Assessment of lung cancer risk due to exposure to radon from coastal sediments

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تقييم اختطار الإصابة بسرطان الرئة الناجم عن التعرُّض للرادون المنبعث من الترسُّبات الساحلية

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الخلاصـة: أجرى الباحثان تقيـيماً لاختطار الإصابة بسرطان الرئة الناجم عن التعرُّض المنزلي لغـاز الـرادون Rn222 المتواجد بصورة طبيعية، في داخل المباني وخارجها، واستخدما سلـسلة مـن المعـادلات لتقـدير تركيـزات الـرادون داخل المباني وخارجها، وما يتـرافق مع ذلك من مخاطر الإصابة بسرطان الرئة، في عـدد مـن المنـاطق الـساحلية في مصر. وقد بلغ متوسط تركيز الرادون 42.98 بيكيريل/م3 داخل المباني (بانحراف معياري قـدره 33.12) و8.63 بيكيريلٍ/م3 خارج المباني (بانحراف معياري قدره 6.16) وبلغ وسطي اختطار الإصابة بالسرطان المحرّض بـالرادون (مقدَّراً بعدد الوفيات لكل مليون شخص) 83.4 في داخل المباني (بانحراف معياري قدره 64.67)، و25.1 خارج المباني (بانحراف معياري قـدره 19.52) وكانـت المعدَّلات أعلـى في المنـاطق الغربيـة مـن البـلاد مقارنـة بالمنـاطق الشرقية، إلا أن أعلى المعدَّلات وجدت في رشيد (دلتا النيل)، وتبين أن التدخين يزيد كثيراً من اختطار الإصابة.

ABSTRACT We conducted a lung cancer risk assessment for internal exposure to naturally occurring ^{222}Rn gas both indoor and outdoor. A series of equations were used to estimate Rn concentrations indoor and outdoor and the associated lung cancer risk in some coastal regions in Egypt. The mean ^{222}Rn concentrations were 42.98 (SD 33.12) Bq/m^3 and 8.63 (SD 6.16) Bq/m^3 indoor and outdoor respectively. The mean risk of radon-induced cancer (deaths per million population) was 83.4 (SD 64.67) indoors and 25.1 (SD19.52) outdoors. Levels were higher for western regions of the country compared to eastern ones but the highest levels were in Rashid (Nile delta). Smoking was shown to increase the risk considerably.

Évaluation du risque de cancer du poumon dû à une exposition au radon provenant de sédiments côtiers

RÉSUMÉ Nous avons mené une évaluation du risque de cancer du poumon lié à l'exposition interne au gaz radon (^{222}Rn) présent à l'état naturel à l'intérieur comme à l'extérieur des habitations. Une série d'équations a été utilisée pour estimer les concentrations en radon en milieu clos et en plein air, ainsi que le risque associé de cancer du poumon dans certaines régions côtières d'Égypte. Les concentrations moyennes de ^{222}Rn étaient respectivement de 42,98 (écart type 33,12) Bq/m^3 et de 8,63 (écart type 6,16) Bq/m^3 à l'intérieur et à l'extérieur des habitations. Le risque moyen de cancer du poumon provoqué par le radon (nombre de décès pour un million d'habitants) était de 83,4 (écart type 64,67) à l'intérieur des habitations et de 25,1 (écart type 19,52) à l'extérieur. Les niveaux étaient plus élevés dans les régions de l'ouest du pays que dans l'est, mais c'est à Rosette dans le delta du Nil que l'on enregistrait les niveaux maximums. Il a été démontré que le tabagisme augmentait considérablement le risque de cancer.

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Introduction

Radon (Rn) is a naturally occurring radioactive, odourless and colourless gas [1]. It is of particular concern because it is ubiquitous, and it is very mobile in the environment [2]. There are 3 isotopes of radon but it is [222]Rn that is of particular epidemiological interest [1].

It is well known that inhalation of the short-lived decay products of [222]Rn provides the main pathways for radiation exposure of the lungs [3]. When [222]Rn gas itself is inhaled, most is exhaled before it decays but [222]Rn progeny may be deposited on the cells lining the airways where they can damage the DNA and potentially cause lung cancer.

It is recognised that [222]Rn is a health hazard in both mining and non-mining environments [4,5]. [222]Rn is the second most important risk factor for lung cancer after smoking, and causes between 6% and 15% of all cases [6]. Exposure to [222]Rn in the home and workplace is one of the main risks of exposure to ionizing radiation, causing tens of thousands of deaths from lung cancer each year [7,8].

The concentration of [222]Rn and [222]Rn daughters in the indoor air depends on the amount of [226]Ra in the soil and how easily [222]Rn products can move through soil and walls and mix with room air. Because [222]Rn is a gas, changes in the atmospheric pressure also affect its emission from the ground and its accumulation in the indoor air [9].

Risk assessment is a method to assess the likelihood that exposure to hazardous agents will harm people or the environment and is conducted to estimate the probability of specific harm to an exposed individual or population [10].

The purpose of our study was to conduct a risk assessment of lung cancer due to inhalation of either indoor or outdoor [222]Rn in Egypt. In order to carry out the risk assessment, a series of equations were systematically used to estimate i) the concentrations of [222]Rn in air that emanated and was exhaled from sediments containing [226]Ra and ii) the risk of death from lung cancer from [222]Rn internal exposure.

Methods

The following estimations and calculations were made.

1. Estimation of [222]Rn concentrations in both the indoor and outdoor environment based on its emanation and exhalation from sediments containing [226]Ra using a combination of previously published equations.
2. Calculation of [222]Rn internal exposure.
3. Calculation of annual effective doses from [222]Rn exposure.
4. Calculation of the risk of death from lung cancer from [222]Rn exposure based on international risk values and the risk assessment model [11,12].
5. Estimation of the risk of death from lung cancer from [222]Rn exposure taking account of the synergistic effects with smoking.

Principles for the risk assessment model

The original values used in these calculations are taken from published data of coastal sandy sediments [13–15]. The [226]Ra values were measured by means of a high resolution, low background gamma spectrometer, using a multichannel analyser and coaxial high-purity germanium detector [13,14]. The geographical locations of the selected regions under consideration are given in Table1, and are located on the Mediterranean coast of Egypt. These sta-

Table 1 **Calculated values of ^{222}Rn concentrations in soil gas (C_{ERn}), exhalation rate of ^{222}Rn to atmosphere (J_d) and ^{222}Rn concentration (C_{Rn}) in indoor and outdoor air in some selected coastal regions in Egypt**

Region	Latitude north	Longitude east	C_{ERn} kBq/m³	J_d Bq/m²h	$C_{Rn\ indoor}$ Bq/m³	$C_{Rn\ outdoor}$ Bq/m³
A Matrouh-1	31°33′40″	25°09′44″	14.819	50.610	50.229	10.107
B Matrouh-2	31°21′39″	27°15′30″	11.255	38.439	38.150	7.676
C Matrouh-3	30°28′16″	28°45′55″	14.718	46.798	46.446	9.345
D Alexandria-1	31°08′53″	29°50′02″	16.944	53.877	53.472	10.759
E Alexandria-2	31°17′32″	30°01′12″	9.006	30.758	30.527	6.142
F Rashid	31°28′26″	30°21′48″	38.117	130.176	129.197	25.996
G Damietta	31°31′37″	31°50′31″	5.221	17.830	17.696	3.561
H Port Said	31°18′40″	32°10′50″	6.293	23.008	22.835	4.595
I North Sinai-1	31°03′50″	32°36′40″	7.020	20.708	20.552	4.135
J North Sinai-2	31°08′31″	33°47′17″	6.761	19.945	19.795	3.983
Black sand[a]	31°28′2″	30°21′48″	325.819	1112.719	1104.348	222.207

[a]*Black sand came from Rashid region.*

tions were selected as large coastal cities based on radiological assessment of the Egyptian Mediterranean coast [15]. Coastal inhabitants of these governorates probably use the marine sediments as building materials. Black sand, which is present in sediments in Rashid, was also assessed for ^{222}Rn emanation and exhalation rates, because it is known to have relatively high amounts of uranium. According to the Egyptian Central Agency for Public Mobilization and Statistics (CAPMAS), the population census estimates ($\times\ 10^3$) on 1 January 2006 of Matrouh, Alexandria, Rashid, Damietta, Port Said and North Sinai governorates were 278, 3885, 4777, 1100, 546 and 317 people respectively.

The results of risk due to exposure to ^{222}Rn and its daughters are presented as risk per million inhabitants because the real population number has spatial and temporal variations. The inhalation rate varies with activity level, age, weight and general physical condition but some of these variations were not taken into account in the present work [16]. This calculation was carried out for inhalation rate of an adult man.

In the present study, the estimated risks were modified according to sex and smoking habit. The population unit was theoretically divided equally into 500 000 males and 500 000 females. The categorization of Rogers and Powell-Griner [17] and Maillie et al. [18] was used to classify smokers as: light smokers (LS) < 25 cigarettes/day and heavy smokers (HS) ≥ 25 cigarettes/day. Former smokers (FS) have a reduced survival when compared with never smokers (NS). We assessed the risk for both males and females for all categories of smoker (NS, FS, LS or HS) according to Shopland, Eyre and Pechcek's relative risk (RR) values [17]. They suggested the values of RR for males for FS, LS or HS as 9.36, 18.8 and 26.9 respectively, and for females as 4.69, 7.3 and 16.3 respectively.

Methods for calculating attributable risk

Calculation of ^{222}Rn emanation and exhalation rates

In order to estimate the amount of indoor and outdoor ^{222}Rn, a series of equations from (1) to (5) was used to calculate the emanation and exhalation rates of ^{222}Rn from its original ^{226}Ra sediment holder. The typical value of the ^{222}Rn emanation coefficient for sand is 0.14. The value of total porosity was changed according to the grain size from 0.43 for fine sand to 0.39 for coarse sand [19]. The concentration of ^{222}Rn emanating from dry sediments gas, C_{ERn} (Bq/m^3), in the absence of ^{222}Rn transport, can be calculated from equation (1) [3,19].

$$C_{ERn} = R\,E\,\rho\,\varepsilon^{-1}\,(1-\varepsilon)$$

Where: R is the ^{226}Ra activity in the sediment particles (Bq/kg), E is the ^{222}Rn emanation coefficient, ρ is the dry bulk density of the soil (kg/m^3) and ε is the total porosity.

Exhalation rate (flux density) of ^{222}Rn at the surface of dry sediments, J_D (Bq/m^{2}s), can be calculated using equation (2) [3].

$$J_D = R\,\lambda\,E\,\rho\,(1-\varepsilon)\,L$$

Where: λ is the ^{222}Rn decay constant (2.1 × 10^{-6}/s) and L is the diffusion length and derived from equation (3) [3,20]

$$L = \left(\frac{D_e}{\lambda}\right)^{\frac{1}{2}}$$

Where: D_e is the effective ^{222}Rn diffusion coefficient (m^2/s) and is derived from equation (4) [20].

$$D_e = D_0\,\varepsilon\,\exp(-6\,\varepsilon\,R_s - 6\,R_s^{14\varepsilon})$$

Where: D_o is the ^{222}Rn diffusivity in open air (1.1× 10^{-5} m^2/s) and R_s is the volumetric water saturation (0 in dry sediments).

The rate of ^{222}Rn entry from sediments in cubic metre volume U (Bq/m^{3}h) is given by equation (5) [3].

$$U = 3.6e3\,\frac{S_B\,J_D}{V}$$

Where: S_B is the surface area of the walls (m^2), J_D is the flux density (Bq/m^{2}h) and V is the volume of the area (m^3).

Calculation of indoor and outdoor ^{222}Rn

The ^{222}Rn concentration in air in a typical room is determined by the equilibrium between the ^{222}Rn gain (exhalation from walls and soil) and loss (ventilation and ^{222}Rn radioactive decay). When the room is open to the outside atmosphere, the ^{222}Rn concentration is low due to the outdoor level. Using the single compartment room model with different ventilation rates, ^{222}Rn concentrations can be estimated either indoor or outdoor according to the ventilation rate. Ventilation rates 1 and 5 h were used to estimate indoor and outdoor ^{222}Rn respectively using equation (6) [21].

$$C_{Rn} = \frac{U}{(\lambda_0 + \lambda_v)}$$

Where: C_{Rn} is the ^{222}Rn concentration (Bq/m^3), λ_0 is the ^{222}Rn decay constant (7.58 × 10^{-3}/h) and λ_v is the ventilation rate (/h).

Calculation of ^{222}Rn exposure

The equilibrium factor (F) as in equation (7) below is the ratio of the equilibrium equivalent ^{222}Rn concentration (C_{EEC}) to the ^{222}Rn concentration (C_{Rn}) [22].

$$F = \frac{C_{EEC}}{C_{Rn}}$$

A special unit, the working level (WL), is used to describe exposure to short-lived radioactive decay products of ^{222}Rn. The WL is defined as any combination of short-lived ^{222}Rn decay products in 1 litre of air that will result in the ultimate emission of 1.3×10^5 MeV of alpha energy [23].

Exposure to ^{222}Rn (WL) both indoors and outdoors can be calculated from the relation in equation (8) (1 Bq/m^3 = 0.27mWL)[3], which can be converted to the form of equation (9).

$$WL = C_{EEC} \frac{0.27}{1000}$$

The working level month (WLM) is the unit of cumulative exposure and defined as the exposure to 1 WL for 170 hours (1 working month) [24] per unit ^{222}Rn concentration (EEC). Exposure to ^{222}Rn (WLM) both indoors and outdoors can be calculated from equation (10) [3,23].

$$WLM = WL \frac{8760}{170}$$

Calculation of annual effective doses from ^{222}Rn exposure

The annual effective doses are derived from equation (11) below [22]. The dose conversion factors used in the calculations in this study were based on the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) values for indoor and outdoor ^{222}Rn as 3.6 and 5.4 (nSv/h)/(Bq/m^3) respectively [22].

$$D_{Rn} = C_{Rn} \, Of \, n \, Df_{Rn}$$

Where: D_{Rn} is the annual effective dose from ^{222}Rn exposure (indoor or outdoor) (mSv/year), C_{Rn} is the concentration of ^{222}Rn in indoor or outdoor air (Bq/m^3), Of is the occupancy factor (7000 hours indoor or 1760 hours outdoor), n is the conversion factor from nano (n) to milli (m) and Df_{Rn} is the dose conversion factor for ^{222}Rn, calculated from equation (12).

$$Df_{Rn} = F \, Dc$$

Where: F is the equilibrium factor (0.4 for indoor and 0.6 for outdoor) and Dc is the dose coefficient (9 EEC).

Calculation of risk of death from lung cancer from ^{222}Rn exposure

According to ICRP [11], the population cancer mortality risk per WLM of whole body dose <R> is given as:

$$< R / E_{WLM} > = \frac{Lung\ cancer\ death\ (LCD)\ per\ 1\,WLM}{1\,000\,000\ person}$$

$$= \frac{350\ LCD}{1\,000\,000}\ per\ WLM$$

Where: R is the number of deaths per 1 000 000 persons due to ^{222}Rn daughter exposure (E_{WLM}) for 1 year.

Results

The calculated ^{222}Rn emanation and exhalation rate values are shown in Table 1. Radon concentrations in indoor and outdoor air were calculated using equation (6) and are also listed in Table 1. The worldwide median value and other national and international values are shown in Table 2 for comparison.

The mean ^{222}Rn concentrations in the areas under investigation were 42.89 (SD 33.12) Bq/m^3 and 8.63 (SD 6.66) Bq/m^3 for indoor and outdoor air respectively. The ^{222}Rn concentration in indoor air ranged from 17.696 Bq/m^3 in Damietta to 129.197 Bq/m^3 in Rashid. The detected ^{222}Rn concentration in outdoor air ranged from 3.561 Bq/m^3 in Damietta to 25.996 Bq/m^3 in Rashid.

The UNSCEAR committee suggests rounded values for the equilibrium factor of 0.4 and 0.6 for the indoor and outdoor en-

Table 2 **National and international environmental values for ^{222}Rn concentration (C_{Rn}) indoors and recommended upper limits**

Environmental values	C_{Rn} indoor (Bq/m³)
National and international	
Worldwide median [3]	46
El-Minia City, Egypt [25]	123
Cairo, Egypt [26]	24–55
Belgium [3]	48
Czech Republic [3]	140
Cyprus [3]	7
Finland [3]	120
Kazakhstan [3]	10
Poland [3]	41
Romania [3]	45
United States [3]	46
Upper limits	
EPA upper limit [8]	148
ICRP upper range [9]	200–400
Sweden upper limit for existing buildings [9]	400
CNSC occupational exposure limit [9]	148
CNSC public exposure limit [9]	70
Threshold range [32]	600–1000

EPA = US Environmental Protection Agency; ICRP = International Commission on Radiological Protection; CNSC = Canadian Nuclear Safety Commission.

vironment respectively [22]. The calculated C_{EEC} values for both the indoor or outdoor environment are shown in Table 3. Indoor C_{EEC} ranged from 7.078 to 51.679 Bq/m³ and outdoor C_{EEC} from 2.136 to 15.597 Bq/m³. The minimum and maximum values of both indoor and outdoor air were seen in Damietta and Rashid respectively.

Exposure to ^{222}Rn as WL and WLM both indoor and outdoor were calculated using equations (9) and (10) (Table 3). The ^{222}Rn exposure (WL) in indoor air ranged from 0.0019 WL in Damietta to 0.014 WL in Rashid. The exposure from outdoor air ranged from 0.0006 WL in Damietta and North Sinai-2 to 0.0042 WL in Rashid. Table 4 gives the international and recommended levels of indoor exposure to ^{222}Rn ($E_{WL\ in}$) for comparison. ^{222}Rn exposure (WLM) in indoor air ranged from 0.098 WLM/y in Damietta to 0.719 WLM/y in Rashid. The exposure from outdoor air ranged from 0.03 WLM/y in Damietta to 0.217 WLM/y in Rashid (Table 3).

The annual effective doses from ^{222}Rn exposure both indoor and outdoor are shown in Table 5. The maximum indoor and outdoor values were 3.256 and 0.247 mSv/y respectively, detected in Rashid. The minimum indoor and outdoor values were 0.446 and 0.034 mSv/y respectively, detected in Damietta.

As regards the estimation of lung cancer attributable to exposure to ^{222}Rn and its progeny, the maximum indoor and outdoor risks were 252 and 76 per million population respectively, in Rashid. The minimum indoor and outdoor risks were 34 and 10 per million population respectively, in Damietta (Table 5).

As seen in the tables, large differences were observed between the black sand and the other samples for all the values estimated.

Figures 1 and 2 show the variations in the risk of death from lung cancer for males and females according to smoking status and exposure to indoor and outdoor ^{222}Rn progeny in each region. The lowest risk was detected in Damietta for both NS males and females with an estimated 17 and 5 deaths per 500 000 due to indoor and outdoor ^{222}Rn exposure respectively. The risk rose steeply to 464 and 140 deaths per 500 000 for HS males and 281 and 85 deaths per 500 000 for HS females respectively.

Table 3 **Calculated values of equilibrium equivalent radon concentrations (C_{EEC}), and exposure (E) to ^{222}Rn (WL and WLM) in both indoor and outdoor air in some selected coastal regions in Egypt**

Region	$C_{EEC\ in}$ Bq/m³	$C_{EEC\ out}$ Bq/m³	$E_{WL\ in}$ WL	$E_{WL\ out}$ WL	$E_{WLM\ in}$[a] WLM/y	$E_{WLM\ out}$ WLM/y
A Matrouh-1	20.092	6.064	0.0054	0.0016	0.280	0.084
B Matrouh-2	15.260	4.606	0.0041	0.0012	0.212	0.064
C Matrouh-3	18.578	5.607	0.0050	0.0015	0.258	0.078
D Alexandria-1	21.389	6.456	0.0058	0.0017	0.298	0.090
E Alexandria-2	12.211	3.685	0.0033	0.0010	0.170	0.051
F Rashid	51.679	15.597	0.0140	0.0042	0.719	0.217
G Damietta	7.078	2.136	0.0019	0.0006	0.098	0.030
H Port Said	9.134	2.757	0.0025	0.0007	0.127	0.038
I North Sinai-1	8.221	2.481	0.0022	0.0007	0.114	0.035
J North Sinai-2	7.918	2.390	0.0021	0.0006	0.110	0.033
[b]Black sand	441.739	133.324	0.1193	0.0360	6.146	1.855

[a]The recommended annual effective dose limit is 4 WLM/year [28].
[b]Black sand came from Rashid region.

Discussion

The estimated results are discussed according to the risk assessment model steps.

These steps can be summarized as hazard identification, hazard characterization, exposure assessment, dose assessment and risk characterization [23,24].

Hazard identification and characterization

The investigation of ^{222}Rn emanation and exhalation rates showed different patterns between the regions west of Rashid (Matrouh and Alexandria governorates) from the regions east of Rashid (Damietta, Port Said, North Sinai governorates). ^{222}Rn exhalation rates in western regions were higher than eastern regions. This may be due to the presence of uranium in the mineral structure of the sediments. Rashid had the highest ^{222}Rn exhalation rate. It is located at the end of Rashid estuary, which is characterized by the presence of black sand in its sediments. Our study demonstrated large differences

Table 4 **International and recommended levels of indoor exposure to ^{222}Rn ($E_{WL\ in}$)**

International and recommended levels	$E_{WL\ in}$ WL
EPA background level [9]	0.004
EPA upper limit [9]	0.02
WHO recommended levels [9]	0.11
Canada action level [9]	0.10
Canada target level [9]	0.02
United States [9]	0.02
Sweden existing buildings, permitted maximum levels [9]	0.11

EPA = US Environmental Protection Agency; WHO = World Health Organization.

Table 5 **Calculated values of annual effective doses (AED) and the risk due to exposure to [222]Rn and its daughters in both indoor and outdoor air in some selected coastal regions in Egypt**

Region	AED$_{in}$ mSv/y	AED$_{out}$ mSv/y	Risk$_{in}$ per million	Risk$_{out}$ per million
A Matrouh-1	1.266	0.096	98	30
B Matrouh-2	0.961	0.073	74	22
C Matrouh-3	1.170	0.089	90	27
D Alexandria-1	1.347	0.102	104	31
E Alexandria-2	0.769	0.058	59	18
F Rashid	3.256	0.247	252	76
G Damietta	0.446	0.034	34	10
H Port Said	0.575	0.044	44	13
I North Sinai-1	0.518	0.039	40	12
J North Sinai-2	0.499	0.038	39	12
Black sand[a]	27.830	2.112	2151	649

[a]Black sand came from Rashid region.

between the black sand and the samples taken from other regions for all factors estimated. The presence of black sand in this region has been previously reviewed [13]. The high [222]Rn exhalation rates of some dry sediments indicate that [222]Rn could contribute significantly to the lung dose rate in houses built with these sediments. The concentration of indoor [222]Rn can decrease rapidly with increasing ventilation rate.

The mean concentration of indoor [222]Rn (42.89 Bq/m^{3}) is lower than the worldwide median value (46 Bq/m^{3}) [3]. The international published mean values in randomly selected dwellings in some countries for indoor [222]Rn concentrations show wide variations; some of them are relatively higher such as the Czeck Republic (140 Bq/m^{3}), Finland (120 Bq/m^{3}) and Minia City, Egypt (123 Bq/m^{3}) and others are lower such as Cyprus (7 Bq/m^{3}) and Kazakhstan (10

Bq/m^{3}) [3,25]. The arithmetic mean values 39.5, 41, 45, 46 and 48 Bq/m^{3} for Cairo-Egypt, Poland, Romania, United States and Belgium respectively [3,26] are the most comparable with our value. The estimated indoor [222]Rn concentrations were lower than the published upper limits except for Rashid (129.197 Bq/m^{3}) which was higher than the Canadian Nuclear Safety Commission public exposure limit (70 Bq/m^{3}).

The mean indoor [222]Rn concentration in the western regions was higher [43.76 (SD 9.35) Bq/m^{3}] than eastern regions [20.22 (SD 2.12) Bq/m^{3}]. The same was true for outdoor [222]Rn. Again Rashid had the highest [222]Rn concentration both indoor and outdoor. Very high [222]Rn concentrations were found for pure black sand (1104.35 and 222.21 Bq/m^{3} for indoor and outdoor [222]Rn respectively).

The US Environmental Protection Agency (US EPA) suggests modifications to homes when [222]Rn levels exceed 148 Bq/m^{3} (EPA action level) [8]. The Canadian Nuclear Safety Commission uses 148 Bq/m^{3} as the upper limit for annual occupational exposure and 70 Bq/m^{3} as the annual exposure limit for the general public [9]. On the other hand, the National Council on Radiation Protection and Measurements remedial action level is twice as high as the EPA limit at 296 Bq/m^{3} [8,27].

According to [222]Rn classification of soil reported by Ljungquist [28], the majority of the estimated values of indoor [222]Rn in our study are around the normal risk level (10.0–50.0 Bq/m^{3}). Matrouh-1 and Alexandria-1 fell between normal risk and high risk. The only region that could be categorized as a high risk area was Rashid.

Exposure assessment

The main contribution to the exposure of the population to natural radiation comes from the inhalation of short-lived [222]Rn
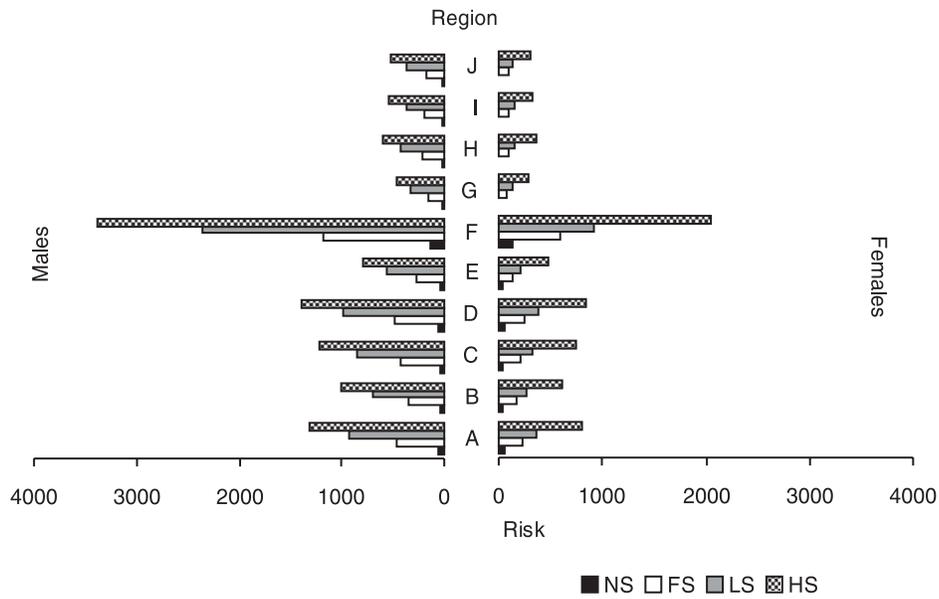
Figure 1 **Estimated risk of death from lung cancer due to indoor radon exposure per 500 000 by sex for never smokers (NS), former smokers (FS), light smokers (LS) and heavy smokers (HS)**
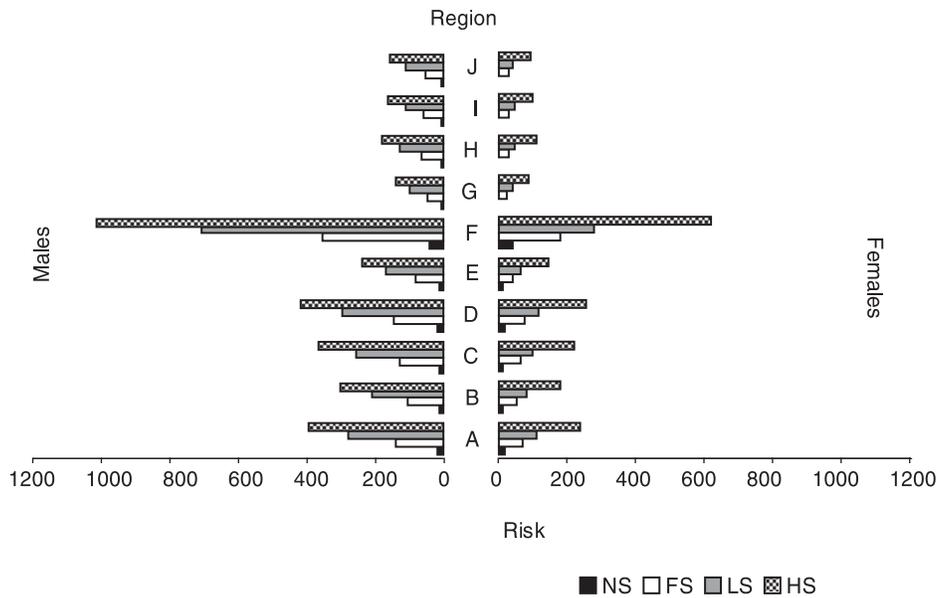

Figure 2 **Estimated risk of death from lung cancer due to outdoor radon exposure per 500 000 by sex for never smokers (NS), former smokers (FS), light smokers (LS) and heavy smokers (HS)**

decay products. Direct measurements of the concentrations of all short-lived decay products of [222]Rn are difficult and limited. They are estimated from considerations of equilibrium between [222]Rn and its decay products. Applying the classification of indoor exposure of Walsh and Lowder [23], where an exposure around 0.05 WL is considered high and 0.5 WL extremely high, the estimated exposure levels in our study are all less than this guideline. Walsh and Lowder also noted that the outdoor exposure is generally near 0.001 WL. The outdoor exposure levels in our regions are in line with this guideline except Rashid which has a higher value (0.0042 WL).

The western regions had exposure values slightly higher than the EPA-recommended background value (0.004 WL) [9]; Rashid showed a considerably higher value. On the other hand, the eastern regions had lower values.

Dose assessment

Actual measurement of lung dose is not feasible, and measurement of 1 or more parameters related to the lung deposition of [222]Rn daughters has been used as proxy for actual lung dose. In the home it is only feasible to measure [222]Rn concentration or [222]Rn daughter concentrations [21].

The mean annual effective doses from [222]Rn exposure in our study are consistent with the worldwide values 1.0 and 0.1 mSv/y for indoor and outdoor exposures respectively [22]. The same pattern was again observed between the western and eastern regions, the western regions having higher means for both indoor and outdoor air than the eastern regions. Rashid again also had the highest annual effective dose.

The annual effective doses calculated are well below the recommended dose limits of 20 mSv/y (corresponding to 4 WLM or 3000 Bq/m^{3} [222]Rn gas concentration)

averaged over 5 consecutive years or an effective dose of 50 mSv (corresponding to 10 WLM or 8000 Bq/m^{3} [222]Rn gas concentration) in any single year [29]. UNSCEAR gives the annual effective dose equivalent per capita from natural sources in areas of normal radiation background as 900 μSv/y for internal exposure of [222]Rn and [222]Rn daughters until polonium-214 [30].

Risk characterization

Risk characterization is the final step of risk assessment. The attributable risk is defined as the excess lung cancer rate in a population due to [222]Rn exposure as a fraction of the total lung cancer rate [27]. The number of annual lung cancer deaths that can be attributed to residential exposure to [222]Rn and [222]Rn daughters is 350 per 10[6] population per WLM/year, based on the risk value recommended by ICRP [11], where 350 is the number of persons that will be expected to die per 1 000 000 persons due to exposure to 1 WLM/year.

We calculated that the overall mean number of radon-induced lung cancer deaths was 83.4 (SD 64.67) and 25.1 (SD 19.52) deaths per million for indoor and outdoor exposures respectively. Compared with a risk estimation value for the Greek population of 65 deaths per million [31], our values are slightly higher for indoor but lower for outdoor exposure. The same pattern was observed between the western and the eastern regions, the western regions having higher means for both indoor and outdoor risks with 85 (SD 18.38) and 25.6 (SD 5.5) deaths per million respectively compared with the eastern regions with 39.25 (SD 4.11) and 11.75 (SD 1.26) deaths per million respectively. Rashid had the highest estimated risks with 252 and 76 deaths per million for indoor and outdoor [222]Rn exposure respectively.

The US regulatory agencies assumed in cancer risk assessment that risk is directly proportional to dose and that there is no threshold of carcinogenesis. On the other hand, it has been established in recent years that there is a threshold for lung cancer induction by [222]Rn in humans of around 600 to 1000 Bq/m³ in air for permanent intake, in particular at home and at the working place in areas of high natural uranium/radium geological situations [32]. All the estimated values in our study were below this threshold range, except for black sand which was higher.

For smokers the risk of lung cancer is significantly higher due to the synergistic effects of [222]Rn and smoking [8]. Our results show an increased risk of [222]Rn-induced death from lung cancer among smokers compared with non-smokers, highlighting the importance of the synergistic effect of [222]Rn exposure and tobacco exposure.

Conclusion

The majority of our estimates for indoor [222]Rn are within the normal risk level. However, Matrouh-1 and Alexandria-1 fell between normal and high risk while Rashid can be classified as a high risk area. The estimated risk of radon-induced lung cancer death in Rashid was 252 and 76 deaths per million for indoor and outdoor [222]Rn exposure respectively. Furthermore smoking increased the risk of death from radon-induced cancer.

Our data suggest that increased attention needs to be paid to exposure to radon and the associated health risks in order to preserve public health and reduce the incidence of cancer. The estimated values for lung cancers possibly due to indoor [222]Rn should be considered preliminary. Further epidemiological studies should be undertaken to examine the suggested hypothesis.

References

1. Hall FR, Boudette EL, Olzzewski WJ. Geologic controls and radon occurrence in New England, pp 15-29 In: Graves B, ed. *Radon, radium and other radioactivity in ground water: hydrogeologic impact and application to indoor airborne contamination*. Proceedings of the NWWA Conference, April 7–9, 1987, Somerset, New Jersey. Chelsea, Missouri, Lewis Publishers, 1987.

2. *Risk Assessment Guidance for Superfund Volume I Human Health Evaluation Manual (Part A) Interim Final*. Washington DC, Office of Emergency and Remedial Response, 1989:10-1–10-37 (EPA/540/1-89/002).

3. United Nations Scientific Committee on the Effects of Atomic Radiation. *Sources and effects of ionizing radiation. Report to the General Assembly of the United Na-* *tions with scientific annexes*, Volume 1. New York, United Nations Sales Publication, 2000**.**

4. Canadian Centre for Occupational Health and Safety (2005). Physical agents, radon in buildings (http://www.ccohs.ca/oshanswers/phys_agents/radon.html, accessed 9 February 2008).

5. International Commission on Radiological Protection. *Limits on inhalation of radon daughters by workers*. Oxford, Pergamon Press, 1981 (Publication 32).

6. International Commission on Radiological Protection. *Protection against radon-222 at home and at work*. Oxford, Pergamon Press, 1993 (Publication 65).

7. *WHO launches project to minimize risks of radon*. Geneva, World Health Organization, 2005 (Notes for the media 2005).

8. World Health Organization. Ionizing radiation in our environment: radon. (http://www.who.int/ionizing_radiation/env/radon/en/index.html, accessed 9 February 2008).

9. *Technical Support Document for the 1992 Citizen's Guide to Radon*. Washington DC, US Environmental Protection Agency,1992 (EPA 400-R-92-011).

10. Committee on Risk Assessment of Hazardous Air Pollutants, Board on Environmental Studies and Toxicology, Commission on Life Sciences, National Research Council. *Science and judgement in risk assessment*. Washington DC, National Academy Press, 1994:120–6, 186–7.

11. ICRP (International Commission on Radiological Protection). *Protection against radon-222 at home and at work*. Pergamon Press, Oxford, 1994 (ICRP Publication 65).

12. Teuschler LK. *Research planning for cumulative risk assessment*. Paper presented at the ORD/Regional Cumulative Risk Assessment Workshop, Dallas, Texas, 4–8 November, 2002 (http://www.epa.gov/osp/presentations/cumrisk/teuschler.pdf, accessed 10 February 2008).

13. Saleh IH et al. *Monitoring of ^{40}K in seawater–sediment–biota system along the Egyptian Mediterranean coast*. Paper presented at the Arab Conference of Biophysics, Cairo, Egypt, 23–25 August 2003.

14. Saleh IH et al. *Spatial and temporal variations of uranium and thorium series along the Egyptian Mediterranean coast*. Paper presented at the International Conference on Isotopes in Environmental Studies – Aquatic Forum, Monte Carlo, Monaco, 25–29 October 2004.

15. El-Gamal A et al. *Radiological assessment of the Egyptian Mediterranean coast*. Paper presented at the International Conference on Isotopes in Environmental Studies – Aquatic Forum, Monte Carlo, Monaco, 25–29 October 2004.

16. *Soil screening guidance for radionuclides: Technical background document*. Washington DC, Environmental Protection Agency, 2000 (EPA/540-R-00-006).

17. Rogers RG, Powell-Griner E. Life expectancies of cigarette smokers and nonsmokers in the United States. *Social science & medicine*, 1991, 32, 1151–9.

18. Maillie HD et al. The influence of life table corrections for smokers and nonsmokers on the health effects of radon using the BEIR IV method. *Health physics*, 1994, 66(6):615–20.

19. Shopland DR, Eyre HJ, Pechcek TF. Smoking attributable cancer mortality in 1991: Is lung cancer now the leading cause of death among smokers in the United States? *Journal of the National Cancer Institute*, 1991, 83:1142–8.

20. Yu C et al. *Data collection handbook to support modelling impacts of radioactive material in soil*. Argonne, Illinois, Environmental Assessment and Information Science Division, Argonne National Laboratory, 1993.

21. Bierma TJ, Toohey RE. Correlation of lung dose with Rn concentration, potential α-energy concentration and daughter surface deposition: A Monte Carlo analysis. *Health physics*, 1989, 57(3):429–37.

22. Vanmarcke H. UNSCEAR 2000: sources of ionizing radiation. (http://www.laradioactive.com/fr/site/pages/RadioPDF/unscear_artificielle.pdf, accessed 10 February 2008).

23. Walsh PJ, Lowder WM. *Assessing the risk from exposure to radon in dwellings*. Oak Ridge, Tennessee, Oak Ridge National Laboratory, Health and Safety Research Division, 1983.

24. Nazaroff WW, Nero AV. *Radon and its decay products in indoor air*. New York, John Wiley & Sons, 1988:74.

25. Mohamed A. Study on radon and radon progeny in some living rooms. *Radiation protection dosimetry*, 2005, 117(4):402–7.

26. Maged AF, Ashraf FA. Radon exhalation rate of some building materials used in Egypt. *Environmental geochemistry and health*, 2005, 27(5–6):485–9.

27. Lubin JH, Boice JD. Estimating Rn-induced lung cancer in the United States. *Health physics*, 1989, 57(3):417–27.

28. Ljungquist K. *Probabilistic design for evaluation of indoor environment* [Thesis]. Lulea, Lulea University of Technology, Department of Civil and Mining Engineering, 2003.

29. *Radiation protection against radon in workplaces other than mines*. Vienna, International Atomic Energy Agency, 2003 (Safety Reports Series No. 33).

30. El-Naggar AM. An overview of radiation ecology and health hazards. In: El-Raey M, ed. *Proceedings of the First Symposium of Environmental Sciences, Alexandria, Egypt*. Alexandria, UNARC/Moharem Bey Press, 1988:56–64.

31. Papastefanou C, Manolopoulou M, Charalampous S. Exposure from radioactivity in building materials. *Health physics*, 1984, 47(5):207–14.

32. Becker K. One century of radon therapy. *International journal of low radiation*, 2004, 1(3):333–57.

Guide on safe food for travellers

The advice given in this guide is important for every traveller, and of particular importance for high-risk groups, i.e. infants and young children, pregnant women, elderly and immunocompromised individuals, including those with HIV/AIDS.

The WHO Five Keys to Safer Food were specifically adapted to travellers and WHO is looking for partners to disseminate this message. Following the example of the Five Keys poster, now translated into almost 50 languages, WHO strongly encourages the translation, reproduction and dissemination of these recommendations.

The guide is available in 7 languages including English, French and Arabic and can be downloaded at: http://www.who.int/foodsafety/publications/consumer/travellers/en/index.html