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Lung Cancer Risks Due to the Radon in Cigarette Tobacco[1]

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Abstract—Thirty-one tobacco samples were evaluated for the activity concentrations of radon and radium using solid-state nuclear track detectors (CR-39). The detectors were exposed for a period of 150 days to different types of cigarette tobacco. The highest values of 364 Bq m^{-3} for radon and 31.4 Bq kg^{-1} for radium were obtained for MIA2 sample, and the lowest values of 20.2 Bq m^{-3} for radon and 1.74 Bq kg^{-1} for radium, for SUM sample. According to the estimate, this range of radon levels corresponds to the lung cancer incidence in the range 22–396 cases per million smoker per year. The annual effective dose in general and for lungs in particular, the surface and mass exhalation rate, the equivalent equilibrium concentration of radon, and absorbed dose to tissues and lungs were calculated. The highest values were obtained for MIA2 sample, and the lowest values, for SUM sample.

Keywords: radon, tobacco, effective dose, lung cancer risk, CR-39 detectors

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Many kinds of tobacco are grown in the world, with a variety of uses. The types of tobacco vary according to tobacco classes in various countries. The tobacco quality is influenced by nitrogen fertilization, plant density, topping time and height, and harvesting and curing procedures. A tobacco leaf contains a complex mixture of chemical components: cellulose products, starches, proteins, sugars, alkaloids, pectic substances, hydrocarbons, phenols, fatty acids, and inorganic minerals [1]. It has been known for over 20 years that all types of tobacco contain radioactive ^{210}Po, which emits α-particles, and radioactive ^{210}Pb, which emits β-particles and is a precursor of ^{210}Po. There is a degree of consensus about how tobacco becomes radioactive. Most soils contain radioactive elements such as radium, which decays into ^{210}Pb and ^{210}Po. In addition, phosphate ore used as fertilizer in tobacco fields may contain such isotopes in relatively high concentrations. Thus, it was anticipated that tobacco plants can absorb ^{210}Pb and ^{210}Po through their roots. During tobacco processing, the radiation is not completely removed [2, 3]. The sticky compound that seeps from the trichomes is water-insoluble, and adhering particles are not washed off with the rain. They remain during curing, cutting, and manufacture into cigarettes. Lead-210 and polonium-210 can be absorbed into tobacco leaves directly from the soil or by absorbing radon from the air with the subsequent decay into ^{210}Pb and ^{210}Po. However, it is more important that fine sticky hairs (trichomes, Fig. 1) [4] on both sides of tobacco leaves grab airborne radioactive particles. According to the environment protection agency (EPA) estimates, radon is the number one cause of lung cancer among non-smokers and the second leading cause of lung cancer after cigarette smoke [5].

Radon is responsible for about 21 000 lung cancer deaths every year. About 3000 of these deaths occur among people who never smoked. According to the World Health Organization (WHO) data, radon causes up to 15% of lung cancers worldwide [6]. Syed [7] studied whether the cigarette tobacco itself was a potential source of indoor radon and measured the levels of radon in tobacco samples of 15 different brands using CR-39 as a solid-state nuclear track detector (SSNTD). The results showed that the ^{222}Rn concentration in cigarette tobacco samples ranged from 97 to 204 Bq m^{-3}. The levels of radon released from all investigated samples was significantly higher than the background level. The annual equivalent doses

[1] The text was submitted by the authors in English.

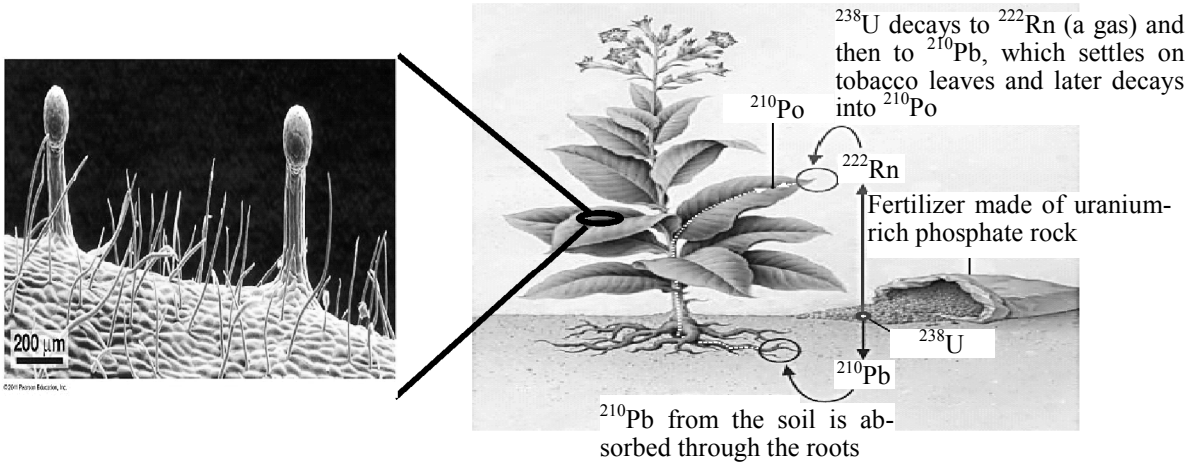

Fig. 1. Sticky hair-like structures on both sides of tobacco leaves [4].

from use of these tobacco samples ranged from 1.67 to 3.52 mSv year^{-1}. The result refers to the dual (chemical and radioactive) effect of smoking as a risk factor for lung cancer. Laith [8] showed that the ^{222}Rn concentrations in cigarette tobacco samples ranged from 228 to 778 Bq m^{-3} with an average of 432 Bq m^{-3}, with the radon-induced lung cancer risks varying from 103 to 353 cases per million people with an average value of 196. Excellent correlation was observed between the radon concentration and lung cancer cases per year per million people for different brands of tobacco.

The aims of the present work were to evaluate the activity concentrations of radon and radium in tobacco and to calculate the risk parameter, namely, the number of smokers (per million smokers per year) who can be expected to get lung cancer as a result of smoking a particular type of cigarettes.

THEORY

Activity Concentrations of Radon Gas and Radium

The activity concentration of radon (C_{Rn}, Bq m^{-3}) in cigarette tobacco at secular equilibrium is given by the equation [9]

$$C_{Rn} = \rho/(KT), \quad (1)$$

where ρ is the track density (mm^{-2}); K, experimental calibration factor equal to 0.0022 (mm^{-2})/(Bq day m^{-3}); and T, exposure time (days).

To calculate the activity concentration of ^{226}Ra (C_{Ra}, Bq kg^{-1}) in cigarette tobacco samples, we used the following equation [10]:

$$C_{Ra} = \rho hA/(mKT_e), \quad (2)$$

where ρ is the track density (track mm^{-2}); h, distance between the detector and the top of sample (0.07 m); A, surface area of the sample in the plastic cylinder; K, calibration coefficient for CR-39; T_e, effective exposure time (h); and m, sample weight [11]:

$$T_e = T + (1/\lambda)(e^{-\lambda T} - 1), \quad (3)$$

where λ is decay constant of radon gas (0.1814 day^{-1}), and T is the exposure time (days).

Radon Dose Estimation

The annual effective dose from indoor radon concentration, E_{Rn} (mSv year^{-1}), was calculated using the UNSCEAR model [12]:

$$E_{Rn} = C_{Rn}FHTD, \quad (4)$$

where F is an equilibrium factor (0.4), H is the occupancy factor (assumed equal to 0.8 for this work), T is the number of hours in a year (8760 h year^{-1}), and D is the dose conversion factor [9.0 × 10^{-6} mSv/(Bq m^{-3} h)].

The annual effective dose for smoker lung from radon gas inhalation, E_L (mSv year^{-1}), was calculated using the following equation [12]:

$$E_L = E_{Rn}W_RW_T, \quad (5)$$

where W_R is radiation weighting factor equal to 20 for α-particles, and W_T is the tissue weighting factor equal to 0.12 for lungs.

The equivalent dose for bronchial areas of human lungs was calculated using the conversion factor of 1.0 × 10^{-5}mSv/(Bq h m^{-3}) [13]. It should be taken into

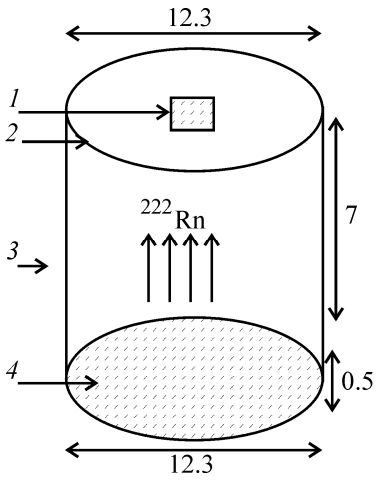

Fig. 2. Radon gas estimation with CR-39 detector. Plastic container volume 831.8 cm^3; the dimensions are in centimeters. (*1*) CR-39 detector, (*2*) cover, (*3*) plastic container, and (*4*) sample (fine powder, 10 g).

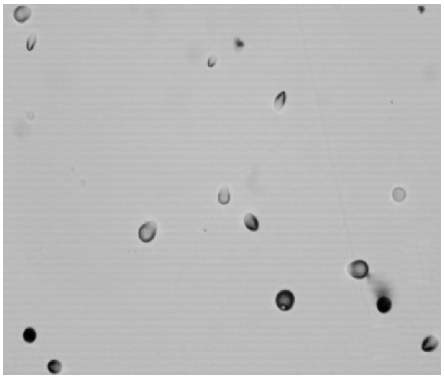

Fig. 3. ^{222}Rn α-particle tracks on CR-39 detector after exposure with MIA2 sample.

account that radon, in contrast to its daughter elements, is a noble gas and resides constantly in the lung air (C_{Rn}, air); it also dissolves partly in soft tissue. Assuming the solubility coefficient in the soft tissues equal to 0.4 and taking into account the behavior of daughter elements, we used the following relationship for tissues [14]:

$$D_{\text{soft tissue}}\ [\text{nGy h}^{-1}] = 0.005 C_{\text{Rn,air}}\ [\text{Bq m}^{-3}]. \quad (6)$$

In the case of lungs, the radon content in the lung air must be taken into account. Assuming that the volume of air in human lungs is 3.2×10^{-3} m^3 and that the short-lived decay products will remain in the lungs, we used the following relationship for calculating the dose rate [14]:

$$D_{\text{lungs}}\ [\text{nGy h}^{-1}] = 0.04 C_{\text{Rn,air}}\ [\text{Bq m}^{-3}]. \quad (7)$$

Calculation of Radon Exhalation Rate

The radon exhalation rate from any sample is defined as the flux of radon released from the surface of the material. The surface (E_A, Bq m^{-2} day^{-1}) and mass (E_m, Bq g^{-1} day^{-1}) exhalation rates can be calculated as follows [15]:

$$E_A = CV\lambda/\{A[T + \lambda^{-1}(e^{-\lambda T} - 1)]\}, \quad (8)$$

$$E_m = CV\lambda/\{m[T + \lambda^{-1}(e^{-\lambda T} - 1)]\}, \quad (9)$$

where C is the integrated radon exposure (Bq day m^{-3}); V, volume of air in the cup (831.8×10^{-6} m^3); λ, ^{222}Rn decay constant (0.1812 day^{-1}); A, surface area of the sample (118.76×10^{-4} m^2); m, tobacco sample weight (10 g); and T, exposure time (150 days).

Lung Cancer Risk

The lung cancer risk is defined as the excess death incidence per million persons per year due to lung cancer caused by radon and its short-lived daughters. This parameter (LCMPY) is calculated using the following equation [16]:

$$\text{LCMPY} = (18 \times 10^{-6}\ \text{years mSv}^{-1}) E_L \times 10^6. \quad (10)$$

EXPERIMENTAL

Thirty-one samples of cigarette tobacco have been collected from Iraqi markets. They were ground and sifted using a special sieve (630 μm). Each sample (approximately 10 g, which corresponds to 20 cigarettes) was placed in a plastic cup. Figure 2 shows the dimensions of this cup, which minimize the effect of thoron gas and α-emitters. Pieces of CR-39 (1 cm^2, thickness 500 μm, density 1.36 g cm^{-3}, Pershore Molding Ltd., the United Kingdom) were fixed in the top cover of the plastic cup, and the samples were placed at the bottom of the container. The detector was exposed to radon gas released from the samples for 150 days.

After that, the CR-39 detectors were subjected to chemical etching to reveal α-particle tracks from ^{222}Rn (Fig. 3). Etching was performed with a 6 M NaOH solution at 70°C for 6.5 h on a water bath. Such conditions are considered as optimum.

After the etching completion, the detectors were removed from the etchant solution and washed with distilled water and methanol for 30 min. Then, they were dried and examined with a microscope at 360×

Table 1. Track density, activity concentrations of radon and radium (with standard errors), and standard deviation σ for tobacco samples of different origins[a]

Sample code	Country of origin	Track density, track mm^{-2}	σ	^{222}Rn activity concentration, Bq m^{-3}	^{226}Ra activity concentration, Bq kg^{-1}
AKH	Armenia	50 ± 3	9.66	152 ± 9	13.1 ± 0.8
ARD1	UK	70 ± 6	17.40	212 ± 17	18.3 ± 1.44
ARD2	UK	113 ± 6	19.50	343 ± 19	29.6 ± 1.6
ASP1	Germany	112 ± 7	21.61	338 ± 21	29.2 ± 1.8
ASP2	Germany	32 ± 5	14.50	96 ± 14	8.3 ± 1.2
DAV	Germany	73 ± 5	16.15	222 ± 15	19.2 ± 1.3
ELE	USA	25 ± 5	16.60	76 ± 16	6.5 ± 1.4
GAU1	EU	42 ± 6	18.99	126 ± 18	10.9 ± 1.6
GAU2	France	8 ± 3	9.21	25 ± 9	2.2 ± 0.8
GHA	Yemen	13 ± 3	10.00	40 ± 10	3.5 ± 0.8
GIT	EU	35 ± 3	9.21	106 ± 9	9.2 ± 0.8
GOL	Germany	45 ± 5	14.50	136 ± 14	11.8 ± 1.2
CRA	Turkey	77 ± 6	19.27	232 ± 18	20.1 ± 1.6
IRA	Iraq	52 ± 6	20.11	157 ± 19	13.5 ± 1.7
KEN	UK	11.67 ± 0.19	0.61	35.4 ± 0.6	3.05 ± 0.05
MAC	Brazil	110 ± 6	18.12	333 ± 17	28.8 ± 1.5
MAR	Turkey	36.7 ± 1.4	4.30	111 ± 4	9.6 ± 0.4
MEN	Germany	27 ± 5	16.91	81 ± 16	7.0 ± 1.4
MIA1	USA	73 ± 8	25.75	222 ± 25	19.2 ± 2.1
MIA2	USA	120 ± 9	29.23	364 ± 28	31.4 ± 2.4
MIK1	USA	35 ± 3	9.21	106 ± 9	9.2 ± 0.8
MIK2	USA	90 ± 10	32.41	273 ± 31	24 ± 3
MIN	USA	83 ± 10	32.10	253 ± 31	22 ± 3
OSC1	USA	55 ± 5	16.85	167 ± 16	14.4 ± 1.4
OSC2	USA	67 ± 4	11.33	202 ± 11	17.4 ± 0.9
PIN1	South Korea	7 ± 4	11.95	25 ± 11	2.2 ± 1.0
PIN2	South Korea	25.0 ± 2.3	7.32	76 ± 7	6.5 ± 0.6
PRE	Bulgaria	60 ± 6	19.27	182 ± 18	15.7 ± 1.6
ROT	Germany	82 ± 9	29.84	248 ± 29	21.4 ± 2.5
SUM	Iraq	6.7 ± 0.5	1.46	20.2 ± 1.4	1.74 ± 0.12
WES	Germany	46.7 ± 2.0	3.65	141 ± 4	12.2 ± 0.3
Maximum		120 ± 9	32.41	364 ± 28	31.4 ± 2.4
Minimum		6.7 ± 0.5	0.61	20.2 ± 1.4	1.74 ± 0.12
Average		54 ± 5	15.71	164 ± 15	14.2 ± 1.3

[a] Area of the field of view 0.06 mm^2. The standard error is $\sigma n^{-1/2}$, n = 10 (number of images).

magnification of the objective lens and 40× and 9× camera zooms. The tracks were counted per unit area using a special glass slide with 1 cm x–y scale used to calibrate the picture dimensions. The camera was interfaced with a computer, and the image was presented on the computer screen (Fig. 4). Ten images were taken for each sample to calculate the average number of tracks. The track density ρ was calculated by dividing the average number of tracks by the area of the field of view (0.06 mm^2).

RESULTS AND DISCUSSION

Calculation of the activity concentrations of radon and radium. Radon is a class no. 1 carcinogen and the second leading cause of lung cancer after smoking, Either smoking or radon exposure can independently increase the risk of lung cancer. However, exposure to both greatly enhances that risk [17, 18]. The results of measuring the activity concentration of Rn in tobacco samples [Eq. (1)] are given in Table 1.

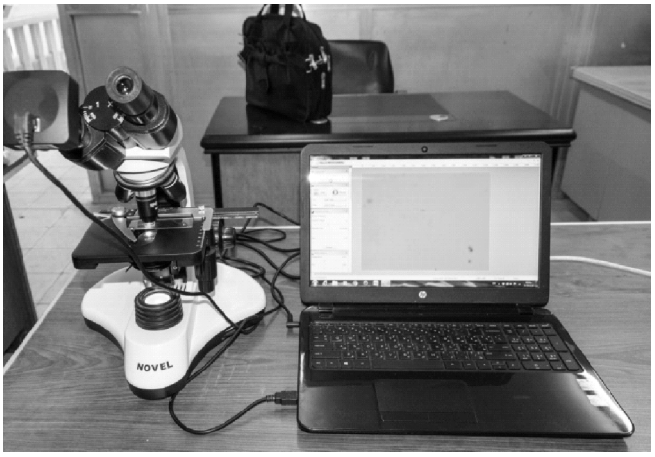

Fig. 4. Installation consisting of an optical microscope, a camera, and a computer.

The data obtained show that MIA2 sample of American origin is characterized by the highest activity concentration of Rn (364 ± 28 Bq m^{-3}), and SUM sample of Iraqi origin, by its lowest level (20.2 ± 1.4 Bq m^{-3}), with the overall average of 164 ± 15 Bq m^{-3} (Fig. 5). The activity of radium [Eq. (2)] varied from 1.74 ± 0.12 Bq kg^{-1} in SUM sample to 31.4 ± 2.4 Bq kg^{-1} in MIA2 sample with the average of 14.2 ± 1.3 Bq kg^{-1}. Table 1 presents the track densities and activity concentrations of radon and radium with standard deviation in tobacco samples of different origins.

Annual effective dose. We calculated the annual effective dose for radon gas inhalation for the whole body and lung of smokers (mSv $year^{-1}$). The results are given in Table 2 and Fig. 6. For the whole body, the maximal value was 9.17, the minimal, 0.51, and the average, 4.15 mSv $year^{-1}$. For lungs, the respective quantities were 22.02, 1.22, and 9.96 mSv $year^{-1}$.

Absorbed dose for soft tissue, D_S, and lungs, D_L. We calculated the absorbed dose for soft tissues, D_S, and lungs, D_L. The values ranging from 0.1 to 1.82 nGy h^{-1} with an average of 0.82 nGy h^{-1} were obtained for D_S, and the values ranging from 0.81 to 14.55 nGy h^{-1} with an average of 6.58 nGy h^{-1}, for lungs (Table 2). Figure 7 shows the correlation between the absorbed dose rate and activity concentration of radon. As can be seen, the lung tissues are considerably more sensitive to radiation than the soft tissues.

Radon exhalation rate. The surface exhalation rate was calculated using Eq. (8). The maximum was 3.33,

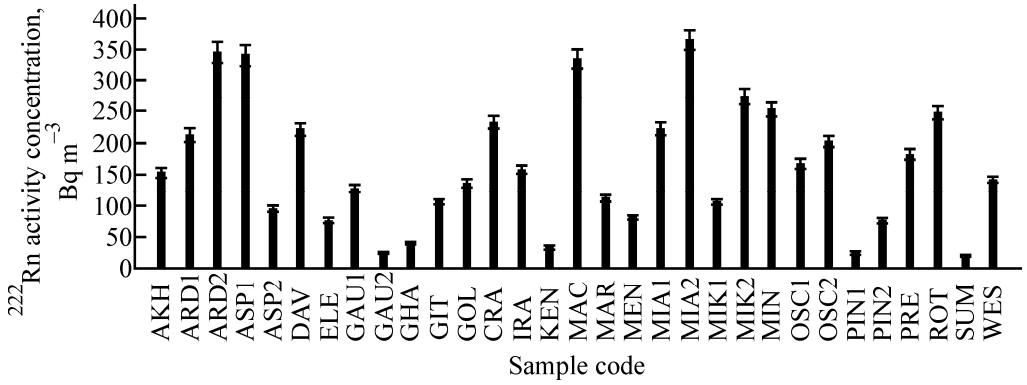

Fig. 5. Activity concentration of radon in tobacco samples.

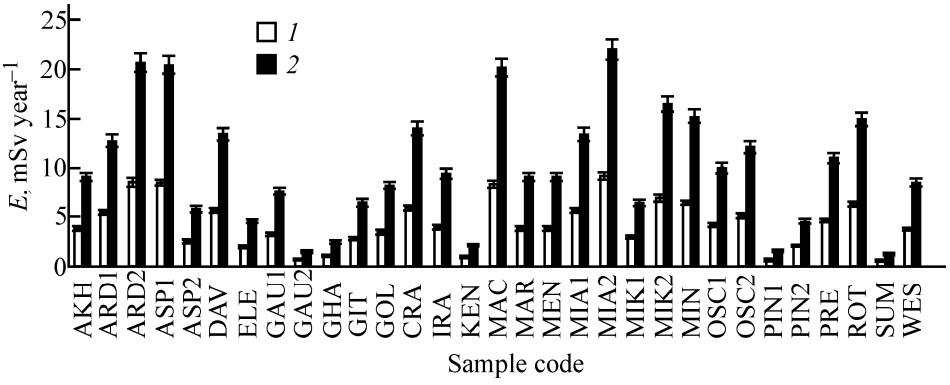

Fig. 6. Annual effective dose from radon in tobacco (*1*) for the whole body and (*2*) for lungs.

Table 2. Parameters of risk associated with radon and expected lung cancer incidence per million smokers per year

Sample code	E_{Rn},[a] mSv year^{-1}	E_L, mSv year^{-1}	D_S, nGy h^{-1}	D_L, nGy h^{-1}	E_A, mBq m^{-2} min^{-1}	E_m, mBq kg^{-1} min^{-1}	LCMPY
AKH	3.82	9.17	0.76	6.06	1.39	1.65	165.13
ARD1	5.35	12.84	1.06	8.48	1.94	2.31	231.19
ARD2	8.66	20.79	1.72	13.74	3.15	3.73	374.30
ASP1	8.54	20.49	1.69	13.54	3.10	3.68	368.80
ASP2	2.42	5.81	0.48	3.84	0.88	1.04	104.58
DAV	5.61	13.46	1.11	8.89	2.04	2.42	242.20
ELE	1.91	4.59	0.38	3.03	0.69	0.82	82.57
GAU1	3.19	7.65	0.63	5.05	1.16	1.37	137.61
GAU2	0.64	1.53	0.13	1.01	0.23	0.27	27.52
GHA	1.02	2.45	0.20	1.62	0.37	0.44	44.04
GIT	2.68	6.42	0.53	4.24	0.97	1.15	115.59
GOL	3.44	8.26	0.68	5.45	1.25	1.48	148.62
CRA	5.86	14.07	1.16	9.29	2.13	2.53	253.21
IRA	3.95	9.48	0.78	6.26	1.43	1.70	170.64
KEN	0.89	2.14	0.18	1.41	0.32	0.38	38.53
MAC	8.41	20.18	1.67	13.33	3.05	3.62	363.29
MAR	2.80	6.73	0.56	4.44	1.02	1.21	121.10
MEN	2.04	4.89	0.40	3.23	0.74	0.88	88.07
MIA1	5.61	13.46	1.11	8.89	2.04	2.42	242.20
MIA2	9.17	22.02	1.82	14.55	3.33	3.95	396.32
MIK1	2.68	6.42	0.53	4.24	0.97	1.15	115.59
MIK2	6.88	16.51	1.36	10.91	2.50	2.97	297.24
MIN	6.37	15.29	1.26	10.10	2.31	2.75	275.22
OSC1	4.20	10.09	0.83	6.67	1.53	1.81	181.65
OSC2	5.10	12.23	1.01	8.08	1.85	2.20	220.18
PIN1	0.64	1.53	0.13	1.01	0.23	0.27	27.52
PIN2	1.91	4.59	0.38	3.03	0.69	0.82	82.57
PRE	4.59	11.01	0.91	7.27	1.67	1.98	198.16
ROT	6.24	14.98	1.24	9.90	2.27	2.69	269.72
SUM	0.51	1.22	0.10	0.81	0.19	0.22	22.02
WES	3.57	8.56	0.71	5.66	1.30	1.54	154.13
Maximum	9.17	22.02	1.82	14.55	3.33	3.95	396.32
Minimum	0.51	1.22	0.10	0.81	0.19	0.22	22.02
Average	4.15	9.96	0.82	6.58	1.51	1.79	179.34

[a] E_{Rn} is the effective annual dose for the whole body.

the minimum, 0.19, and the average, 1.51 mBq m^{-2} min^{-1} (Table 2). The mass exhalation rate was calculated using Eq. (9). The maximum was 3.95, the minimum, 0.22, and the average, 1.79 mBq kg^{-1} min^{-1} (Table 2).

Expected lung cancer incidence per million smokers per year (LCMPY). The estimation of LCMPY from data in Table 2 and Fig. 8 shows that the maximal value is about 396, the minimal value, about 22, and the average, about 179. These data refer specifically to the risk related to exposure to radon in tobacco, and these figures can increase as a result of exposure to other radionuclides found in cigarette smoke, such as ^{210}Po, ^{210}Pb, and other radionuclides of the uranium and thorium series.

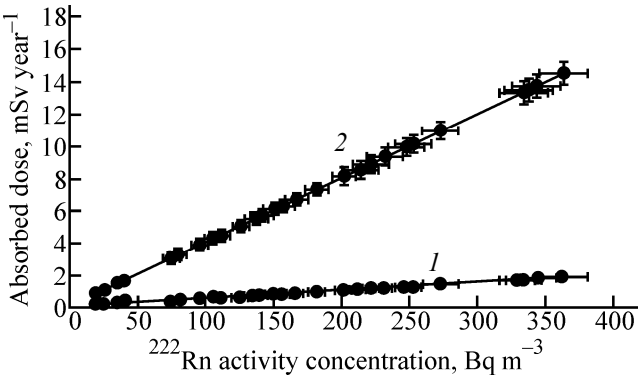

Fig. 7. Relationship between the absorbed dose and activity concentration of radon (*1*) for soft tissues (regression equation $D = 0.005C_{Rn} - 8 \times 10^{-16}$) and (*2*) lungs (regression equation $D = 0.04C_{Rn} - 6 \times 10^{-15}$).

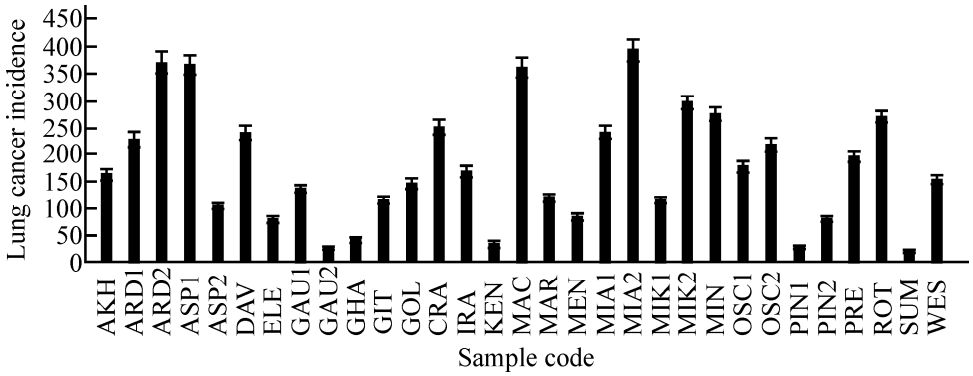

Fig. 8. Expected lung cancer incidence per million smokers per year for various tobacco brands.

Thus, the annual effective dose and excess lung cancer risk increase with increasing radon concentration. The highest concentration of radon in MIA2 sample may reflect the natural occurrence of ^{238}U in soils of the region where the tobacco is cultivated, to increased radon concentrations in the surrounding air, and to introduction of radionuclides with phosphate fertilizers. Relatively large amount of radon and radium in tobacco samples may be the main cause of lung cancer in smokers. The serious tension in Iraq since 2003 led to an increase in tobacco smoking and may be responsible for an increase in the lung cancer incidence in Iraq.

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