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α-Radiation dose at bronchial bifurcations of smokers from indoor exposure to radon progeny

(radiation carcinogenesis/inhalation toxicology/lung dosimetry/bronchial cancer)

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ABSTRACT **Synergistic interactions of indoor radon progeny with the cigarette smoking process have been evaluated experimentally. Smoking enhances the air concentration of submicron particles and attached radon decay products. Fractionation in burning cigarettes gives rise to the association of radon progeny with large particles in mainstream cigarette smoke, which are selectively deposited in "hot spots" at bronchial bifurcations. Because smoke tars are resistant to dissolution in lung fluid, attached radon progeny undergo substantial radioactive decay at bifurcations before clearance. Radon progeny inhaled during normal breathing between cigarettes make an even larger contribution to the α-radiation dose at bifurcations. Progressive chemical and radiation damage to the epithelium at bifurcations gives rise to prolonged retention of insoluble ^{210}Pb-enriched smoke particles produced by tobacco trichome combustion. The high incidence of lung cancer in cigarette smokers is attributed to the cumulative α-radiation dose at bifurcations from indoor radon and thoron progeny—^{218}Po, ^{214}Po, ^{212}Po, and ^{212}Bi—plus that from ^{210}Po in ^{210}Pb-enriched smoke particles. It is estimated that a carcinogenic α-radiation dose of 80–100 rads (1 rad = 0.01 J/kg = 0.01 Gy) is delivered to ≈10^7 cells (≈10^6 cells at individual bifurcations) of most smokers who die of lung cancer.**

Estimates of the risk of lung cancer due to exposure to indoor radon progeny (1, 2) and that due to cigarette smoking have been treated as two independent problems. However, uranium miners who smoked cigarettes experienced an exceptionally high incidence of lung cancer (3). Doll (4) pointed out that the excess of lung cancer deaths among smoking uranium miners is a multiplicative effect, which suggests possible synergistic interactions between radon progeny and the cigarette-smoking process. This paper discusses experimental evidence on the properties of indoor radon progeny, their interactions with smoke particles, their modification within burning cigarettes, and their distribution and persistence in smoker's lungs. A preliminary estimate of the cumulative α-radiation dose (α-dose) at the segmental bifurcations of smokers is made.

Indoor radon

Airborne radon-222 and its radioactive decay products are ubiquitous; their concentrations are about 10 times higher indoors than in outside air in summer and much higher inside energy-efficient homes in winter. Natural radon gas, emanating from radium in soils, is present at high concentrations in soil gases and enters homes through unpaved basements and crawl spaces and through wet and porous structural materials. Building materials containing radium-226 and dissolved radon in water from artesian wells also contribute to indoor radon. The average indoor radon level is about 1 pCi/liter of air (1 Ci = 3.7 × 10^{10} Bq). Indoor radon levels vary widely from this average. One study (5) showed radon concentrations ranging from 5 to 33 pCi/liter in 9 of 22 residential structures.

Experimental methods

The properties and dynamics of indoor radon progeny were determined in laboratory chamber experiments by using radioactivity and aerosol measurement techniques. Small chambers ranging from 10 to 60 liters in volume, each with a solution standard of radium-226 acidified to 0.1 M HNO_3, were used as sources of known radon and radon progeny concentration. Radon concentrations were determined by standard techniques. Radon progeny determinations were made by collecting the aerosol particles on filters or multistage cascade impactors. The activity on each filter and each impactor stage was determined by low-level β^--particle counting methods (6), which provided sufficient sensitivity for particle-size measurements of radon progeny at levels of only 10–100 pCi/liter of air. In some chamber experiments, a dry thorium-228 source of thoron was used to prepare ^{212}Pb-tagged aerosols. The 10.6-hr half-life of ^{212}Pb makes it a convenient tracer for the study of radon-progeny aerosols.

Concentrations of small particles were determined with a modified Rich 100 CN (condensation nuclei) Monitor, a stable portable system for determining the air concentration of particles from 0.02- to 1.0-μm diameter over the concentration range of 10^2–10^7 particles per cm^3. Particle size determinations were made with a modified Battelle-type cascade impactor calibrated to provide five stages of impaction with aerodynamic diameter intervals as follows: >4.0 μm, 2.0–4.0 μm, 1.0–2.0 μm, 0.5–1.0 μm, and 0.25–0.50 μm. Particles below 0.25-μm diameter were collected on an efficient backup filter. These experimental techniques are described in more detail elsewhere (6, 7).

Dependence of airborne radon progeny on particle concentration

Inhalation exposure to indoor radon progeny is highly dependent on the concentration and size distribution of small particles in room air. The radioactive decay sequence and half-lives for

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Abbreviations: WL, working level (unit of radon-progeny exposure for uranium miners); WLM, unit of WL months (1 WLM = exposure to 1.0 WL for 170 hr); α-dose, α-radiation dose; AMAD, activity median aerodynamic diameter.

radon and its short-lived decay products is as follows:

$$^{222}\text{Rn} \xrightarrow{\alpha} {}^{218}\text{Po} \xrightarrow{\alpha} {}^{214}\text{Pb} \xrightarrow{\beta^-} {}^{214}\text{Bi} \xrightarrow{\beta^-} {}^{214}\text{Po} \xrightarrow{\alpha} {}^{210}\text{Pb} \xrightarrow{\beta^-}$$

3.8 day	3.05 min	27 min	19.7 min	1.6×10^{-4} sec	22 yr

When radon atoms decay by α-particle emission in air, the positively charged ^{218}Po recoil nuclei rapidly associate with polar molecules to form ions, which diffuse rapidly and become attached to airborne particles or to walls and surfaces. The fraction of indoor radon progeny attached to airborne particles is highly dependent on particle concentration. Pollack (8) showed that the rate of disappearance of small particles in a closed chamber can be expressed by the differential equation:

$$dZ/dt = -\gamma Z^2 - \lambda Z,$$

where Z denotes the concentration of particles and dZ/dt is the rate of decrease in particle concentration. The term γZ^2 represents the decrease in particle concentration due to coagulation, whereas the λZ term represents the reduction in particle concentration caused by deposition on chamber walls and surfaces. For natural Aitken particles (<0.2-μm diameter), the linear term becomes important when Z falls below ≈5,000 particles per cm^3 because the ratio λ/γ for Aitken particles is ≈1,000 (8). The presence of large particles provides a very effective sink for ions and small particles (9). Thus, for example, the coagulation constant for attachment of 0.001-μm-radius particles to 1.0-μm-radius particles is 250 times that for the self-coagulation of 0.001-μm particles (9).

These mechanisms have important implications for the air concentration, the attached fraction, and the size distribution of indoor radon-progeny aerosols. For clean, filtered indoor air with Aitken particle concentrations of $<10^3$ per cm^3, deposition of radon-progeny ions on walls and surfaces is rapid and substantial. As indoor particle concentrations increase from 10^3 to 10^5 per cm^3, the attached fraction of airborne radon decay products increases progressively. A single burning cigarette in a closed room gives rise to particle concentrations of ≈10^5 per cm^3 and, because of rapid coagulation, most of the radon decay products are associated with large particles of low mobility. In smoke-filled rooms, airborne radon progeny approach equilibrium with radon, limited only by ventilation rates and particle sedimentation.

Size distribution of radon-progeny aerosols in mainstream smoke

Modification of radon-progeny aerosols as they pass from room air through a burning cigarette and into mainstream smoke is discussed elsewhere (7). Typical size distributions for radon progeny particles in mainstream cigarette smoke are shown in Fig. 1. The extremely concentrated cloud of particles and vapors in mainstream smoke, with ≈10^{10} particles per cm^3 (10, 11), could not be passed directly through the multistage impactor because of rapid obstruction of the critical orifice. This difficulty was avoided by removing the fifth impactor stage and backup filter. Based on ^{212}Pb tracer experiments, the activity median aerodynamic diameter (AMAD) of radon progeny in mainstream smoke is between 1 and 2 μm (Fig. 1) for an air flow rate of 1.1 liter/min (the average puff velocity for smokers) through the burning cigarette and impactor. Only a few percent of the total radon-progeny activity was present on particles of <0.5-μm diameter.

As cigarette smoke passes from the butt, at exit temperatures up to 90°C, into the lung at 37°C, the larger smoke particles will undergo further rapid growth due to condensation and coagulation in the dense smoke column, similar to the rapid growth observed for inhaled hygroscopic particles (12). It is noted also that the dense column of smoke particles and vapors flows and settles as an ensemble, exhibiting sedimentation rates characteristic of individual particles of much larger diameter (13).

Selective particle deposition in the bronchial tree

Radon progeny on large mainstream smoke particles will be deposited in the tracheobronchial tree with a highly nonuniform distribution. Deposition in the right upper lobe of the human lung may approach twice that in each of the other four lobes (14, 15). Such particles are deposited with higher surface densities in the lobar and segmental bronchi than elsewhere within each lung lobe (15). Bell (16, 17) showed that selective deposition at bifurcations takes place for particles in both the diffusion and impaction subranges and results in highly localized "hot spots" at bifurcations. The hot spot intensities increase steeply with particle size >1.0-μm diameter, and ranged up to 25 times the average surface concentration for particles of 5.7-μm diameter (16, 17). Because of rapid growth of smoke particles during transit

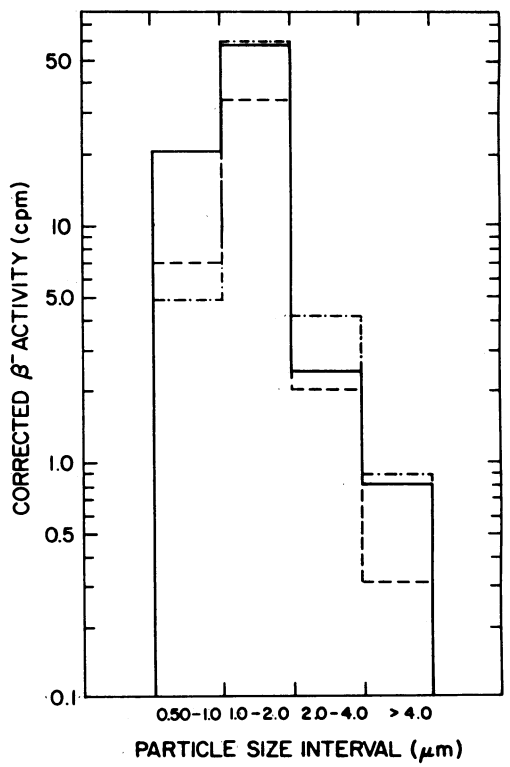

FIG. 1. Size distributions for ^{212}Pb activity in mainstream cigarette smoke after passing ^{212}Pb-tagged smoke particles through burning cigarettes at a flow rate of 1.1 liters/min, the average puff velocity for smokers (10). The dense mainstream smoke column was passed directly, without dilution or delay, from the cigarette butt through a 6-cm length of tubing and upward through the modified, four-stage cascade impactor. Results show an AMAD between 1.0 and 2.0 μm.

to bifurcations and behavior of the dense mainstream smoke column (13), radon-progeny concentrations deposited in small areas (≈10 mm^2 at each bifurcation) may be 10–20 times higher than average surface concentrations.

That inhaled tobacco tars are highly concentrated at segmental bifurcations of cigarette smokers is borne out by several lines of evidence. Using a full-scale model of the human oral cavity and respiratory tract, Ermala and Holsti (18) determined the distribution of inhaled cigarette smoke. They observed highly localized tar deposits in the tonsillar region, at the vocal cords, and at the tracheal and bronchial bifurcations—sites closely correlated with the clinical frequency of cancer of the respiratory tract in smokers. Auerbach *et al.* (19) evaluated changes in the bronchial epithelium in relation to cigarette smoking and found that the frequency of hyperplasia, of lesions with cilia absent, and of carcinoma *in situ* (*i*) increased progressively, (*ii*) were much higher at bifurcations, and (*iii*) were highest in smokers who died of lung cancer. Thus, precancerous lesions in smokers occur primarily at sites of selective deposition of tobacco tars with which most of the radon-progeny α-particle activity is associated.

Persistence of smoke particles deposited at segmental bifurcations

The local α-dose delivered to small tissue volumes at bifurcations depends on the solubility and persistence of the smoke particles in relation to the half-life, or the effective half-life, of each α-particle-emitting radioisotope (Table 1). ^{218}Po, with a half-life of 3.05 min, undergoes substantial radioactive decay at sites of deposition before clearance by any mechanism. Potentially, ^{214}Po can make a far greater contribution to the α-dose than can ^{218}Po because there are 5–15 times as many ^{214}Po precursor atoms—^{214}Pb and ^{214}Bi—than ^{218}Po atoms in the usual mixtures of radon progeny in indoor air. When radon decay products are deposited in the lung, there is an initial ingrowth and/or slow decay of ^{214}Bi and ^{214}Po for 15–30 min; thereafter the mixture, including ^{214}Po, undergoes radioactive decay with an effective half-life of ≈33 min. Thus, essentially complete decay of ^{214}Po can take place locally if the particle residence time is 2–3 hr. Thoron progeny—^{212}Bi and ^{212}Po—also may contribute to α-irradiation of the bronchial epithelium of smokers (7). After ^{212}Pb deposition, ^{212}Bi and ^{212}Po will grow in for several hours and then undergo radioactive decay with an effective half-life of 10.6 hr. Complete α-particle decay of thoron progeny would require a local particle residence time of 2–3 days.

Removal of soluble aerosols deposited on the bronchial epithelium is rapid because of transport by blood and lung fluid, with local clearance half-times as short as 7–13 min (22). Thus, except for ^{218}Po, radon progeny attached to hygroscopic Aitken nuclei and other soluble aerosols are rapidly cleared before radioactive decay. Transport of insoluble particles from the segmental bronchi by mucus flow takes place with transit times ranging from 18 to 37 min (23). However, clearance of insoluble particles from bifurcation sites may be much slower, with half-times ranging from hours to days for 10–20% of the deposited particles (24). Clearance rates usually have been determined in experiments with single inhalation exposures of test animals with normal, effective clearance mechanisms. However, due to progressive damage to the epithelium at bifurcations of smokers, leading to lesions with loss of cilia (19), particle retention times will increase with smoking rate and duration of smoking in years. Albert *et al.* (25) demonstrated that most cigarette smokers had impaired bronchial clearance, with an average half-time of 172 min. Particles that resist clearance would include those deposited at bifurcations in lesions with cilia absent. Particle half-residence times of 172 min are sufficient for nearly complete decay of ^{214}Po from deposited radon progeny associated with smoke tars—particles that we have determined to be highly resistant to dissolution in simulant lung fluid. Ermala and Holsti (18) report that the percutaneous absorption of tars through the intact epidermis of laboratory animals is a slow process and that the bronchial epithelium is incapable of absorbing more than negligible amounts of tar—further indication that radon progeny associated with smoke tar particles deposited at bifurcations may persist for substantial α-particle decay of ^{214}Po before clearance.

^{210}Pb-enriched smoke particles produced by tobacco trichome combustion are highly insoluble (20, 21). Little *et al.* (26) observed high local concentrations of ^{210}Po at individual bifurcations of smokers. These high local concentrations of ^{210}Po can be explained by the presence of insoluble, ^{210}Pb-enriched smoke particles, a possibility confirmed in experimental studies which showed that high concentrations of ^{210}Po in bronchial tissue of smokers are accompanied by higher concentrations of ^{210}Pb (27).

The α-dose to segmental bronchi of smokers

Since recognition that lung cancer in uranium miners can be attributed to α-radiation from inhaled radon progeny, estimates of the α-dose to basal cells of the bronchial epithelium have been made with various dosimetry model assumptions and reviewed elsewhere (23, 28). The unit of radon-progeny exposure used for uranium miners is the working level (WL), defined as any combination of short-lived radon decay products per liter of air that will result in the emission of 1.3×10^5 MeV of α-radiation by decay of ^{218}Po and ^{214}Po. Cumulative exposure is measured in units of working level months (WLM), where one WLM is exposure to 1.0 WL for 170 hr. The average α-dose to basal cells in the bronchi of miners is estimated to be between 0.3 and 1.0 rad per WLM (28, 29). These estimates were made by assuming (*i*) that the attached fraction is associated with highly soluble condensation nuclei with an AMAD between 0.1 and 0.3 μm

Table 1. Origin and properties of indoor radon and thoron progeny in mainstream cigarette smoke

α-Particle-emitting (and precursor) radioisotopes	Effective half-life	α-Particle energy, Mev	Solubility	Penetrating fraction
^{218}Po	3.05 min	6.0	Insoluble†	>0.5*
^{214}Po (^{214}Pb, ^{214}Bi)	≈33 min	7.7	Insoluble†	0.4–0.5*
^{212}Po (^{212}Pb)	10.6 hr	8.78 (64%)	(Uncertain)	0.4–0.5*
^{212}Bi (^{212}Pb)	10.6 hr	6.0 (36%)	(Uncertain)	0.4–0.5*
^{210}Po‡	138 days	5.3	Soluble	>0.25‡
^{210}Po (^{210}Pb)‡	22 yr	5.3	Insoluble	0.05–0.10‡

*Fraction passing from indoor air, through burning cigarette, into mainstream smoke (7).
†Undergo radioactive decay at bifurcations before clearance.
‡From tobacco trichome combustion (20, 21).

and (*ii*) that the rate of soluble particle clearance by various mechanisms is sufficiently rapid that the fraction of deposited potential α-radiation energy that is adsorbed in a 40-g mass of tracheobronchial tissue is 80% for ^{218}Po, 40% for ^{214}Pb, and 50% for ^{214}Bi—equivalent to an average α-dose of 0.3 rad per WLM in 40 g of bronchial tissue (29). Such model assumptions are clearly not applicable for estimating the α-dose at bifurcations of smokers.

At first glance, the contribution of radon progeny in mainstream smoke to the α-dose at bifurcations of smokers would appear to be relatively insignificant because only ≈1 liter of indoor air passes through each burning cigarette, or ≈20 liters per pack, compared to ≈10^3 times larger volume of air inhaled each day. However, this factor of 1,000 in inhaled air volume is largely counterbalanced when we consider (*i*) that some of the mainstream smoke particles are deposited in hot spots at bifurcations with concentrations that may range up to 20 times the average surface concentrations in segmental bronchi, and (*ii*) that much of the α-dose from particles deposited at bifurcations is concentrated in small tissue volumes of ≈0.1 g—not distributed uniformly throughout 40 g of tracheobronchial tissue. Thus, the highly localized α-dose from mainstream smoke particles deposited at segmental bifurcations may add significantly to that contributed by radon progeny inhaled during normal respiration between cigarettes.

Estimated cumulative α-doses at segmental bifurcations of smokers and at basal cells in the bronchi of nonsmokers are compared in Table 2. Exposure to an indoor radon-progeny level of 0.005 WL is assumed for nonsmokers and 0.01 WL for smokers. For nonsmokers a dose of 0.3–1.0 rad per WLM, the range for uranium miners (28), is assumed. For smokers, indoor radon progeny inhaled between cigarettes is, in part, attached to smoke tar particles, which are nonuniformly deposited and somewhat resistant to clearance. For this component, an average α-dose at bifurcations is conservatively assumed to be 0.6–2.0 rad per WLM—only twice the average basal cell dose (28).

To this one must add the α-dose from ^{218}Po and ^{214}Po in mainstream smoke particles deposited at bifurcations. By assuming that 1 liter of room air passes through each cigarette and that 45% of radon progeny atoms penetrate into mainstream smoke (Table 1), a smoker exposed to 0.01 WL will inhale 2.1 × 10^7 radon-progeny atoms in 40 yr for a smoking rate of one pack per day. It is further assumed that some 15–30% of radon-progeny atoms in mainstream smoke are deposited on epithelial surfaces in segmental bronchi and that about one-sixth of this fraction, 0.5–1.0 × 10^6 atoms, is deposited at the carina of the 10 bifurcations with hot spots of highest concentration. The hot spot at each bifurcation is about 10 mm^2 in area (16, 17). For a 1.0-cm^2 combined area of hot spots, the tissue volume irradiated by 7.7-MeV α-particles from ^{214}Po, with a track length of 70 μm in tissue of unit density, is 1.4 × 10^{-2} cm^3, or 0.014 g of tissue—≈10^7 cells. On this basis, the cumulative α-dose from ^{214}Po in this small tissue volume is 4.2–8.4 rads. ^{218}Po contributes an added 10% for a total of 4.6–9.2 rads (Table 2, line 8).

The α-dose from indoor thoron progeny also contributes to the total α-dose at segmental bifurcations of smokers. One study (30) indicates an average ^{212}Pb/^{214}Pb activity ratio of 0.07 for indoor air, corresponding to an atom ratio of 1.65. Thus, there are about the same number of ^{212}Pb atoms as ^{222}Rn progeny atoms. The potential α-dose from ^{212}Po and ^{212}Bi decay products of ^{212}Pb would equal that from ^{214}Po only if particle residence times were tens of hours. Albert *et al.* (25) reported that the time required for 90% bronchial clearance of insoluble particles exceeded 10 hr for 6 of 15 cigarette smokers. The persistent 10% may include that fraction deposited in hot spots at bifurcations and in lesions with cilia absent. The latter are found with highest incidence in smokers age >40 yr (19). It is likely that the contribution from ^{212}Po and ^{212}Bi occurs mainly in this age group with an added α-dose at bifurcations comparable to that from ^{214}Po for 40- to 60-yr-old smokers (Table 2).

The contribution of α-radiation at segmental bifurcations of smokers from ^{210}Po in ^{210}Pb-enriched particles produced by tobacco trichome combustion (20) also must be included. Little *et al.* (26) observed ^{210}Po levels of 7.5–14 pCi/g in individual segmental bifurcated specimens in 7 of 37 cigarette smokers. These bifurcation samples were as small as 0.1–0.2 cm^2 in area. These authors assumed that the observed activity was uniformly dis-

Table 2. Estimated α-dose at bifurcations of smokers and at basal cells in bronchi of nonsmokers

α-Particle emitters	Age interval, yr	Exposure level, WL	Cumulative exposure, WLM	Cumulative α-dose, rad
		Nonsmokers		
^{218}Po + ^{214}Po	0–60	0.005	15.5	4.6–15.5*
^{212}Po + ^{212}Bi	0–60	—	—	0.5–1.5†
Total	0–60	—	—	5.1–17
		Smokers		
^{218}Po + ^{214}Po	0–20	0.005	5.2	1.5–5.2
	20–60	0.01	20.6	12.4–41.2‡
^{212} + ^{212}Bi	0–60	—	—	1.4–4.6†
Subtotal	0–60	—	—	15–51
^{214}Po + ^{218}Po, MSS§	20–60	0.01	—	4.6–9.2 (1 pack/day)
^{212}Po + ^{212}Bi, MSS§	40–60	—	—	2.3–4.6 (1 pack/day)¶
^{210}Po (^{210}Pb)	40–60	—	—	16–32 (20% of smokers)‖
Total at bifurcations	0–60	—	—	38–97 (1 pack/day)
				61–143 (2 packs/day)

* Range: 0.3–1.0 rad/WLM at basal cells of nonsmokers (28).
† Approximately 10% of radon progeny contribution.
‡ Range: 0.6–2.0 rad/WLM at bifurcations of smokers (see text).
§ MSS, mainstream smoke particles, 2.5–5% on 1.0 cm^2 at bifurcations.
¶ Equal to ^{214}Po α-dose in 40- to 60-yr-old smokers.
‖ ^{210}Po at 10–20 pCi/g in epithelium at bifurcations (26).

tributed in the epithelial layer over the area of each bifurcation specimen. On this basis they estimated an average α-dose of 20 rads/25 yr in this small epithelial volume and suggested that the dose would be higher in smaller, localized hot spots. It is assumed here that the ^{210}Po at bifurcations of the $\approx$20% of smokers is 10–20 pCi/g of epithelium for smokers age >40 yr, contributing another 16–32 rads to the local α-dose (Table 2). Thus, the total α-dose to segmental bifurcations of smokers is estimated to be from 38–97 rads for a smoking rate of one pack per day (Table 2). For a smoking rate of two packs per day, the contributions of mainstream smoke particles are doubled, giving an estimated total α-dose of 61–143 rads (Table 2).

Discussion

Based on the foregoing evaluations, it is apparent that smokers exposed to average indoor radon-progeny levels receive surprisingly high cumulative α-doses in hot spots at bronchial bifurcations. Brues pointed out (31) that tumors arise focally in small irradiated tissue volumes. It has been demonstrated (32) that α-particle interactions with mammalian cells in culture are very effective in producing malignant transformations in small surviving cell populations for α-doses >80 rads. Thus, there should be a high probability of inducing a malignant transformation at individual bifurcations at which $\approx 10^6$ cells have been subjected to a cumulative α-dose of 80–100 rads.

The age-related incidence of bronchial cancer in smokers, duration of smoking in years to the fifth power, indicates a multistage process of cancer induction involving at least two stages of DNA transformation (4). It is proposed here that most bronchial cancers in smokers are induced by multiple α-particle interactions with basal and epithelial cells at bronchial bifurcations. The 7.7-MeV α-particles from ^{214}Po, which penetrate readily to the depth of basal cells at bifurcations, may be expected to play the primary role as initiators. It is a well-established principle in radiation carcinogenesis that initiation must be followed by a stimulus for cell division (33). For promotion of bronchial cancer in smokers, an enhanced mitotic rate due to lethal α-particle interactions, primarily with epithelial cells at bifurcations, is suggested here as one important stimulus for cell division. The reduced incidence of lung cancer in smokers who have stopped smoking indicates that α-particle interactions also may be implicated in the final stage of DNA transformation.

For a given smoking rate, smokers exposed to the highest indoor radon and thoron levels should experience the highest risk and the earliest incidence of lung cancer. This possibility can be tested cytogenetically with methods described by Brandom *et al.* (34), who showed that chromosome aberrations in cultured peripheral blood lymphocytes are a sensitive measure of cumulative exposure to radon progeny. If most smokers who develop bronchial cancer are those with the highest cumulative radon-progeny exposure, they should exhibit the highest prevalence of the indicator aberrations. Cigarette smokers exposed occupationally to inhalation of fibrous aerosols or toxic chemicals—agents that damage the bronchial epithelium and impair clearance—may experience bronchial cancer at lower cumulative radon-progeny exposures.

Improved α-dose estimates will require more and better experimental evidence on the properties and dynamics of radon-progeny aerosols in indoor air and mainstream smoke, on deposition patterns for dense smoke columns in hollow casts of the upper human bronchial tree, and on the microdistribution and persistence of radioactive smoke particles in hot spots and lesions at bifurcations of smokers.

Lung cancer is only one of the serious chronic health effects of cigarette smoking (35), and indoor radon progeny may be a factor in the etiology of some of the others—cancers of the larynx, pharynx, and esophagus in particular.

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