10^{-1}	2.22×10^{-1}	2.69×10^{-1}	1.32×10^{-1}	0	9.49×10^{-2}	9.69×10^{-2}	1.15×10^{-1}	6.87×10^{-2}	9.72×10^{-4}
0.1354	1.77×10^{-1}	1.80×10^{-1}	2.07×10^{-1}	1.19×10^{-1}	1.24×10^{-5}	6.76×10^{-2}	6.85×10^{-2}	7.95×10^{-2}	5.12×10^{-2}	1.21×10^{-3}
0.1581	1.57×10^{-1}	1.60×10^{-1}	1.80×10^{-1}	1.10×10^{-1}	2.86×10^{-5}	5.66×10^{-2}	5.72×10^{-2}	6.58×10^{-2}	4.37×10^{-2}	1.30×10^{-3}
0.1694	1.49×10^{-1}	1.51×10^{-1}	1.69×10^{-1}	1.05×10^{-1}	3.88×10^{-5}	5.21×10^{-2}	5.26×10^{-2}	6.04×10^{-2}	4.07×10^{-2}	1.34×10^{-3}
0.2010	1.30×10^{-1}	1.32×10^{-1}	1.44×10^{-1}	9.60×10^{-2}	5.83×10^{-5}	4.21×10^{-2}	4.24×10^{-2}	4.81×10^{-2}	3.38×10^{-2}	1.43×10^{-3}
0.2394	1.08×10^{-1}	1.09×10^{-1}	1.19×10^{-1}	8.10×10^{-2}	1.26×10^{-4}	3.39×10^{-2}	3.41×10^{-2}	3.87×10^{-2}	2.74×10^{-2}	1.49×10^{-3}
0.2507	1.08×10^{-1}	1.08×10^{-1}	1.17×10^{-1}	8.18×10^{-2}	1.17×10^{-4}	3.25×10^{-2}	3.26×10^{-2}	3.66×10^{-2}	2.67×10^{-2}	1.50×10^{-3}
0.2562	1.03×10^{-1}	1.04×10^{-1}	1.12×10^{-1}	7.87×10^{-2}	1.27×10^{-4}	3.11×10^{-2}	3.12×10^{-2}	3.53×10^{-2}	2.55×10^{-2}	1.52×10^{-3}
0.3888	6.62×10^{-2}	6.66×10^{-2}	7.15×10^{-2}	5.28×10^{-2}	2.89×10^{-4}	1.86×10^{-2}	1.87×10^{-2}	2.09×10^{-2}	1.57×10^{-2}	1.62×10^{-3}
0.5516	4.60×10^{-2}	4.69×10^{-2}	4.88×10^{-2}	3.83×10^{-2}	3.93×10^{-4}	1.19×10^{-2}	1.20×10^{-2}	1.32×10^{-2}	1.06×10^{-2}	1.68×10^{-3}
0.5672	4.39×10^{-2}	4.51×10^{-2}	4.69×10^{-2}	3.66×10^{-2}	4.11×10^{-4}	1.16×10^{-2}	1.17×10^{-2}	1.30×10^{-2}	1.02×10^{-2}	1.68×10^{-3}
0.5886	4.20×10^{-2}	4.34×10^{-2}	4.49×10^{-2}	3.51×10^{-2}	4.24×10^{-4}	1.12×10^{-2}	1.12×10^{-2}	1.24×10^{-2}	9.84×10^{-3}	1.69×10^{-3}
0.6918	3.50×10^{-2}	3.67×10^{-2}	3.73×10^{-2}	2.98×10^{-2}	4.69×10^{-4}	9.20×10^{-3}	9.25×10^{-3}	1.02×10^{-2}	8.26×10^{-3}	1.71×10^{-3}
0.8153	2.87×10^{-2}	3.04×10^{-2}	3.07×10^{-2}	2.47×10^{-2}	5.17×10^{-4}	7.73×10^{-3}	7.79×10^{-3}	8.51×10^{-3}	7.02×10^{-3}	1.72×10^{-3}
0.9258	2.47×10^{-2}	2.61×10^{-2}	2.64×10^{-2}	2.14×10^{-2}	5.50×10^{-4}	6.84×10^{-3}	6.91×10^{-3}	7.53×10^{-3}	6.25×10^{-3}	1.73×10^{-3}
1.2350	1.76×10^{-2}	1.86×10^{-2}	1.89×10^{-2}	1.55×10^{-2}	6.04×10^{-4}	5.24×10^{-3}	5.29×10^{-3}	5.71×10^{-3}	4.89×10^{-3}	1.75×10^{-3}
1.6938	1.22×10^{-2}	1.28×10^{-2}	1.32×10^{-2}	1.10×10^{-2}	6.55×10^{-4}	4.14×10^{-3}	4.19×10^{-3}	4.48×10^{-3}	3.93×10^{-3}	1.76×10^{-3}
1.8570	1.11×10^{-2}	1.16×10^{-2}	1.19×10^{-2}	9.97×10^{-3}	6.69×10^{-4}	3.90×10^{-3}	3.95×10^{-3}	4.21×10^{-3}	3.72×10^{-3}	1.76×10^{-3}

Table H.6. Values of absorbed fraction, $AF(T \leftarrow S)_{\beta^+}$, for positrons

Target (T)	ET_1	ET_2	ET_2	ET_2	BB_{bas}	BB_{bas}	BB_{bas}	BB_{bas}	BB_{bas}
Source (S)	Surface	Surface	Bound	Sequestered	Fast Mucus	Slow Mucus	Bound	Sequestered	AI
Average Energy, MeV									
0.0502	3.23×10^{-2}	1.26×10^{-2}	1.32×10^{-1}	1.11×10^{-1}	3.12×10^{-2}	3.55×10^{-2}	2.03×10^{-1}	1.03×10^{-1}	3.44×10^{-13}
0.0914	6.77×10^{-2}	4.30×10^{-2}	9.07×10^{-2}	8.25×10^{-2}	8.42×10^{-2}	8.65×10^{-2}	1.46×10^{-1}	1.02×10^{-1}	1.87×10^{-10}
0.1300	6.53×10^{-2}	4.59×10^{-2}	7.14×10^{-2}	6.48×10^{-2}	8.57×10^{-2}	8.69×10^{-2}	1.14×10^{-1}	8.77×10^{-2}	1.24×10^{-7}
0.1418	6.20×10^{-2}	4.44×10^{-2}	6.67×10^{-2}	6.04×10^{-2}	8.22×10^{-2}	8.32×10^{-2}	1.06×10^{-1}	8.27×10^{-2}	4.30×10^{-7}
0.2013	4.49×10^{-2}	3.24×10^{-2}	4.83×10^{-2}	4.39×10^{-2}	6.08×10^{-2}	6.13×10^{-2}	7.41×10^{-2}	6.08×10^{-2}	1.49×10^{-5}
0.2155	3.94×10^{-2}	2.82×10^{-2}	4.32×10^{-2}	3.94×10^{-2}	5.35×10^{-2}	5.40×10^{-2}	6.58×10^{-2}	5.41×10^{-2}	3.08×10^{-5}
0.2416	3.74×10^{-2}	2.69×10^{-2}	4.02×10^{-2}	3.68×10^{-2}	5.11×10^{-2}	5.15×10^{-2}	6.08×10^{-2}	5.11×10^{-2}	3.45×10^{-5}
0.2498	3.48×10^{-2}	2.48×10^{-2}	3.81×10^{-2}	3.49×10^{-2}	4.75×10^{-2}	4.79×10^{-2}	5.75×10^{-2}	4.80×10^{-2}	4.72×10^{-5}
0.3595	2.46×10^{-2}	1.74×10^{-2}	2.68×10^{-2}	2.49×10^{-2}	3.42×10^{-2}	3.44×10^{-2}	3.91×10^{-2}	3.42×10^{-2}	9.76×10^{-5}
0.4918	1.68×10^{-2}	1.18×10^{-2}	1.90×10^{-2}	1.78×10^{-2}	2.35×10^{-2}	2.36×10^{-2}	2.70×10^{-2}	2.37×10^{-2}	1.73×10^{-4}
0.7353	1.06×10^{-2}	7.57×10^{-3}	1.24×10^{-2}	1.18×10^{-2}	1.47×10^{-2}	1.49×10^{-2}	1.69×10^{-2}	1.51×10^{-2}	2.43×10^{-4}

Target (T)	BB_{sec}	BB_{sec}	BB_{sec}	BB_{sec}	BB_{sec}	bb_{sec}	bb_{sec}	bb_{sec}	bb_{sec}	bb_{sec}
Source (S)	Fast Mucus	Slow Mucus	Bound	Sequestered	AI	Fast Mucus	Slow Mucus	Bound	Sequestered	AI
Average Energy, MeV										
0.0502	1.91×10^{-1}	2.18×10^{-1}	4.26×10^{-1}	8.16×10^{-2}	6.38×10^{-13}	1.80×10^{-1}	1.91×10^{-1}	2.39×10^{-1}	1.03×10^{-1}	2.28×10^{-4}
0.0914	2.63×10^{-1}	2.71×10^{-1}	3.16×10^{-1}	1.45×10^{-1}	3.38×10^{-10}	1.25×10^{-1}	1.27×10^{-1}	1.39×10^{-1}	8.66×10^{-2}	7.72×10^{-4}
0.1300	2.31×10^{-1}	2.34×10^{-1}	2.47×10^{-1}	1.47×10^{-1}	1.83×10^{-7}	8.64×10^{-2}	8.65×10^{-2}	9.25×10^{-2}	6.70×10^{-2}	1.09×10^{-3}
0.1418	2.16×10^{-1}	2.18×10^{-1}	2.28×10^{-1}	1.42×10^{-1}	6.96×10^{-7}	7.69×10^{-2}	7.68×10^{-2}	8.23×10^{-2}	6.06×10^{-2}	1.16×10^{-3}
0.2013	1.50×10^{-1}	1.51×10^{-1}	1.58×10^{-1}	1.09×10^{-1}	2.87×10^{-5}	4.69×10^{-2}	4.68×10^{-2}	5.08×10^{-2}	3.83×10^{-2}	1.40×10^{-3}
0.2155	1.31×10^{-1}	1.32×10^{-1}	1.40×10^{-1}	9.72×10^{-2}	6.05×10^{-5}	4.05×10^{-2}	4.05×10^{-2}	4.44×10^{-2}	3.31×10^{-2}	1.45×10^{-3}
0.2416	1.23×10^{-1}	1.23×10^{-1}	1.29×10^{-1}	9.33×10^{-2}	6.78×10^{-5}	3.59×10^{-2}	3.58×10^{-2}	3.90×10^{-2}	3.00×10^{-2}	1.48×10^{-3}
0.2498	1.14×10^{-1}	1.15×10^{-1}	1.21×10^{-1}	8.71×10^{-2}	9.33×10^{-5}	3.39×10^{-2}	3.39×10^{-2}	3.72×10^{-2}	2.81×10^{-2}	1.50×10^{-3}
0.3595	7.85×10^{-2}	7.85×10^{-2}	8.19×10^{-2}	6.38×10^{-2}	1.94×10^{-4}	2.02×10^{-2}	2.02×10^{-2}	2.21×10^{-2}	1.76×10^{-2}	1.61×10^{-3}
0.4918	5.31×10^{-2}	5.35×10^{-2}	5.60×10^{-2}	4.40×10^{-2}	3.43×10^{-4}	1.36×10^{-2}	1.37×10^{-2}	1.50×10^{-2}	1.20×10^{-2}	1.66×10^{-3}
0.7353	3.28×10^{-2}	3.45×10^{-2}	3.48×10^{-2}	2.81×10^{-2}	4.83×10^{-4}	8.50×10^{-3}	8.55×10^{-3}	9.33×10^{-3}	7.71×10^{-3}	1.71×10^{-3}

Table H.7. Algebraic functions used to approximate AF(T←S) for alpha-, electron-, negatron- and positron-emitting sources

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Function 1

$$AF(x) = a_1 e^{a_2[\log(\log(x)+a_3)]^2} + a_4 e^{a_5[\log(\log(x)+a_6)]^2} + a_7 e^{a_8[\log(\log(x)+a_9)]^2} + a_{10} e^{a_{11}[\log(\log(x)+a_{12})]^2}$$

Function 2

$$AF(x) = [1 - e^{-(x/a_{10})^{a_{11}}}][a_1(1 + a_2 e^{a_3 x} + a_4 e^{a_5 x} + a_6 e^{a_7 x} + a_8 e^{a_9 x})]$$

Function 3

$$AF(x) = \left\{\begin{matrix} a_2 & x < \dfrac{1}{a_4} \\ a_2 e^{-[a_3 \log(a_4 x)]^2} & x \geq \dfrac{1}{a_4} \end{matrix}\right\} + \left\{\begin{matrix} a_1 - a_2 & x < \dfrac{1}{a_6} \\ (a_1 - a_2) e^{-[a_5 \log(a_6 x)]^2} & x \geq \dfrac{1}{a_6} \end{matrix}\right\} + a_7 e^{-[a_8 \log(a_9 x)]^2}$$

Table H.8. Fitted values of parameters for substitution in algebraic functions to approximate AF(T ← S)$_{\alpha}$ for alpha-emitting sources

Case	Function	Fitted Value of Following Parameter											
		1	2	3	4	5	6	7	8	9	10	11	12
ET$_1$-surface	1	0.01796145	-3119.876	0.1900499	0.08115775	-332.282	-0.04370656	0.0385861	-1773.797	0.1467869	0.05591718	-884.288	0.08164135
ET$_2$-surface	1	0.001987374	-5601.585	0.1983734	0.06499644	-917.1186	-0.03310157	0.02179814	-2029.563	0.140741	0.02757517	-1792.149	0.07648437
ET$_2$-bound	3	0.1818	0.07177234	2.16186	0.4142823	0.6751693	0.9448594	0.0116813	7.590152	0.1566737	-	-	-
ET$_2$-seq.	1	0.004805373	-432.9348	0.2460405	0.06266583	-48.09133	0.2673597	0.05482465	-26.64634	0.2542903	0.03330228	-304.8436	0.3973314
BB$_{bas}$-fast	1	0.06983329	-1184.593	0.08742065	0.0240528	-2526.069	0.1479149	0.006534014	-12165.92	0.2029002	0.1142872	-416.8058	-0.03285549
BB$_{bas}$-slow	1	0.06992142	-1036.153	0.09166263	0.0319672	-2478.645	0.1784789	0.00769929	-4477.944	0.2313976	0.1134538	-376.5693	-0.03556158
BB$_{bas}$-bound	3	0.25	0.01563289	6.835241	0.3650127	1.836431	0.2704326	0.03526641	8.848307	0.08170446	-	-	-
BB$_{bas}$-seq.	1	0.02216691	-394.8869	0.1127097	0.1350273	-169.1389	0.2650755	0.00726001	-470.5375	0.4806218	0.07464973	-133.0544	-0.05250502
BB$_{bas}$-Al	-	-	-	-	-	-	-	-	-	-	-	-	-
BB$_{sec}$-fast	1	0.1752043	-381.9491	0.158163	0.01589757	-1162.612	0.3911134	0.2871758	-111.7757	-0.0161215	0.08175596	-528.7388	0.2770516
BB$_{sec}$-slow	1	0.09272864	-318.2638	0.1371357	-0.01108624	-1824.432	0.1549195	0.2892277	-29.22377	0.009140343	0.02527141	-353.2921	0.387492
BB$_{sec}$-bound	3	0.5	0.2663222	1.247913	0.395056	2.595532	0.2349517	0.09375073	6.073588	0.08536083	-	-	-
BB$_{sec}$-seq.	1	0.09811496	-390.2333	0.1676271	0.01968822	-859.2531	0.2946132	0.1328864	-163.7452	-8.938576 $\times 10^{-3}$	0.03513111	-3222.807	-0.0542812
BB$_{sec}$-Al	-	-	-	-	-	-	-	-	-	-	-	-	-
bb$_{sec}$-fast	1	0.04305129	-394.2624	0.4336853	0.07326854	-152.643	0.3898331	0.1704198	-44.87835	0.2104057	0.005133497	-741.4282	0.2740834
bb$_{sec}$-slow	1	0.007152097	-1449.924	0.3744433	0.1897075	-30.60365	0.329908	0.05060541	-113.7795	0.3189578	-4.889305 $\times 10^{-3}$	-580.5995	0.1890273
bb$_{sec}$-bound	3	0.4	0.2330375	1.606937	0.6944076	1.617835	0.2810387	-0.02880487	7.887438	0.240524	-	-	-
bb$_{sec}$-seq.	1	0.06082015	-217.5413	0.4092593	0.09193827	-25.71987	0.1000563	0.0118824	-1568.605	0.1839267	0.02114782	-417.2795	0.1039428
bb$_{sec}$-Al	1	9.583849 $\times 10^{-5}$	-792.4591	0.2191848	9.621604 $\times 10^{-4}$	-133.7145	-0.1589139	3.212547 $\times 10^{-4}$	-309.0881	0.06662389	1.811347 $\times 10^{-5}$	-1487.62	0.3003989

Table H.9. Fitted values of parameters for substitution in algebraic functions to approximate AF(T←S)$_e$ for electron-emitting sources

Case	Function	Fitted Value of Following Parameter											
		1	2	3	4	5	6	7	8	9	10	11	12
ET_1←surface	1	0.065053	-354.406	2.014387	0.036335	-991.429	2.125458	0.019842	-24.6374	1.580302	0.046065	-100.628	1.835525
ET_2←surface	1	0.009434	-18.2563	1.521565	0.010917	-1134.08	2.108072	0.030823	-80.0744	1.78897	0.039695	-234.006	1.959684
ET_2←bound	3	0.1818	0.012801	0.790806	13.45734	1.162724	53.70593	-0.00902	11.51802	10.27388	-	-	-
ET_2←seq.	1	0.036493	-17.099	1.957065	0.012268	-490.983	2.372073	0.013901	-80.9776	1.766727	0.121082	-89.8524	2.286418
BB_{bas}←fast	1	0.022208	-23.543	1.526898	0.055161	-678.604	2.076011	0.052048	-89.4917	1.772334	0.077509	-288.868	1.957359
BB_{bas}←slow	1	0.024444	-23.3706	1.562825	0.028798	-705.929	2.123317	0.057382	-87.789	1.808263	0.083806	-281.914	1.99725
BB_{bas}←bound	3	0.25	0.023337	0.867548	14.66598	1.381178	33.94687	-0.0168	8.056959	11.69128	-	-	-
BB_{bas}←seq.	1	0.084383	-43.1191	1.918628	0.117906	-169.24	2.234064	0.001411	-86.001	1.263035	0.009699	-16.5773	1.414384
BB_{bas}←AI	2	0.000393	-400.456	-1.80563	777.7234	-1.732	3.733329	-10.2482	-379.908	-1.66248	0.287203	-	-
BB_{sec}←fast	1	0.219072	-180.389	2.123581	0.072201	-21.9379	1.724434	0.010307	-1090.27	2.323796	0.165766	-67.5677	1.939
BB_{sec}←slow	1	0.190302	-131.282	2.113636	0.061225	-18.8215	1.792023	0.049712	-394.019	2.350691	0.15794	-46.6822	1.963819
BB_{sec}←bound	3	0.5	0.07042	0.886749	19.05802	1.54244	27.37533	-0.03274	6.968345	13.33513	-	-	-
BB_{sec}←seq.	1	-0.20809	-572.72	2.174599	0.278314	-476.006	2.168483	0.125274	-69.2237	1.918443	0.058332	-21.8086	1.689866
BB_{sec}←AI	2	0.000786	-859.74	-1.61489	1689.772	-1.57364	124.4556	-25.1186	-832.213	-1.53368	0.287178	-	-
bb_{sec}←fast	1	0.112968	-358.216	2.393708	0.131671	-170.786	2.268427	0.015445	-18.7936	1.870242	0.101948	-60.4808	2.088622
bb_{sec}←slow	1	0.025629	-538.817	2.535345	0.175729	-48.4179	2.257859	0.018913	-16.7686	2.055972	0.071751	-189.165	2.344306
bb_{sec}←bound	3	0.4	0.048063	0.711481	149.3354	1.621245	45.538	-0.03676	6.960692	22.59052	-	-	-
bb_{sec}←seq.	1	0.059129	-139.756	2.153796	0.059699	-53.6711	2.02631	0.010356	-16.8711	1.82904	0.085985	-306.92	2.369979
bb_{sec}←AI	2	0.001772	-2.64463	-16.7712	1.116624	-2.11559	3.291514	-46.8517	-1.27588	-2.11622	0.04	-	-

Table H.10. Fitted values of parameters for substitution in algebraic functions to approximate $AF(T \leftarrow S)_\beta$ for negatron-emitting sources

Case	Function	Fitted Value of Following Parameter											
		1	2	3	4	5	6	7	8	9	10	11	12
ET_1-surface	1	0.007260547	-214.975	2.138641	0.042368	-72.4619	2.277767	0.022782	-22.0916	1.691069	0.022747	-59.75927	1.941653
ET_2-surface	1	0.01331365	-15.6042	1.845584	0.001949	-197.04	2.440315	0.027893	-32.5319	2.080803	0.003504	-1961.651	2.168247
ET_2-bound	3	0.1818	0.005491	0.624598	13.86767	0.911726	109.2302	0.006082	8.85072	26.44496	-	-	-
ET_2-seq.	1	0.04801472	-17.2882	2.175034	-4.883634×10^{-4}	-2992.341	1.441663	0.013695	-17.2668	2.17597	0.05804	-42.80398	2.587552
BB_{bas}-fast	1	0.01065945	-21.2405	1.501157	0.007667	-144.422	2.40235	0.073701	-31.5976	2.064326	0.002144	-11.89227	1.485352
BB_{bas}-slow	1	0.001019174	-461.785	1.68968	0.003389	-237.087	2.520264	0.075876	-31.0442	2.097391	0.014213	-18.83598	1.536484
BB_{bas}-bound	3	0.25	0.052229	1.052155	11.1468	1.11143	63.96697	-0.02104	1.387472	5.617411	-	-	-
BB_{bas}-seq.	1	0.037944	-17.7681	1.987425	0.075468	-28.3941	2.379867	3.445695×10^{-4}	-0.17368	0.410269	0.005617	-30.8274	1.702996
BB_{bas}-Al	2	0.000393	-399.076	-1.92481	776.0208	-1.86139	1.074593	-13.1079	-378.607	-1.79829	0.125493	-	-
BB_{sec}-fast	1	0.143302	-17.7531	2.190977	0.006898	-27.6829	1.815797	0.034881	-32.2445	1.864587	0.077187	-57.9359	2.250686
BB_{sec}-slow	1	0.106393	-50.9856	2.059853	0.087523	-20.5774	1.794522	0.178955	-79.912	2.361594	0.032524	-141.552	2.688903
BB_{sec}-bound	3	0.5	0.359364	0.980582	29.60645	1.72647	58.14844	-0.06287	1.4409	5.434251	-	-	-
BB_{sec}-seq.	1	0.001561	-422.127	1.68267	0.128516	-26.127	2.105497	0.015492	-192.227	2.573017	0.02262	-17.1193	1.582392
BB_{sec}-Al	2	0.000786	-858.987	-1.80744	1689.334	-1.76746	1.491341	-17.0219	-831.919	-1.72768	0.135082	-	-
bb_{sec}-fast	1	0.118654	-42.9886	2.542548	0.017149	-163.798	2.364503	0.002686	-0.07416	1.999984	0.064615	-27.5346	2.115816
bb_{sec}-slow	1	0.009441	-107.098	1.967708	0.027929	-117.991	2.346719	0.148723	-20.6229	2.490604	0.001544	-3.06218	0.2665706
bb_{sec}-bound	3	0.4	0.384747	1.081031	117.5969	0.278079	11116.34	0.011772	3.932391	25.07208	-	-	-
bb_{sec}-seq.	1	0.007053	-517.297	2.360246	0.052797	-27.4988	2.131317	0.00355	-4.04509	1.550754	0.061775	-41.8298	2.527532
bb_{sec}-Al	2	0.001772	1.187132	-6.50216	-0.93579	-4.92343	-1.55613	-12.3008	-0.04425	-1.11709	0.028217	-	-

Table H.11. Fitted values of parameters for substitution in algebraic functions to approxiamte $AF(T \leftarrow S)_{\beta}$, for positron-emitting sources

Case	Function	Fitted Value of Following Parameter									
		1	2	3	4	5	6	7	8	9	10
ET_1-surface	1	0.05322816	-21.71451	2.00191	0.01714905	-130.3817	1.964898	-	-	-	-
ET_2-surface	1	0.04431926	-42.17116	1.973219	0.006364313	-18.8606	1.38528	0.003121981	-619.5877	1.856081	-
ET_2-bound	3	0.1818	0.03912537	0.7279522	62.07332	1.13077	70.05861	0.002588461	9.489306	6.71969	-
ET_2-seq.	1	0.1125952	-18.71891	2.401096	0.001646783	-495.9539	1.863785	0.002025164	-6.601281	1.991395	-
BB_{bas}-fast	1	0.1807752	-30.55993	2.321773	0.003371729	-12.24436	1.031105	-	-	-	-
BB_{bas}-slow	1	0.03151836	-93.69928	1.955103	0.00297028	-243.6406	1.483551	0.05984907	-19.91434	1.978257	-
BB_{bas}-bound	3	0.25	0.04072582	0.7468408	45.66627	1.210492	49.99281	0.005529276	6.964317	7.948904	-
BB_{bas}-seq.	1	0.1082752	-19.90269	2.193376	0.005193127	-284.8619	1.889372	-	-	-	-
BB_{bas}-AI	2	0.000393	0.3820852	-5.888078	15.64833	-6.227923	-0.5064243	-0.6857757	-16.19697	-5.74402	0.1488892
BB_{sec}-fast	1	0.2223405	-21.31977	2.120883	0.05309095	-130.6415	1.96757	-	-	-	-
BB_{sec}-slow	1	0.278994	-35.0835	2.123887	0.03064369	-19.41535	1.482641	0.01636537	-383.9252	1.874274	-
BB_{sec}-bound	3	0.5	0.4160702	1.261345	43.47673	0.7699746	39.87167	0.01733794	-6.178277	8.513134	-
BB_{sec}-seq.	1	0.1456244	-24.753	2.00227	0.004632916	-9.655873	1.182674	0.009628979	-544.2251	1.860261	-
BB_{sec}-AI	2	0.000786	-863.2728	-1.606256	1697.492	-1.569777	1.250145	-12.01085	-835.9406	-1.533899	0.1464553
bb_{sec}-fast	1	0.1807752	-30.55993	2.321773	0.003371729	-12.24436	1.031105	-	-	-	-
bb_{sec}-slow	1	0.1912379	-34.05969	2.330431	0.006024704	-8.283113	1.555655	-	-	-	-
bb_{sec}-bound	3	0.4	0.3672543	1.321432	71.06928	0.550374	229.7179	0.004494271	5.856029	9.402349	-
bb_{sec}-seq.	1	0.1004748	-30.38266	2.263786	0.005187536	-5.466993	1.802651	0.006954227	-221.8221	1.939597	-
bb_{sec}-AI	2	0.0017722	1.769239	-16.12147	8.876924	-16.75289	-11.95439	-16.12309	-0.1860699	-2.2441	0.03374213