CONF-8909190--1

PNL-SA--17851

DE90 008608

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September 1989

Presented at the
1989 Technical Exchange Meeting
Grand Junction, Colorado
September 18-19, 1989

Work supported by
the U. S. Department of Energy
under Contract DE-AC06-76RLO 1830

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REASSESSMENT OF FACTORS INFLUENCING LUNG DOSE FROM RADON DAUGHTERS[a]

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Recent research findings allow for better representation of several biological and physical factors in the modeling of dose to the lung from exposure to radon daughters. New information is available on the efficiency of the nose in filtering unattached radon daughters from inhaled air, the thickness of bronchial epithelium and location of sensitive target cells, the size distribution of unattached daughters and of the fraction of daughters attached to room aerosols, and the variability of these aerosol conditions in actual homes. This information is used here in an updated dosimetry model to reassess the relationship between indoor exposure and bronchial dose, and to evaluate variability with room conditions.

The bronchial dosimetry model described by James (1987; 1988) has been updated by incorporating a more comprehensive treatment of lung ventilation and aerosol deposition behavior (Egan et al. 1989). The sensitive targets are considered to be the nuclei of secretory cells, in both bronchial and bronchiolar epithelia. According to the new data reported by Bowden and Baldwin (1989), these nuclei are located 10 to 30 μm beneath the tissue surface in the bronchi and 10 to 20 μm in the bronchioles. The result of updating the dosimetry calculation is shown in Figure 1, which gives the mean dose to target cell nuclei per unit exposure to potential α-energy (in Working Level Month, [WLM]) as a function of the median particle size of the radon daughter aerosol (represented by the activity median diffusion diameter [AMDD] in 10^{-9} m). The effect of the new calculation is mainly to increase the estimate of dose for radon daughter aerosols of large median size (i.e., AMDD > 300 nm) inhaled at the higher breathing rate during exercise. This is relatively unimportant in assessing doses from indoor exposure, but may be significant for underground miners.

The dose conversion coefficients shown in Figure 1 do not include the effect of partial filtration of ultrafine particles by the nose or mouth. Swift and Strong[a] studied the deposition of unattached ^{218}Po in several different casts made from the nasal and oral passages of adult males. They found that the deposition efficiency is approximately 70% in both the nasal or oral passages. Their data are plotted in Figure 2 against the empirical parameter $Q^{-1/8} \times D^{2/3}$, which was found by Cheng et al. (1988) to represent deposition of larger particles in the nose and mouth by turbulent diffusion, where Q is the flow rate in Lpm and D is the particle diffusion coefficient in $cm^2\ s^{-1}$.

(a) This research is supported by the Office of Health and Environmental Research of the U.S. Department of Energy, under Contract DE-AC06-76RLO 1830.

(b) 1989 - personal communication, National Radiological Protection Board [NRPB], UK.

Swift and Strong's results are represented by the following expression for the deposition efficiency, ϵ:

$$\epsilon = 1 - \exp(-12.5\ Q^{-1/8}\ D^{2/3}) \qquad (1)$$

Figure 3 compares curves of nasal deposition efficiency as a function of flow rate, which are predicted by Equation (1), with values measured by George and Breslin (1969) in three experimental subjects who inhaled unattached ^{218}Po. The data are consistent with the predicted insensitivity of deposition to the flow rate, $Q^{-1/8}$. George and Breslin did not measure the diffusion coefficient of the unattached ^{218}Po under their experimental conditions, and it is now known that this may vary in the range of 0.03 to 0.08 $cm^2\ s^{-1}$. However, the value of 0.045 $cm^2\ s^{-1}$ that is implied by Swift and Strong's data from nasal casts (Equation [1]) is considered to be realistic.[a]

Figure 4 shows how the conversion coefficient from exposure to dose is predicted to vary with radon daughter aerosol size when Equation (1) is used to represent the filtration efficiency of the nose (or mouth). In indoor air, a particle size of about 0.09 nm ($D = 0.045\ cm^2\ s^{-1}$) can be taken to characterize the unattached fraction of radon daughter potential α-energy (Tu and Knutson 1988; Reineking, Becker, and Pörstendorfer 1988). The corresponding value of the dose conversion coefficient, D^u, is found to be 92 mGy/WLM. The AMDD of the attached fraction has been shown to depend on the source of aerosol particles in room air (Pörstendorfer, Reineking, and Becker 1987; Reineking, Becker and Pörstendorfer 1988). These authors reported average values of 130 nm and 188 nm, respectively, for the AMDD of "attached" potential α-energy. It is reasonable to adopt an intermediate value of 150 nm as a current "best estimate." The corresponding value of the dose conversion coefficient is found to be 5.6 mGy/WLM. However, the aerosol particles on which radon daughters are attached are likely to grow larger in the humid air of the respiratory tract. The experimental evidence indicated that these condensation nuclei grow rapidly under conditions of saturated humidity, to approximately double the size of the ambient aerosol (George and Breslin 1969; Sinclair, Countess, and Hoopes 1974; Pörstendorfer and Mercer 1978). Doubling the AMDD of attached potential α-energy from 150 nm to 300 nm is found to reduce the dose conversion coefficient to 3.6 mGy/WLM. This value is proposed to characterize the dose conversion coefficient, D^a, for "attached" radon daughter potential α-energy in indoor air. On these bases, it is found that exposure to radon daughter potential α-energy in the "unattached" state gives approximately a 25 times greater dose than exposure to the same quantity of potential α-energy in the "attached" state. Thus, the dose is approximately doubled by each 4% increment in the unattached fraction of potential α-energy.

Reineking and Pörstendorfer (1989) have studied the variability of radon daughter equilibrium and the unattached fraction of potential α-energy under a variety of conditions in actual homes. The implications of their findings for the assessment of lung dose are illustrated in Figures 5 through 7.

(a) E. O. Knutson, Environmental Measurements Laboratory, personal communication.

Figure 5 indicates the uncertainty in dose estimation introduced by assuming that dose is simply proportional to the exposure to potential α-energy (WLM), irrespective of the variability in unattached fraction. The value of dose given by applying a fixed conversion coefficient of 8.3 mGy/WLM is plotted against the "best estimate" obtained by resolving the "unattached" and "attached" components of the exposure (WLM^u and WLM^a), where

$$D\ (mGy) = D^a \times WLMa + D^u \times WLM^u \qquad (2)$$

The value of 8.3 mGy/WLM corresponds to the rounded estimate of 10 mSv/WLM for the effective dose equivalent per unit exposure recommended by the National Radiological Protection Board in the United Kingdom (NRPB 1987; James et al. 1988). Each point plotted in the figure represents the average of several measurements of f_p made in different rooms of several homes. The open circles represent rooms where the ventilation rate was low (< 5 air changes per hour) and there was no identifiable source of aerosol particles. The solid circles represent conditions in rooms with various strong sources of aerosol particles, such as cooking and gas heating; solid triangles represent cigarette smoke. The lines drawn in the figure show the regression of dose estimated from total WLM against the "best estimate." It is seen that the coefficient of determination is high (denoted by $r^2 = 0.78$) for rooms without aerosol sources, while it is low (denoted by $r^2 = 0.22$) in the presence of strong sources. On average, the conversion coefficient of 8.3 mGy/WLM underestimates the best estimate of dose by about 30% in rooms without aerosol sources (indicated by $b = 0.71$), while for rooms with strong sources it tends to overestimate the dose (indicated by $b = 1.14$).

The uncertainty introduced by basing the dose assessment on exposure to radon gas is indicated by Figure 6. In this case, the values of dose are estimated by applying the following dose conversion coefficient (NRPB 1987; James et al. 1988):

$$\text{Exposure to } 20\ Bq/m^3 \text{ for 1 year} = 1\ mSv \text{ (effective dose equivalent)} \qquad (3)$$

The coefficient of determination is found to be reasonably high in relation to the best estimate of dose, irrespective of the presence or absence of aerosol sources ($r^2 = 0.59$ and 0.77). To evaluate the "best estimate" of annual dose, the annual exposure was calculated from the measured concentrations of potential α-energy on the assumption that the occupancy factor is 65% (ICRP 1987). This corresponds to 33.5 periods of 170 hours (Working Months) per year. The ratio of the potential α-energy to the radon concentration (equilibrium factor, F) was found by Reineking and Pörstendorfer (1989) to be 0.28 in rooms without aerosol sources, and 0.40 in rooms with sources. Accordingly, on the average, their data indicated that the estimate of 1 mSv per 20 Bq/m^3 of radon concentration overestimates the annual dose in rooms without sources by about 55% ($b = 1.55$), and in rooms with sources by about 77% ($b = 1.77$).

Finally, Figure 7 indicates the level of uncertainty introduced by basing the dose assessment only on a measured concentration of unattached potential α-energy in room air. In this case, the coefficient of determination is very high for rooms without aerosol sources (denoted by $r^2 = 0.96$), and reasonably high in rooms with sources ($r^2 = 0.70$). On the average, it is found that unattached potential α-energy contributes 74% ($b = 0.74$) of the total dose in rooms without sources, and 56% ($b = 0.56$) of the total dose in rooms with sources.

These data support the practical view that exposure to radon gas is a reliable indicator of dose in the home. Furthermore, the observation that in most situations unattached radon daughters contribute the major component of lung dose lends credence to the idea that long-lived α-activity accumulated on a sample surface can be used to estimate dose in epidemiological studies. The quality of the dose estimate achievable by this means will depend primarily on how well the airborne concentration of unattached daughters is determined by the rate of plateout to exposed surfaces. This is averaged by the measurement technique over a protracted period of past exposure.

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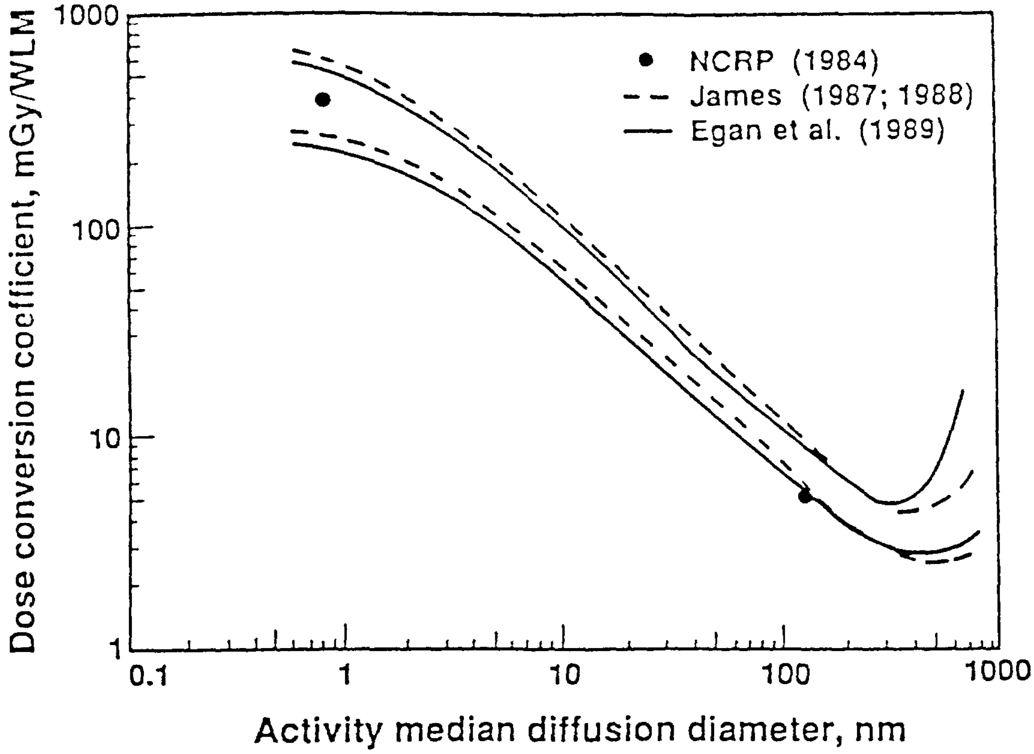

FIGURE 1. Comparison of the Conversion Coefficient from Exposure to Bronchial Dose (mGy/WLM) Calculated for an Adult Male as Functions of Radon Daughter Aerosol Size Using the Deposition Models of James (1987; 1988) or Egan et al. (1989) with Values Derived by the National Council of Radiation Protection and Measurements (NCRP) (1984). These dose conversion coefficients exclude the effect of nasal or oral filtration of very small particles.

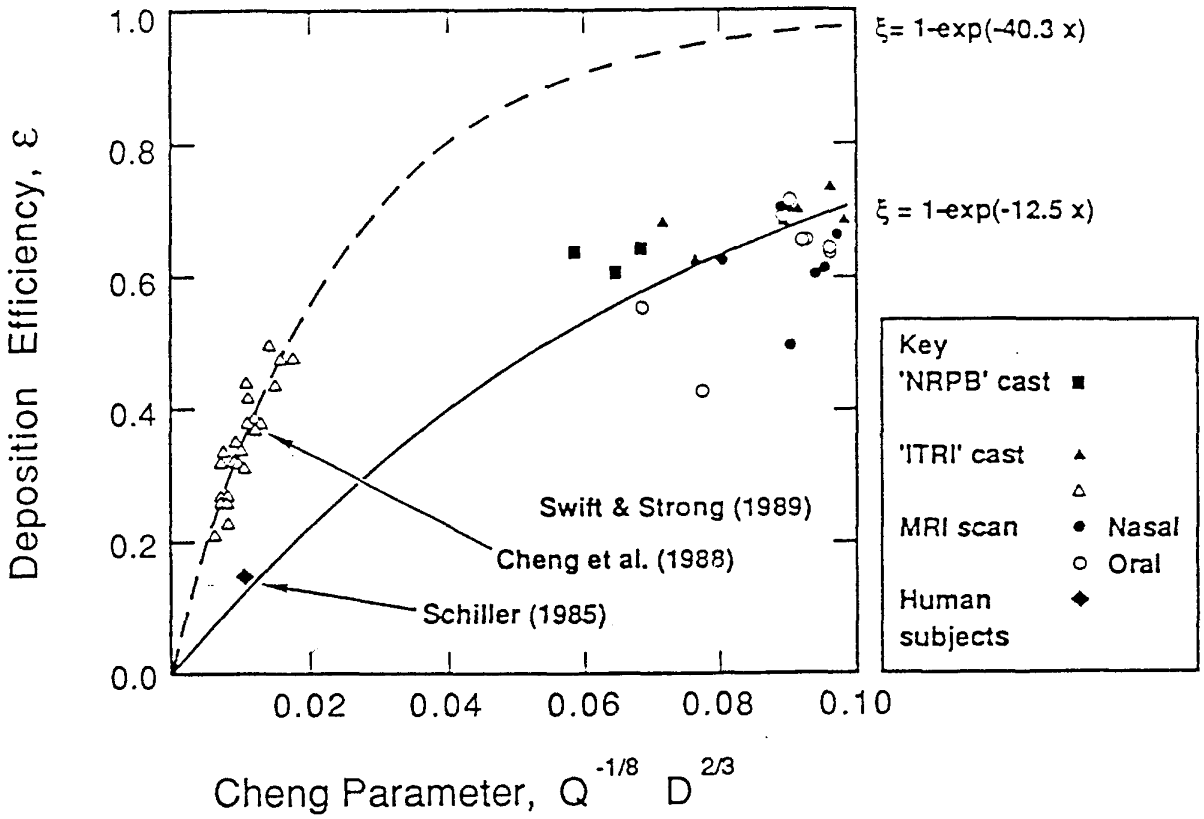

FIGURE 2. Experimental Data on Deposition of Sub-Micron-Sized Particles in the Human Nose or Oral Passageway, Plotted Against the Cheng Turbulent Diffusion Parameter, X. Data for $X \leq 0.02$ were obtained by Cheng et al. (1988) by drawing particles through a hollow cast made from both the nasal and oral passages of a cadaver. The single datum point at $X \sim 0.02$ was obtained by Schiller (1985) from a study of volunteer subjects. Data for $X \geq 0.06$ were obtained by Swift and Strong (1989) by drawing unattached ^{218}Po through several different hollow nasal casts, including one made from a magnetic resonance image (MRI) scan of a living subject. The solid curve shows the nasal deposition efficiency function fitted to the data of Swift and Strong (both nasal and oral). The dashed curve shows the function fitted to the data of Cheng et al. for both nasal and oral casts.

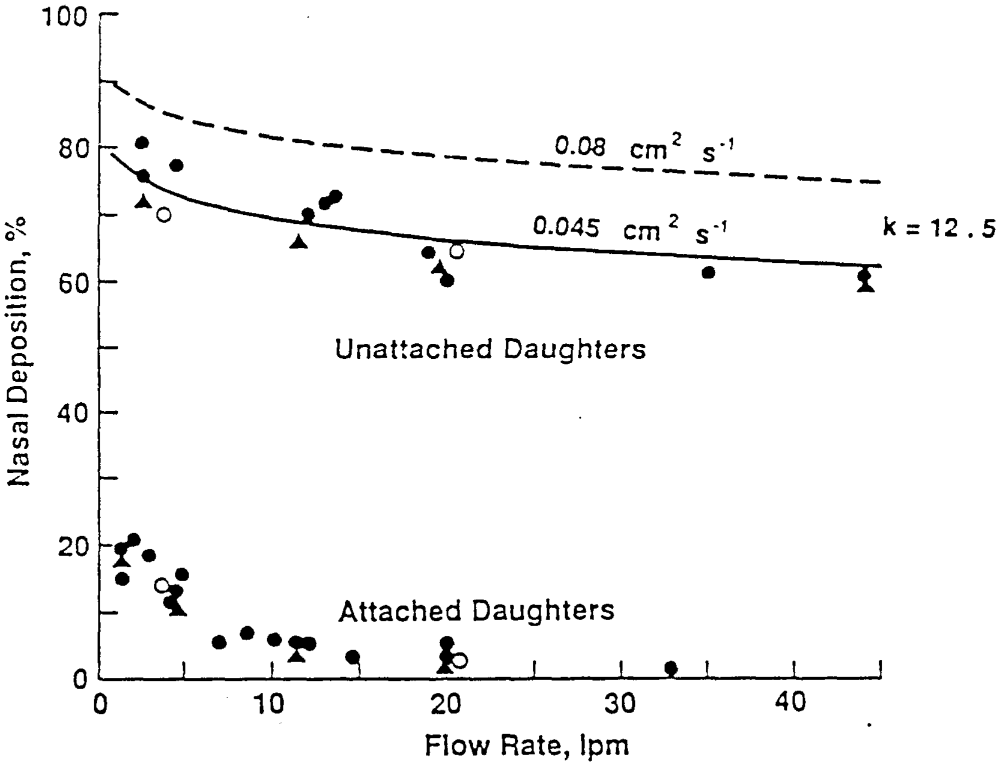

FIGURE 3. Nasal Deposition of Unattached and Attached Radon Daughters Measured by George and Breslin (1969) in Several Human Subjects. The curves show values of nasal deposition predicted by the efficiency function with the exponential parameter k = 12.5 (see Figure 2) for two values of the diffusion coefficient of unattached ^{218}Po.

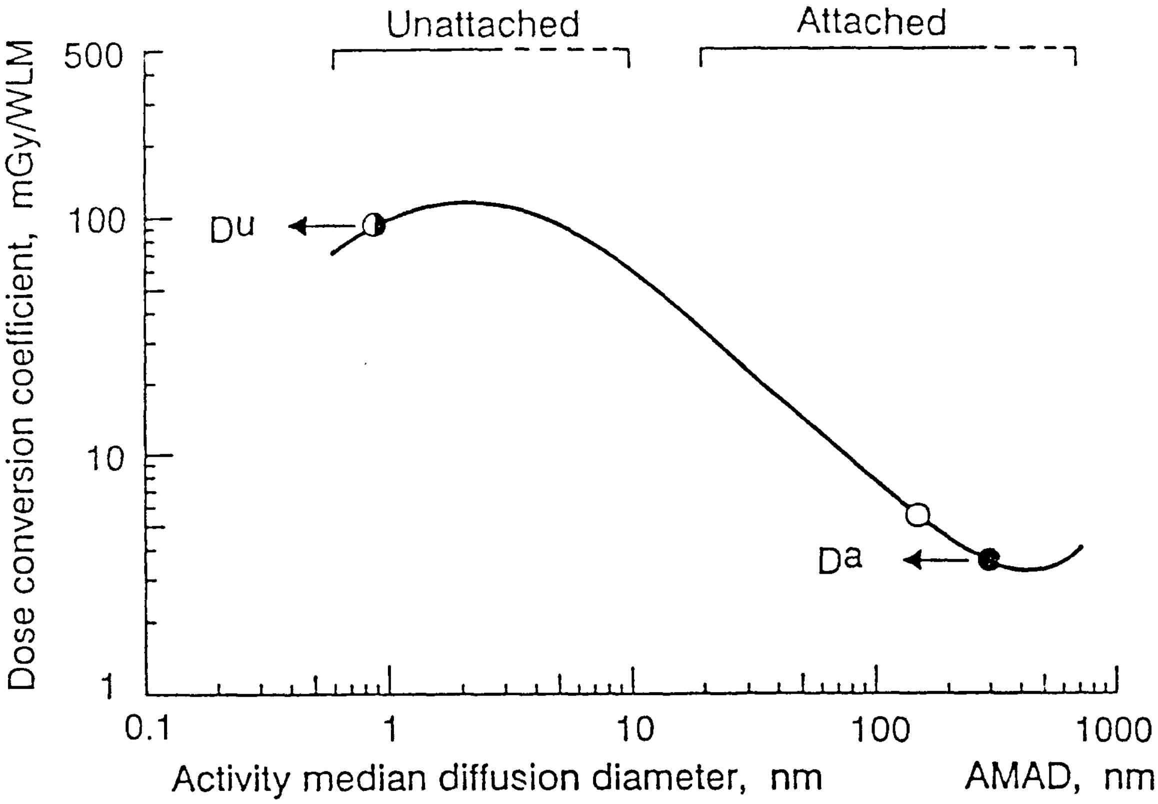

FIGURE 4. Dose Conversion Coefficients for Exposure in Homes to Radon Daughter Potential α-Energy (mGy/WLM) Calculated as a Function of the Aerosol Activity Median Diffusion Diameter (AMDD). D^u and D^a indicate proposed reference values for the typical particle size of unattached daughters and for the typical AMDD of the attached aerosol after humid growth in the respiratory tract.

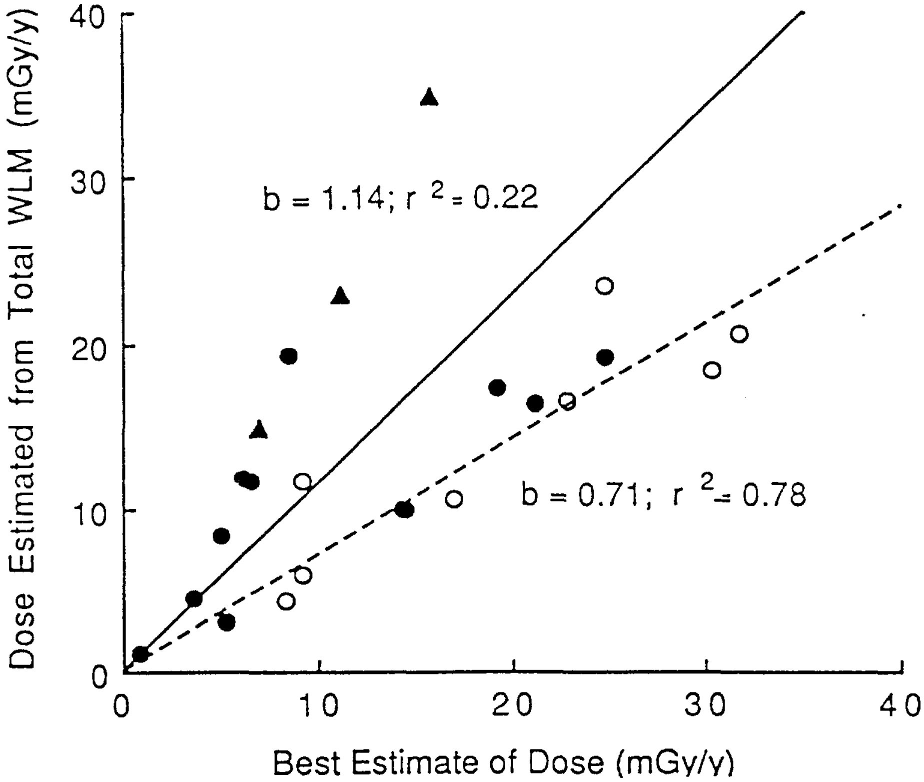

FIGURE 5. Correlation of the Dose (mGy/y) Estimated from Total Exposure to Potential α-Energy (WLM/y) with the Best Estimate Obtained by Taking into Account the Unattached Fraction. Each datum point relates to Reineking and Pörstendorfer's (1989) measurements of the potential α-energy concentration and unattached fraction in a particular room under natural domestic conditions. The symbols are described in the text.

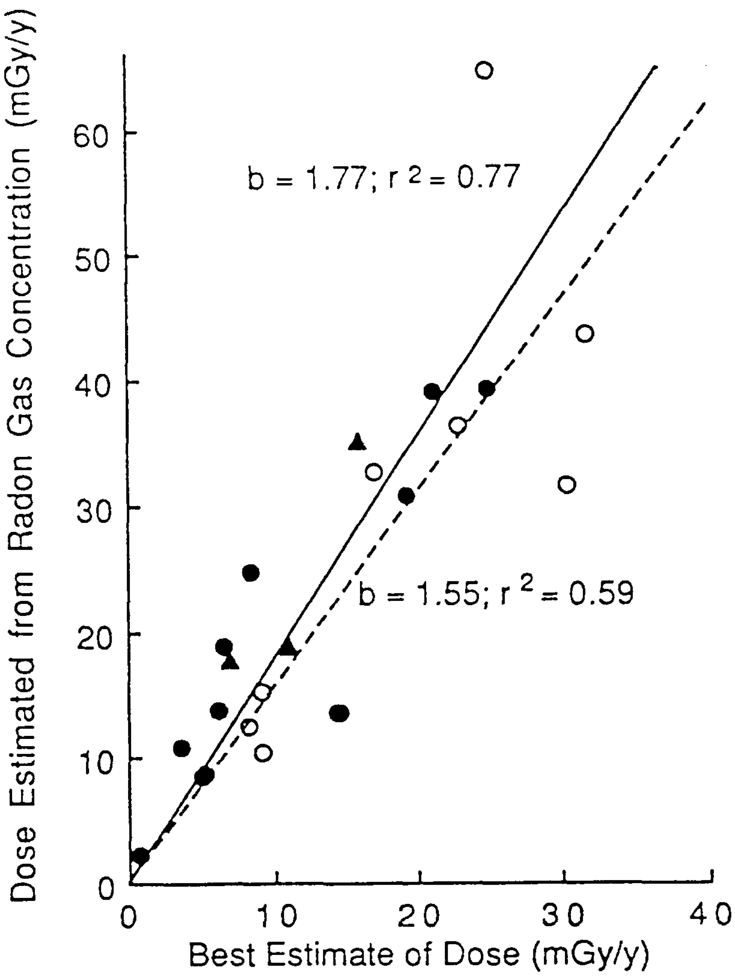

FIGURE 6. Correlation of the Dose (mGy/y) Estimated from the Concentration of Radon Gas with the Best Estimate Obtained from the Measured Concentration of Potential α-Energy and Unattached Fraction. The symbols are as described for Figure 5.

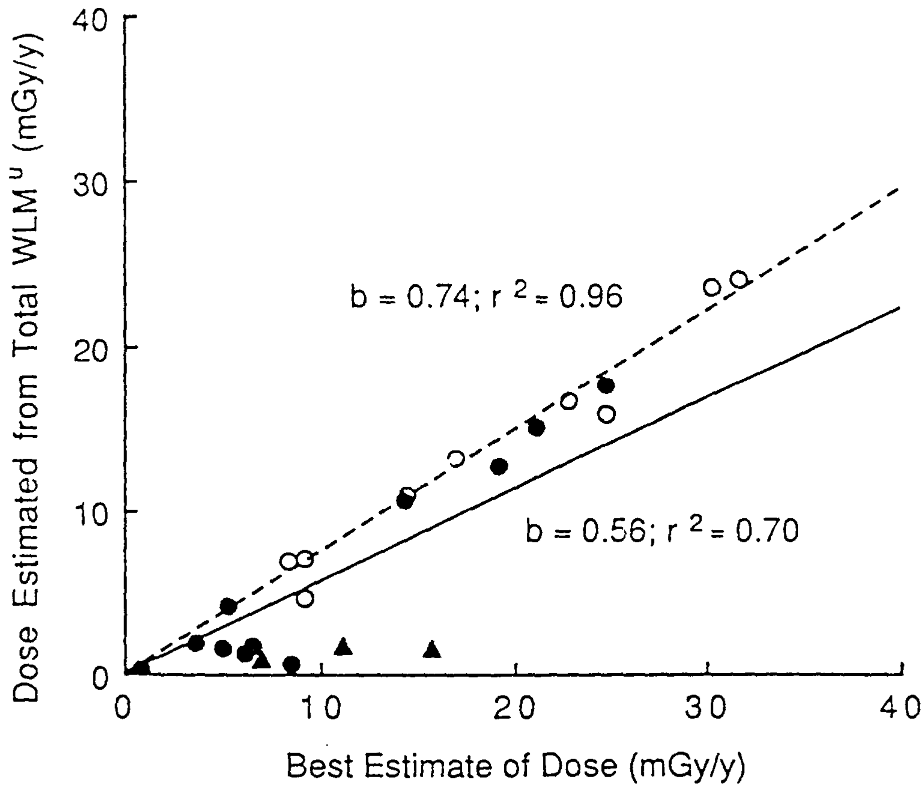

FIGURE 7. Correlation of the Dose (mGy/y) Estimated from the Concentration of Unattached Potential α-Energy with the Best Estimate that Includes the Additional Dose from the Attached Fraction. The symbols are as described for Figure 5.