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Comparative risk assessment of residential radon exposures in two radon-prone areas, Ştei (Romania) and Torrelodones (Spain)

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ABSTRACT

Radon and radon progeny are present indoors, in houses and others dwellings, representing the most important contribution to dose from natural sources of radiation. Most studies have demonstrated an increased risk of lung cancer at high concentration of radon for both smokers and nonsmokers. The work presents a comparative analysis of the radon exposure data in the two radon-prone areas, Ştei, Transylvania, (Romania), in the near of old Romanian uranium mines and in the granitic area of Torrelodones town, Sierra de Guadarrama (Spain). Measurements of indoor radon were performed in 280 dwellings (Romania) and 91 dwellings (Spain) by using nuclear track detectors, CR 39. The highest value measured in Ştei area was 2650 Bq m^{-3} and 366 Bq m^{-3} in the Spanish region. The results are computed with the BEIR VI report estimates using the age-duration model at an exposure rate below 2650 Bq m^{-3}. We used the EC Radon Software to calculate the lifetime lung cancer death risks for individuals groups in function of attained age, radon exposures and tobacco consumption. A total of 233 lung cancer deaths were observed in the Ştei area for a period of 13 years (1994–2006), which is 116.82% higher than expected from the national statistics. In addition, the number of deaths estimated for the year 2005 is 28, which is worth more than 2.21 times the amount expected by authorities. In comparison, for Torrelodones was rated a number of 276 deaths caused by lung cancer for a period of 13 years, which is 2.09 times higher than the number expected by authorities. For the year 2005 in the Spanish region were reported 32 deaths caused by pulmonary cancer, the number of deaths exceeding seen again with a factor of 2.10 statistical expectations. This represents a significantly evidence that elevated risk can strongly be associated with cumulated radon exposure.

1. Introduction

Lung cancer represents the major cause of cancer death worldwide with approximately 1 million deaths each year. Global statistics (Parkin et al., 2005) estimate that between 10% and 25% of all lung cancer worldwide is not attributable to smoking.

Radon is a chemically inert, naturally occurring radioactive gas without odour, colour or taste. It is formed within the decay chain of ^{238}U, an element found in varying amounts in all rocks and soil all over the world, and can diffuse several meters before decaying into its shorter-lived decay products ^{218}Po, ^{214}Pb, and ^{214}Bi (and ^{214}Po). Inhalation of the ^{222}Rn's short-lived progeny is responsible of about half of the total effective dose received by humans from all natural sources of ionizing radiation, according UNSCEAR 2000 (UNSCEAR, 2000). Since 1988, radon was included as a human carcinogen by the International Agency for Research on Cancer (IARC, 1988). The radon impact in the irradiation of people has lead until present to the conclusion that this element represents the second major risk factor, after tobacco, in triggering lung cancer (EPA, 2003). The main epidemiological evidence for the role of occupational radon exposure in the induction of lung cancer comes from a multitude of studies of miners of uranium, tin and iron ores, conducted mostly in Europe and North America (BEIR VI, 1999; Lubin et al., 1994).

In order to determine the effect of residential radon exposure on lung cancer risk, recent researches have consistently demonstrated an increased risk of lung cancer for both smokers and nonsmokers (Field et al., 2006; Darby et al., 2006), even in the case of normal indoor concentrations ranging from 40 to 300 Bq m^{-3} showing that risk of lung cancer rises by 16% for every 100 Bq m^{-3} increase in residential concentration. Several authorities (EPA, 1992; Euratom, 1990; ICRP 65, 1994) have set action levels which seem to be appropriate by the light of those last findings, above which radon mitigation measures would have to be taken in homes that exceeded such limits.

Our present research has focused on determining and comparing the exposure to indoor radon for the people living in Ştei area, Transylvania, Romania, in the near of old Romanian uranium mines and in the granitic

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radon prone area of Torrelodones town, Sierra de Guadarrama, Spain. Previous measurements in the both areas (Cosma et al., 2007a,b, pp. 10–11; Dinu, 2008; Cosma et al., 2009; Quindós et al., 1991a,b, pp. 449–453; Quindós et al., 2004, 2005) indicate here elevated levels of radon with concentrations one order of magnitude higher than those measured in homes located at non-radon-prone areas. In this context, the present study proposes a predictive assessment of health impact attributable to indoor radon exposure in the both studied areas.

As a first approach we apply the risk estimate model derivate to the BEIR VI to the Romanian and Spanish context with national adaptation based on demographic, smoking and indoor radon exposure data. We used the EC Radon Software (ECRS, 1999–2000) to calculate the lifetime risk for individuals groups in function of attained age, radon exposures and tobacco consumption. The ECRS software is equip with various databases specifying the risk model parameters, demographic data and smoking statistics and represents a valuable tool for exploiting radon measurements from geographical studies when there is a lack of individual information.

Using the available data on the exposure–response between radon exposure and lung cancer mortality risk and on the assessment of dose due to indoor radon exposure, this study is based on quantitative safety risk assessment method associated to an analysis of both variability and uncertainty, which allows measuring a confidence interval related to the prediction.

We aim to develop the further method based on this present model in order to obtain with most accuracy the number of lung cancer deaths attributable to radon.

2. Methods

2.1. Study population and site description

This study measured indoor radon concentration in Ştei and Torrelodones areas in order to determine and compare the magnitude and the effect of residential radon exposure.

An excess of lung cancer incidence has been observed in a region of Ştei, Romania, as showed our recent article about the earlier estimates of lung cancer deaths (Cosma et al., 2009). This is an area composed of the town Ştei and six villages with a total of 16,300 inhabitants, located in the Bihor Mountains, in the North West of Romania. These villages were selected because there was uranium mining activity intensively exploited for almost 60 years in the neighbouring areas. The earlier data reported are presented as two log-normal distributions with the second maximum, being related to the houses built using uranium waste as construction material. Medical records from the period 1996–2006 indicate a total number of 530 cancers for this population. According references, this translates into 133 deaths due to lung cancer (Cosma et al., 2009; Dinu, 2008).

The second investigated area in our study was the town of Torrelodones with a population of about 20,500 inhabitants (INE, 2008), situated in the North of the province of Madrid, Spain. This region, called Sierra de Guadarrama, had before been classified as a high-risk radon emission area because of the porous granite nature of the local subsoil. The previous study of Quindós (Quindós et al., 2005) reported elevated levels of radon exposure in Torrelodones and specified that the 14% of houses have levels above 400 Bq m^{-3} and 30% above 200 Bq m^{-3}. In addition, the geometric mean of radon was found in several researches (Quindós et al., 1991a,b, pp. 449–453; Quindós et al., 2004, 2005) to be about 180 Bq m^{-3}, which is four time higher than the national average value.

Because is difficult to attribute the increased lung cancer incidence to indoor radon in these two prone-areas we have started some local epidemiological analysis, in which smoking history and other possible confounding factors was investigated.

As well as the radon detectors exposures, a total number of 120 detailed questionnaires was prepared and distributed to the participants in the survey. Each questionnaire requested details of the construction materials and the duration of residency and certain personal details of all of the residents, like age, gender, occupation, quantitative smoking habits and the time spent inside the house. A number of 90 questionnaires (75%) were recuperated to the total of 120 distributed. The responding homes contained a representative number of 1120 occupants in Ştei area and 364 residents in Torrelodones town respectively. In total, 1484 inhabitants (47.62% men and 52.38% females) were included representing a sample suitable for analysis. The information on lifestyle variables and demographic parameters was compiled for each person together with measured radon concentration, expressed in Bq m^{-3}.

Because the relation between radon and smoking was found as the most important parameter in the problem of lung cancer, basic information on every individuals smoking history was taken into account by classifying each person as a smoker, a non-smoker or an ex-smoker.

2.2. Radon measurements

The exposure characterization was based on a measurement campaign in randomly selected houses carried out from 2003 to 2007. According to the NRPB Measurements Protocol (Miles and Howarth, 2000), integrated measurements were conducted in the 280 dwellings in Ştei area (Romania) and in the 91 houses at Torrelodones (Spain) using CR-39 track-etched detectors, exposed for a minimum of 6 months period in order to evaluate average indoor radon concentrations. The detectors were placed in the inhabited areas of dwellings, such as bedrooms and living-rooms, at a height of 1–1.5 m from the floor.

Alpha track detectors are inexpensive, reliable and easy to use. Every CR-39 detector is placed under the cap of a cylindrical polypropylene container 55 mm high and 35 mm diameter with a small gap in its upper part which prevents radon decay products and also ^{220}Rn from entering. Then, only alpha particles from radon that has diffused into the container and from the polonium produced inside can strike the detector. After the exposure time an etching process is done. The prolonged etching of CR-39 detectors showed that the background track density remains constant once they are fully etched, thus proving that the background is basically due to the surface defects (Mishra et al., 2005). Radon concentration can be determined by counting the tracks in a given area. The individual error of radon measurements was estimated at less than 10%. The accuracy of this detection system has been periodically checked with the successful participation in national intercomparison campaigns (CSN, 2004).

Radon levels in buildings are usually not constant and large variations can take place over short periods of time, hour to hour, day to day and also over seasonal periods. Track etched detectors provide radon concentration averaged over a period of a few weeks to a year. Given that it is necessary to estimate the annual mean dose from long time measurements, etched track detectors have been used for the longer exposure time radon concentration determinations. Seasonal correction factors are used although its cautious use has been recently stressed (Gillmore et al., 2005).

2.3. Effective doses

To evaluate the effective dose (nSv) the following equation proposed in the UNSCEAR 2000 Publication (UNSCEAR, 2000) can be applied:

$$\text{Dose} = C_a(\varepsilon_r + \varepsilon_d F)O \tag{1}$$

where C_a represent the mean annual radon activity concentration expressed in Bq m^{-3}, ε_r and ε_d are dose conversion factors for radon

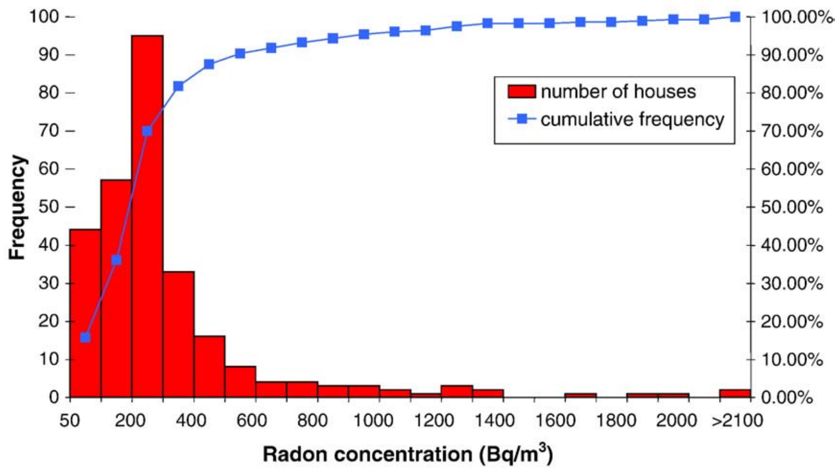

Fig. 1. Distribution of indoor radon concentration in homes in Stei area–Romania.

and its short-lived progeny respectively, $\varepsilon_r = 0.17$ nSv h^{-1}/Bq m^{-3} and $\varepsilon_d = 9$ nSv h^{-1}/Bq m^{-3}, F is the equilibrium factor between radon and its short-lived progeny, assumed as $F = 0.4$ in our study, and O represent the occupational factor for the average European, $O = 0.7 \times 8.76 \times 10^3$ h (UNSCEAR, 2000).

2.4. Risk estimates

The risk model chosen has allowed establishing a relative average risk for the entire life among the whole population. Two hypotheses on the interaction type of tobacco and radon effects have been tested, in agreement with the methodology developed earlier (BEIR VI, 1999). The joint effect of radon and smoking was presumed to be multiplicative and submultiplicative, separately and in turn, respectively.

We adopted a simplified risk model from the BEIR VI model (BEIR VI, 1999), with constant excess relative risk per radon exposure for both sexes and across various age groups and exposure periods. The BEIR VI age-duration risk model uses the most up-to-date data on 11 cohorts of radon-exposed underground miners (BEIR VI, 1999). Under this model the excess relative risk (ERR) varies as a linear function of cumulative radon exposure. The ERR also depends upon time since exposure, attained age and duration of exposure. The ERR decreases with increasing time since exposure and age at exposure, but increases with increasing duration of exposure (for a given total exposure).

The excess relative risk is as follows:

$$\mathrm{ERR} = \beta(\theta_{5-14}W_{5-14} + \theta_{15-24}W_{15-24} + \theta_{25} + W_{25+})\varphi_{\mathrm{age}}\gamma_{\mathrm{dur}} \quad (2)$$

where β is excess relative risk per radon exposure, w_i is radon exposure received in time window i before current age and θ_i is a corresponding weighting coefficient. The coefficient φ_{age} refers to attained age and γ_{dur} to exposure duration (BEIR VI, 1999).

Of particular interest is the linear relative risk model:

$$\mathrm{RR} = 1 + \beta w \quad (3)$$

where w is the cumulative radon exposure, and ß estimate the increment in ERR for unit change in exposure w (BEIR VI, 1999).

The EC Radon Software (ECRS, 1999–2000) was used to calculate the lifetime lung cancer death risks for the subjects groups in function of attained age, radon exposures and tobacco consumption, science Denman et al. (2004) method. For the parameters required by the software we consider the default values provided by the software most appropriate to the demographic data and the smoking prevalence of Spain and Romania, in according with data from WHO Statistical Information System (WHO, 2008).

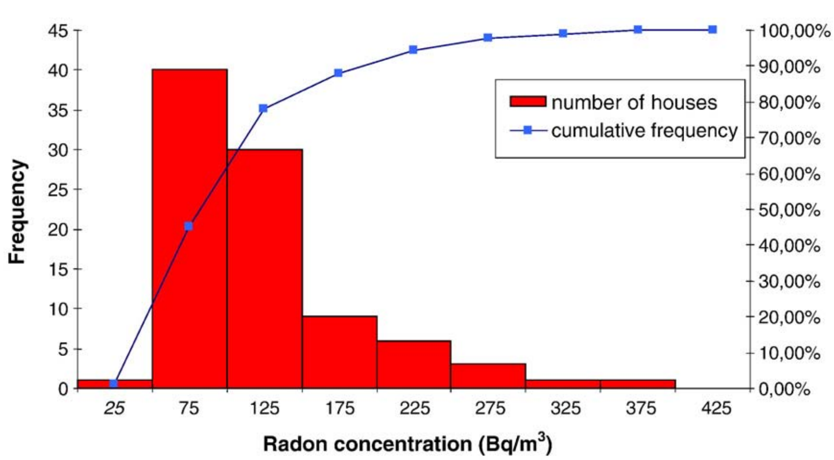

Fig. 2. Distribution of radon concentration in homes in Torrelodones–Spain.

Table 1
Summary statistics of the radon concentration distribution in the different studied areas.

	Number of samples	Arithmetic mean (Bq m^{-3})	Geometric mean (Bq m^{-3})	Geometric S.D.	Range (Bq m^{-3})
Stei	280	229	136	2.26	15–2650
Torrelodones	91	98	85	1.7	16–366

Lung cancer risks associated with radon exposure can be characterized in several ways. The Lifetime relative risk (LRR) was used to describe the lifetime risk of lung cancer among people continually exposed to radon during the path of their lifetime relative to the risk among unexposed individuals (EPA, 2003; BEIR VI, 1999). LRRs were computed with the BEIR VI (exposure-age-duration and exposure-age-concentration), Lubin (Lubin et al., 1994) and Darby (Darby et al., 2006) models, for various exposure scenarios that reflect indoor-radon exposure patterns of interest. These four models of risk and two hypotheses (submultiplicative and multiplicative) on the interaction type of tobacco and radon effects have been tested in order to compare the average estimates.

2.5. Evaluation of mortality

The assessment protocol was based on the methodology developed by the initiators of European epidemiological studies, combined with classical approach proposed by Covello and Merkhofer for the calculation of risk and applied Catelinois et al. (Catelinois et al., 2006; Covello and Merkhofer, 1993; Franke and Pirard, 2006) to estimate the overall risk in France.

The total number of deaths caused by lung cancer, observed annually in the Stei and Torrelodones regions was stratified according to age, gender and geographical settlement.

The expected lung cancer cases for a period of 13 years were taken from the Regional Bihor Cancer Registry, Romania (INS, 2008) and from the Spanish National Statistics Institute and statistical bulletins on death records Code CIE-10, C33-C342 (ISCIII, 2008), respectively. The report is partially complete and in the absence of the cancer incidence data for the rural population of Bihor county, the expected number of cases was determined using the percentages derived by the study of Ferlay et al. (2007), which estimate the cancer incidence and mortality for the 38 European countries in 2006. According Ferlay et al. (2007), the lung cancer continued to be the most common causes of cancer death in men and the third cause of death from cancer in women, with 56% of total cancer deaths occurring in males and 44% in women. We applied to our region the estimates of lung cancer deaths, which account 19.7% (26.6% for all cancer deaths in men and 10.9% in women) of the total cancer deaths for the Romanian population and 20.2% (26.3% for all cancer deaths in men and 12.5% in women) of total cancer deaths for the Spain. A very high percentage of these deaths could be due to smoking, increased exposure to radon and a part simultaneous exposure to radon and smoking (tobacco–radon interaction) leaving the remaining percentage attributable to other risk factors, such as air pollution.

In order to evaluate the number of lung cancer deaths attributable to domestic exposure to radon, the results of radon measurements, the total number of deaths from lung cancer and the exposure–response relationships have been combined under the following expression:

$$N_{\mathrm{Rd},A,d} = \frac{\mathrm{RR}_{A,\mathrm{Rd}} \times N_{T,A,d}}{1 + \mathrm{RR}_{A,\mathrm{Rd}}}, \quad (4)$$

where N_{Rd} represents the annual number of deaths from lung cancer attributable to domestic exposure to radon for groups of individuals under the age A in region d, $\mathrm{RR}_{\mathrm{A,\ Rd}}$ is the lifetime relative risk for groups of individuals under the age A at exposure to radon R_{d} and $N_{T,\ A,\ d}$ represents the total annual lung cancer deaths for groups of individuals characterized by the age A and the region d. This is in agreement with similar estimation in France (Catelinois et al., 2006).

The concern of radon-smoking interaction requires knowing the percentage of smokers in the total population situated in the investigated areas. This value is available from surveys conducted in the region by the National Institute of Statistics (INS, 2008; ISCIII, 2008), subsequently considered by the World Health Organisation (2008) as a reference, and is consistent with the results obtained from questionnaires applied on a sample of 1484 people of the total interest populations. There have been introduced in risk characterization the percentages of smokers by sex, age, and depending on the radon exposure in the studied areas.

The risk fraction as well as the annual number of lung cancer deaths attributable to lifelong radon exposure was estimated for distributions based on the BEIR VI age-duration risk model (BEIR VI, 1999), which is considered to be a reference for the experts.

3. Results and discussion

3.1. Radon levels

The histogram showing the distribution of screening radon concentrations measurements in the studied areas are presented in the Figs. 1 and 2. As it can be seen the results of our measurements follow a log-normal distribution. Table 1 illustrates a summary statistics of the radon concentration measurements.

Radon exposure seems to be of different magnitude in Romania and Spain. Considering the geological and the seasonal corrections, the mean of the radon concentration measures in Ştei is 229 Bq m^{-3}, while the average level measured in Torrelodones is 98 Bq m^{-3}. In comparison, this means that the magnitude of exposure to radon in the area Ştei is 2.33 times greater than similar exposure to radon levels in Spain.

The geometrical mean of radon, GM, in the studied areas were found to be 85 Bq m^{-3} in groundfloor of Torrelodones and 136 Bq m^{-3} in houses of Ştei, higher than the value of the national geometrical mean of indoor radon concentrations, 46 Bq m^{-3} in Spain (Quindós et al., 1991a, b;, pp. 449–453; Quindós et al., 2004, 2005) and 43 Bq m^{-3} in Romania (Cosma et al., 2009; Dinu, 2008) respectively. But in Romania the measurements using integrated detectors started rather late and still

Table 2
Distribution of indoor radon concentration in homes of Ştei and Torrelodones.

Radon concentration levels (Bq m^{-3})	Mean annual radon concentration in Ştei area (Bq m^{-3})	% of population in Ştei area	Mean annual radon concentration in Torrelodones area (Bq m^{-3})	% of population in Torrelodones area
0–99	57	36%	65	66%
100–199	139	34%	139	26%
200–399	268	17%	251	8%
400–599	471	4%	–	–
600–799	694	3%	–	–
800–1000	857	2%	–	–
1000–2650	1550	4%	–	–

Table 3
Distribution of Ştei population by smoking status, sex and measured radon concentration.

Radon concentration (Bq m^{-3})	Percentage of Stei Population in all group's categories (%)					
	Males			Females		
	Non-smokers	Ex-smokers	Smokers	Non-smokers	Ex-smokers	Smokers
0–99	11.79	1.50	3.86	16.50	0.21	2.14
100–199	11.13	1.42	3.64	15.58	0.20	2.02
200–399	5.56	0.71	1.82	7.79	0.10	1.01
400–599	1.31	0.17	0.43	1.83	0.02	0.24
600–799	0.98	0.12	0.32	1.37	0.02	0.18
800–1000	0.66	0.09	0.21	0.91	0.01	0.12
1000–2650	1.31	0.17	0.43	1.83	0.02	0.24
Total	32.74 (%)	4.16 (%)	10.72 (%)	45.83 (%)	0.60 (%)	5.95 (%)

now, only in Transylvania some integrated measurements are available (Cosma et al., 2007a,b, 2009). In both cases, these results indicate high levels of radon in the studied areas.

3.2. Effective doses

According to Eq. (1), the highest average annual effective doses for the whole body from the inhalation of radon were found for the population of the Ştei region with a range of variation from 1.32 mSv to 35.83 mSv. The mean radon concentration value situated in a range of 65–251 Bq m^{-3} in Torrelodones corresponds to an annual effective dose for the whole body of 1.50–5.80 mSv. This results are significantly higher in the Ştei area than the ICRP recommended action level of 3–10 mSv y^{-1} (ICRP 65, 61994) but much higher in the both studies than the national average value of 1.48 mSv and 1.6 mSv previously reported for the Romanian and Spain population (Cosma et al., 2009; Dinu, 2008; Quindós et al., 2004, 2005), respectively.

3.3. Population characteristics

Our analysis included people (47.62% men and 52.38% females) which alive in the 371 investigated houses in Ştei and Torrelodones areas. A percentage about 30% of subjects live in dwellings with elevated radon levels in the Ştei–Bihor county (>200 Bq m^{-3}), while only 8% of the Spanish people in the Torrelodones province are exposed to radon levels higher than the 200 Bq m^{-3} action level (Table 2).

We stratified for smoking (lifelong nonsmokers, current smokers and ex-smokers for >10 years) and measured radon concentration by dividing the individuals into seven and three categories, as can be seen in the Table 3 for Stei area and in the Table 4 for Torrelodones town, respectively.

3.4. Risk estimations

The effects of exposure vary flexibly with the length of time that has passed since the exposure, with the exposure rate and with the attained age. We subdivided study participants according to all categories of measured radon. The lifetime risk for lung cancer death was calculated using ECRS radon software for a total of 42 groups obtained from the combination of genders, classes of radon concentration and the different smoking status considered. The results were in agreement with a linear dose–response relation and the linearity remained significant even when we limited the analysis of measured concentrations at levels below 200 Bq m^{-3} ($P = 0.04$). Figs. 3 and 4 reports the combined results using all data recorded in the two studied areas.

We calculate the average lifetime risk for lung cancer death associated with exposure of all subjects by weighting the risk in each age category by the number of individuals included in respective age group. The weights are proportional to the expected number of person, years for each gender and smoking category. Accordingly, the average lifetime risk obtained for our groups is 3.3×10^{-4} for Stei population and 3.6×10^{-4} for persons exposed in Torrelodones region. These values are similar to results obtained in other studies (Field et al., 2006; Darby et al., 2006).

The lifetime relative risk (LRR) of lung cancer mortality was estimated from the averages values of measured radon levels of 57, 139, 268, 471, 694, 857, 1500 Bq m^{-3} in Stei area and 65, 139, 251 Bq m^{-3} in Torrelodones town, respectively. Those concentrations were converted to annual exposures by assuming equilibrium of 50% between radon and its progeny and consider that 70% of time spent at home. The results are presented in the Figs. 5 and 6.

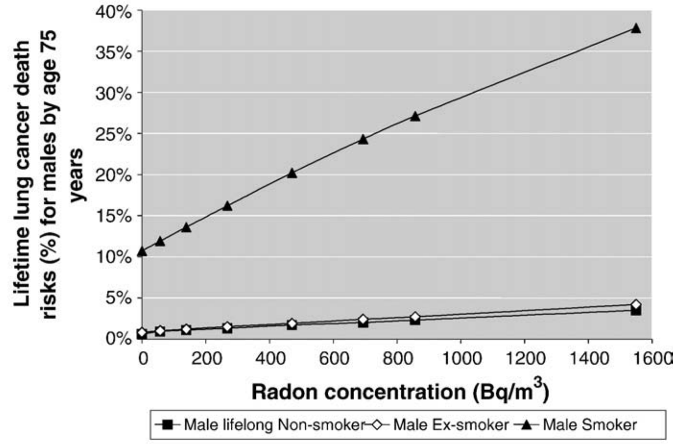

Fig. 3. Lifetime lung cancer death risk for males of combined studied areas by age 75 years versus indoor radon concentration.

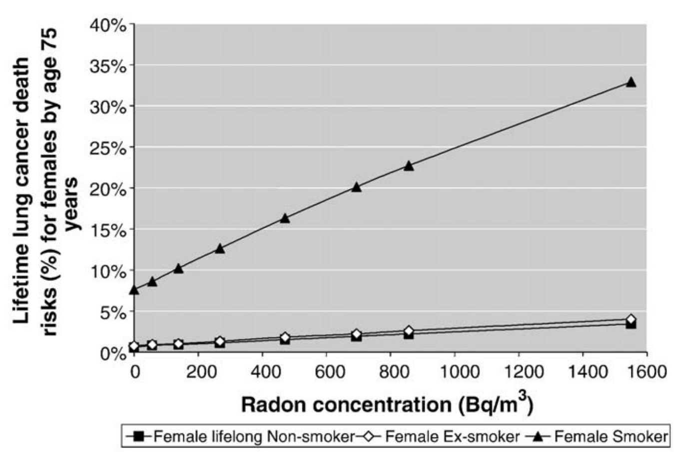

Fig. 4. Lifetime lung cancer death risk for females of combined studied areas by age 75 years versus indoor radon concentration.

Table 4
Distribution of Torrelodones population by smoking status, sex and measured radon concentration.

Radon concentration (Bq m^{-3})	Percentage of Torrelodones population in all group's categories (%)					
	Males			Females		
	Non-smokers	Ex-smokers	Smokers	Non-smokers	Ex-smokers	Smokers
0–99	14.23	2.69	3.71	21.42	1.43	3.31
100–199	4.08	3.24	4.38	14.24	0.15	4.50
200–399	10.11	0.54	4.79	3.03	2.05	2.10
Total	28.42 (%)	6.47 (%)	12.88 (%)	38.69 (%)	3.63 (%)	9.91 (%)

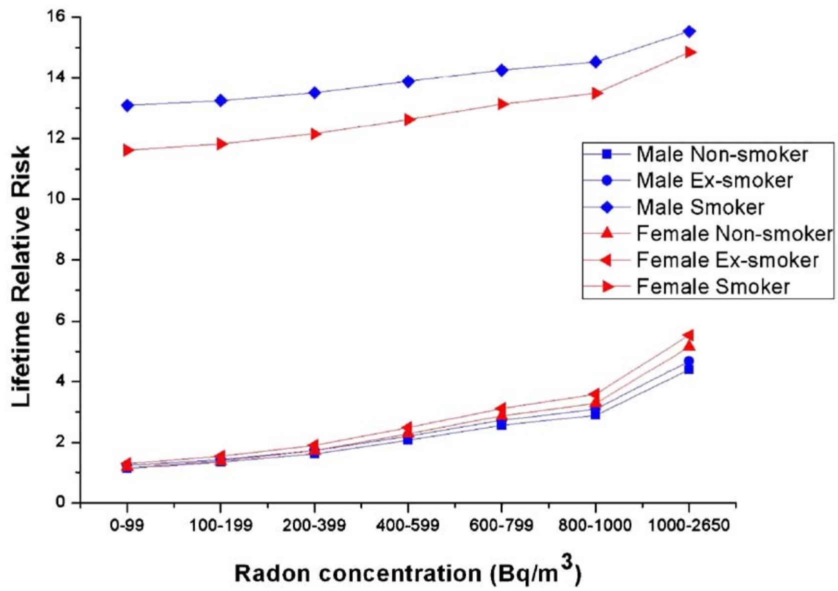

Fig. 5. The estimated lifetime relative risk (LRR) of lung cancer mortality at specified levels of radon exposure in Ştei area.

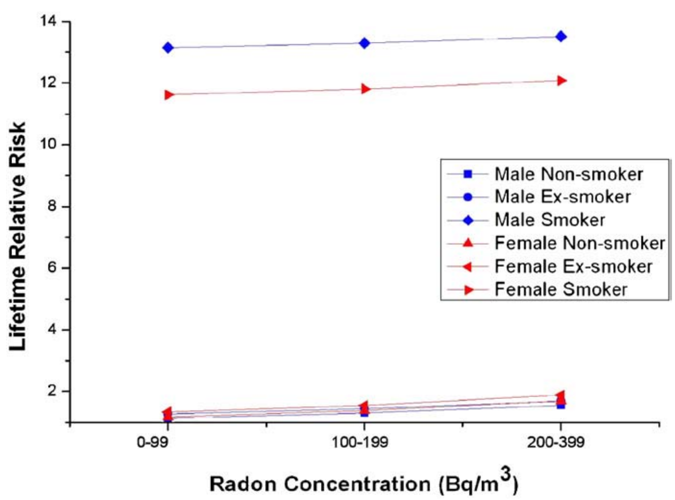

Fig. 6. The estimated lifetime relative risk (LRR) of lung cancer mortality at specified levels of radon exposure in Torrelodones area.

As a first analysis, the estimated values seem to be of the same magnitude in both regions. The calculated risks for smokers of the Spanish region still appear to be slightly higher. This fact can be explained by the smoking prevalence, for which the questionnaires showed that is greater in Torrelodones compared with the Stei area.

As expected, a significant increase in the lifetime risk of lung cancer with radon exposure is observed in both studies. Taking into account all stratifications included in our study based on age, sex and smoking status we estimate an average increase of 0.24 (95% CI, 0.18 to 0.30), in Torrelodones, and 0.23 (95% CI, 0.14 to 0.29) in the Stei region, in the relative risk of lung cancer/100 Bq m^{-3}. The estimated excess relative risk (ERR) of lung cancer/100 Bq m^{-3} measured radon concentration vary insignificantly depending on smoking and gender groups and does not accentuate the heterogeneity between the subject's categories.

Women have a somewhat steeper increase in LRR with increasing exposure than men because of their lower background lung cancer mortality. The higher LRRs in nonsmokers than in smokers also reflect differing background mortality rates (BEIR VI, 1999). We conclude that the basic rate of lung cancer death is significantly lower among women, non-smokers and ex-smokers. As a consequence, the number of deaths due to domestic exposure to radon is much lower in these categories.

3.5. Evaluation of mortality

As the major purpose to our study, we aim to estimate the number of lung cancer deaths attributable to radon by the method described in the Section 2.5.

The estimated annual number of lung cancer deaths attributable to indoor radon exposure in the two investigated areas ranges from 132 (95% confidence interval, 120–144) to 291 (95% CI, 248–302), depending on the model considered. The lowest values obtained for both the number of deaths and for the attributable fraction were estimated by applying the model used in epidemiological studies conducted by Darby. Introducing the method developed by Lubin we find the results similar with those obtained with BEIR VI models.

The lung cancer mortality attributable to radon and smoking for a period of 13 years (1994–2006) and for the year 2005, respectively, was estimated with the BEIR VI exposure age-duration model using the rates of Romanian Statistical Yearbook in the Bihor County as a

Table 5
Lung cancer mortality in the Ştei area for a period of 13 years (1994–2006) using the rates of Romanian Statistical Yearbook in the Bihor County as a standard.

Group	Lung cancer mortality for a period of 13 years (1994–2006)			Lung cancer mortality in the year 2005		
	Observed	Expected	SMR* (95% CI)	Observed	Expected	SMR* (95% CI)
Males, ≤59y	58	17	3.40 (2.53–4.27)	9	3	3.19 (2.49–3.90)
Males, >59 y	142	75	1.89 (1.02–2.76)	15	8	1.88 (1.18–2.58)
Males, all ages	200	92	2.17 (1.30–3.04)	24	11	2.2 (1.50–2.91)
Females, all ages	33	15	2.16 (1.29–3.03)	4	2	2.23 (1.53–2.94)
Total	233	107	2.17 (1.30–3.04)	28	13	2.21 (1.49–2.95)

*Standardized Mortality Ratio.

Table 6
Lung cancer mortality in the Torrelodones town for a period of 13 years (1993–2005) using estimated annual crude rate/100,000 standard population[1].

Group	Lung cancer mortality for a period of 13 years (1993–2005)			Lung cancer mortality in the year 2005		
	Observed	Expected	SMR* (95% CI)	Observed	Expected	SMR* (95% CI)
Males, ≤55 y	62	18	3.44 (2.51–4.69)	7	3	2.33 (2.23–3.45)
Males, >55 y	187	101	1.85 (1.59–2.31)	20	10	1.98 (1.72–2.16)
Males, all ages	249	119	2.10 (1.84–2.56)	27	13	2.09 (1.89–2.33)
Females, all ages	27	13	2.08 (1.86–2.59)	5	2	2.13 (1.93–2.37)
Total	276	132	2.09 (1.84–2.57)	32	15	2.10 (1.90–2.34)

[1]Source, Spanish national statistics institute and statistical bulletins on death records Code CIE-10, C33-C342.
*Standardized Mortality Ratio.

Table 7
The lung cancer deaths and the attributable fraction (FRA) induced by radon in Stei are for a period of 13 years, BEIR VI exposure age-duration model, by sex.

BEIR VI model exposure–age-duration by sex	The total number of lung cancer deaths and FRA attributable to indoor radon exposures in the Ştei area population for a period of13 years (1994–2006)													
	Mean exposure: 57 Bq m^{-3}		Mean exposure: 139 Bq m^{-3}		Mean exposure: 268 Bq m^{-3}		Mean exposure: 471 Bq m^{-3}		Mean exposure: 694 Bq m^{-3}		Mean exposure: 857 Bq m^{-3}		Mean exposure: 1550 Bq m^{-3}	
	% of deaths	Number of deaths	% of deaths	Number of deaths	% of deaths	Number of deaths	% of deaths	Number of deaths	% of deaths	Number of deaths	% of deaths	Number of deaths	% of deaths	Number of deaths
Smokers	11.02	17	22.46	20	35.37	32	48.27	13	57.20	6	61.64	5	72.55	7
Males	10.71	15	21.88	17	34.64	28	47.37	11	56.33	5	60.78	4	71.83	6
Females	13.04	2	25.93	3	40.12	4	53.70	2	62.41	1	66.78	1	77.12	1
Non-smokers	11.15	9	23.67	13	37.45	21	51.31	9	60.74	5	65.61	4	77.42	6
Males	10.71	8	23.08	11	36.71	18	50.50	8	60.00	4	64.91	3	76.85	5
Females	13.79	1	27.01	2	41.86	3	55.95	1	65.03	1	69.60	1	80.47	1
Ex-smokers	10.78	11	23.05	13	36.56	22	49.84	10	59.85	5	65.48	4	77.33	6
Males	11.50	9	24.24	11	38.27	19	52.15	8	61.69	4	66.44	3	78.07	5
Females	13.79	2	28.57	2	43.50	3	57.45	1	66.44	1	71.01	1	81.45	1

standard (Table 5). The total number of lung cancer deaths in homes for the period 1994–2006 is 233, respectively for the year 2005 is 28. In comparison, Table 6 rated for Torrelodones a number of 276 deaths caused by lung cancer for a period of 13 years, which is 2.09 times higher than the number expected by authorities. For the year 2005 in the Spanish region were reported 32 deaths caused by pulmonary cancer, the number of deaths exceeding seen again with a factor of 2.10 statistical expectations.

Tables 5 and 6 illustrate essential aspects about the impact of radon on the studied areas population. The relative risk for young males (≤59 years) of Stei area is about 1.8 times higher than that for aged ≥60 years, while the relative risk for men of Torrelodones under the age less than 55 years is about 1.9 times higher than the age category for more than 55 years, being the difference significant. The observed number of female lung cancer cases is too small to conclude for such effect. No other cancers, except lung-cancer, showed significantly higher mortality rates than the studied population.

The attributable fraction of lung cancer caused by radon was calculated for our groups as the ratio of lifetime lung cancer death risk caused by radon only relative to that from all causes mortality (Covello and Merkhofer, 1993). Tables 7 and 8 shows the estimates of the lung cancer deaths for a period of 13 years and the proportion (FRA) induced by radon in Ştei and Torrelodones area, respectively. Table 7 shows that an estimated 11.15%–77.42% of lung cancer deaths occurring in males and females nonsmokers observed in Ştei area for a period of 13 years was correlated with exposure to radon. For the smokers exposed at the same radon levels the percentage of deaths attributable to radon was between 11.02% and 72.55%. For the ex-smokers the proportion is similar, situated in the range 10.78%–77.33%. Table 8 present the analogous proportion (FRA) and the number of lung cancer deaths induced by radon in Torrelodones for a period of 13 years. By analyzing the number of deaths presented in the same tables in terms of interaction radon-smoking, it can be seen clearly that the risk could be 1.6–1.7 times higher in smokers. Obviously, the highest numbers of deaths is recorded in the categories of smoking among men, both in the region of Stei and in the Spanish city.

An interesting element to assist in the management of risk is to analyze the contribution of different categories of indoor radon exposure. Figs. 7 and 8 present relevant information in this perspective. The percentage of attributable deaths to each level of concentration

Table 8
The lung cancer deaths and the attributable fraction (FRA) induced by radon in Torrelodones for a period of 13 years, BEIR VI exposure age-duration model, by sex.

BEIR VI model exposure–age-duration by sex	The total number of lung cancer deaths and FRA attributable to indoor radon exposures of Torrelodones population for a period of 13 years (1993–2005)					
	Mean exposure: 65 Bq m^{-3}		Mean exposure: 139 Bq m^{-3}		Mean exposure: 251 Bq m^{-3}	
	% of deaths	Number of deaths	% of deaths	Number of deaths	% of deaths	Number of deaths
Smokers	11.79%	43	22.26%	27	33.84%	52
Males	11.50%	39	21.88%	24	33.33%	47
Females	14.53%	4	25.93%	3	38.65%	5
Non-smokers	11.80%	24	23.46%	16	34.83%	34
Males	11.50%	22	23.08%	15	34.21%	31
Females	14.53%	2	27.01%	2	40.48%	3
Ex-smokers	13.33%	26	24.67%	17	37.25%	36
Males	13.04%	23	24.24%	15	36.71%	32
Females	15.97%	3	28.57%	2	42.20%	4

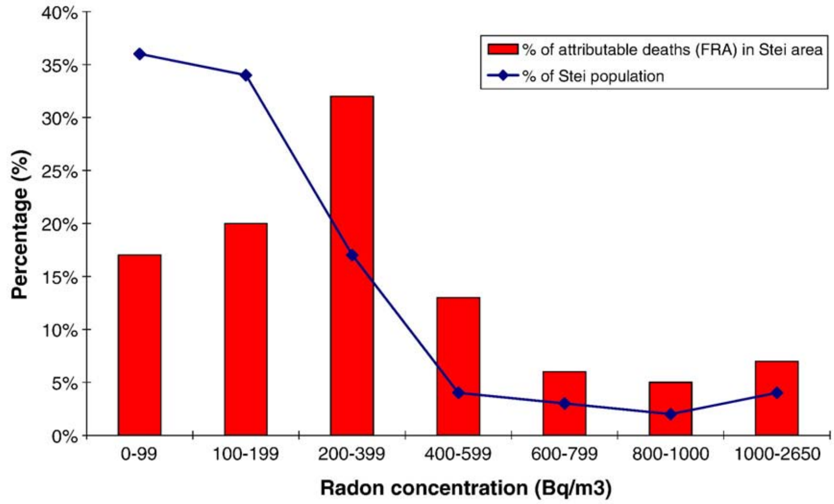

Fig. 7. Proportion of lung cancer deaths attributable to indoor radon exposure by classes of exposure, computation based on arithmetic mean of indoor radon concentration in Stei area according to the age-duration model of the BEIR 6.

didn't show a log normal distribution. It can be seen that the greatest percentage of attributable deaths appears for concentrations higher than 200 Bq m^{-3}, which confirms the adequacy of the usually recommended action level. However, it is important to remark that more than 30% of the deaths could occur at levels below the abovementioned. The increased risk observed for low radon levels is in agreement with some recent similar studies and remind that there isn't safe indoor radon concentration.

3.6. Comparison with other studies of radon

Consistent with our results, several studies have been conducted in order to determine risk estimates from the general population and have found significant association between residential radon exposure and lung cancer risk.

According to a recent European study (Darby et al., 2006), around 9% of lung cancers in Europe may be caused by radon. Global statistics estimate that 15% of lung cancer in men and 53% in women are not attributable to smoking (Parkin et al., 2005).

The current estimated excess relative risks/100 Bq m^{-3} of about 24% in Torrelodones and 23% in Stei area are higher, but remain compatible with that of 16% (5% to 31%) estimated in the European studies (Darby et al., 2006) and also with that of 11% (0 to 28%) reported in a recent combined analysis of North American studies (Field et al., 2006).

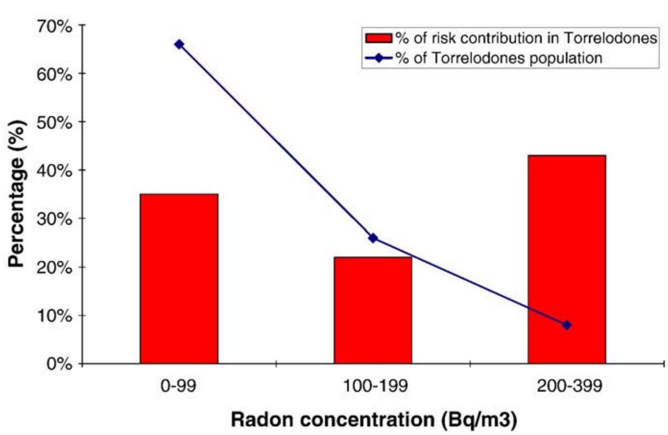

Fig. 8. Percentage of lung cancer deaths attributable to indoor radon exposure by classes of exposure, computation based on arithmetic mean of indoor radon concentration in Torrelodones town according to the age-duration model of the BEIR 6.

Although our study report higher radon concentrations (30% and 8% of measured values were >200 Bq m^{-3} in Stei area and Torrelodones town, respectively, versus 10% in the European collaboration and 5% in the North American studies), the European collaboration, however, has greater power and more extreme statistical significance because it involves twice as many cases of lung cancer.

Our results are also consistent with an analysis of miners (Lubin et al., 1997) exposed to concentrations below 0.5 WL (approximately equivalent to 4600 Bq m^{-3} indoor radon gas in the home) suggested risks were 19–30%/100 Bq m^{-3}. These estimates are higher than, but compatible with the present estimate.

In a case-control study of Pershagen et al. (1994) the estimates of relative risk ranged from 1.3 to 1.8 corresponding to mean radon concentrations of 140–400 Bq m^{-3} and higher than 400 Bq m^{-3}, respectively, which suggest that radon is a probable reason for the higher lung cancer incidence observed.

Another case-control study of radon in France (Franke and Pirard, 2006) show that between 21.5 and 28% of lung cancer deaths would be caused by mean exposures to radon ranged from 98 Bq m^{-3} to 197 Bq m^{-3}. The part attributable to concentrations above 400 Bq m^{-3} would be between 30% and 48%. When reducing exposure in case levels exceed 200 or 400 Bq m^{-3} to lower levels, a significant efficiency on the safety health impact in those regions was observed.

4. Conclusions

If we compare the annual number of deaths for the estimated range of 13 years with the number for the year 2005, increased lung cancer mortality has been observed in the Stei area. The standardized mortality ratio (SMR) is significantly increased for the both sexes.

On the other hand, lung cancer is clearly advancing in the Spanish region, according to data published by the Spanish National Institute of Statistics regarding the expected deaths caused by the pulmonary cancer (Table 6). Mortality rates show an increase of 15% compared to the decade of the 1990s. This situation is explained in a certain amount by the massive increase of population in the Torrelodones town, from 7000–11,000 people during the years 1990 to 12,000–20,500 during the years 2000–2007 (ISCIII, 2008).

The agreement of the present calculations with the Cancer Registry Data support the concept that the ECRS can be used to estimate the risk of indoor radon because reproduce the risk values derived in the BEIR report. A good correlation between medical records and our estimates provided that the different demographic factors as a smoking history and radon levels was investigated and has been properly taken into account. The concept of attributable fraction clearly illustrates that risk factors associated with moderately elevated relative risks may be also important from a public health point of view if large population groups are exposed.

The presented results confirm that indoor radon exposure represent the second factor, after smoking, in the induction of pulmonary cancer. The elevated radon levels in houses, an equally increased relative risk for males and females, mostly non-smokers, and the significantly higher risk for young males may confirm the above assertion. Some radon risk studies of occupationally exposed groups (Pershagen et al., 1994; Pressyanov et al., 1999; Hornung et al., 1998) have evident accentuate in a similar age dependency of the risk.

Furthermore, although the prevalence has started to decrease among men in countries like the United States, it is still rising in Romania and Spain. Even though smoking has decreased appreciably here in recent years, we will have to wait more than a decade before the prevalence of lung cancer will start to decline. This result shows that indoor radon exposure is a serious public health problem in the both radon-prone areas.

Complementarily to the measurement campaigns, when high radon levels are found remedial actions have to be taken into consideration. The aim of radon remediation is not only to reduce indoor radon levels but to do so with minimal impact on the building structure and occupants. In existing houses, the methods to reduce radon concentration are based on dilution and/or pressure changes by means of a pressure modifying sump, often in conjunction with an extraction fan. On the other hand, for new build houses, the installation of radon proof membrane across the entire footprint of the house seems to be the most useful way to prevent radon entry (Scivyer, 2007).

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