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Short communication

Indoor radon levels in Greek schools

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ABSTRACT

Radon and gamma dose rate measurements were performed in 512 schools in 8 of the 13 regions of Greece. The distribution of radon concentration was well described by a lognormal distribution. Most (86%) of the radon concentrations were between 60 and 250 Bq m^{-3} with a most probable value of 135 Bq m^{-3}. The arithmetic and geometric means of the radon concentration are 149 Bq m^{-3} and 126 Bq m^{-3} respectively. The maximum measured radon gas concentration was 958 Bq m^{-3}. As expected, no correlation between radon gas concentration and indoor gamma dose rate was observed. However, if only mean values for each region are considered, a linear correlation between radon gas concentration and gamma dose rate is apparent. Despite the fact that the results of radon concentration in schools cannot be applied directly for the estimation of radon concentration in homes, the results of the present survey indicate that it is desirable to perform an extended survey of indoor radon in homes for at least one region in Northern Greece.

1. Introduction

Radon is a colourless and odourless radioactive gas that is and always has been a natural component of the air we breathe. Radon is produced by the radioactive decay of radium, a naturally occurring radioactive element that is found in trace amounts in all soils as well as building materials. Radon gets into buildings mainly through cracks in floors or gaps around pipes or cables. Long-term exposure to high levels of radon can irradiate lung tissue and increase the risk of lung cancer. Recent studies (WHO, 2009) have confirmed that the risk is evident even at levels much lower than earlier studies suggested.

About one half of the effective dose from natural sources is estimated to be delivered by inhalation of the short-lived radon decay products. Due to this fact radon is the most "popular" subject of studies on environmental radioactivity. Large-scale radon surveys have been performed in many countries (UNSCEAR, 2000). In Greece, two relatively large radon surveys have been carried out from 1995–1998 in 1277 dwellings (Nikolopoulos et al., 2002) and from 1999–2006 in 561 workplaces (Clouvas et al., 2007) respectively. Smaller surveys concerning radon measurements only in schools were performed by Papaefthymiou and Georgiou (2007) in the town of Patras, Geranios et al. (2001) in the town of Kalamata and Clouvas et al. (2009) in the area of Xanthi.

In the present work, the results from 1024 passive radon detectors (electrets), installed in 512 schools in 8 of the 13 administrative regions of Greece, are presented and discussed. In addition gamma dose rate measurements in the schools are also reported.

2. Materials and methods

Greece is divided into 13 administrative regions (Fig. 1). From 1999 to 2010, 1024 passive radon detectors (electrets) were installed in 512 schools in 8 of the 13 regions of Greece. Table 1 presents the code number of the 8 regions, their corresponding names, population, area, the number of schools measured, the number of towns-villages where the measurements where performed and the duration in days of the radon measurements.

The detectors were installed in the teacher's or director's office. About 78% of the offices were located in the ground floor, 20% in the first floor and 2% in the second floor. Greek schools are of masonry structure (concrete-brick). Most school offices were ventilated only by operable windows (natural ventilation). In each office two passive detectors (short or long term electrets) were installed about 1–2 m above the ground. In this way, the risk of an erroneous result, due to a failure of one detector, was reduced. The very good correlation between the radon gas concentration measured by the two electrets, is shown in Fig. 2 .The electret ionization chamber (Kotrappa et al., 1998) is a small passive integrating device, designed for short or long term exposures. The device consists of a 50 mL conducting plastic chamber containing an electret. Radon

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Fig. 1. Code number and location of the 13 regions of Greece.

gas passively diffuses into the chamber through filtered inlets, and the alpha particles emitted by the decay process of radon ionize air molecules. Ions produced inside the chamber volume are collected onto the surface of the electret, causing a reduction of its surface charge. The electret voltage decreases in proportion to the integrated radon concentration. A voltage reader is used to measure the electret surface voltage. Using appropriate calibration factors and the exposure time, the mean radon concentration RnC (Bq m^{-3}) can be calculated from equations 1,2

$$\mathrm{RnC} = [(V_I - V_F/\mathrm{CF}\cdot T) - (G_{\mathrm{amma}}\cdot C_1)]\cdot 37 \tag{1}$$

$$\mathrm{CF} = C_2 + C_3\cdot(V_I + V_F)/2 \tag{2}$$

V_I and V_F are the initial and final electret voltage respectively, T is the exposure time in days, G_{amma} is the gamma background in μR/h, C_1, C_2, C_3 are constants which are given by the manufacturer and they depend on the electret (short or long term) and on the volume of the conducting plastic chamber. During the installation of the detectors, indoor gamma dose rate measurements, with a portable NaI(Tl) detector, were also performed. The gamma dose rate measurement is important for the evaluation of the radon concentration measured by the electrets (equation (1)). Radon measurements based on electret detectors are affected by the gamma background radiation, which also contribute to the electret discharge (Kotrappa et al., 1992). Therefore, the radon measurement results must be appropriately corrected for gamma background radiation, especially when measuring radon in areas of high-gamma background.

Table 1
Code number of the different regions presented in Fig. 1, their corresponding names, population, area, the number of schools measured, the number of towns–villages where the measurements where performed and the duration in days of the radon measurements.

No	Region	Population	Area km^3	Number of schools measured	Number of towns–villages measured	Duration of radon measurements in days
1	East Macedonia and Thrace	611,067	14,157	129	54	137–318
2	Central Macedonia	1,931,870	18,811	117	27	110–399
3	West Macedonia	303,857	9451	99	27	120–273
5	Thessaly	760,714	14,037	50	5	258–389
8	West Greece	605,329	15,549	13	7	168
11	North Aegean	206,121	3836	31	3 islands	287
12	South Aegean	302,686	5286	62	6 islands	143–207
13	Crete	601,131	8336	11	3	224

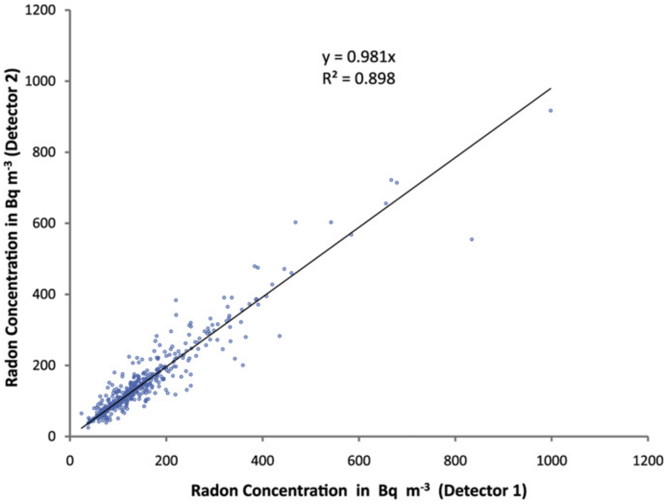

Fig. 2. Correlation between the radon gas concentrations measured by the two electrets.

3. Results and discussion

Fig. 3 presents the frequency distribution of the radon gas concentration (Bq m^{-3}) in the 512 schools. The values presented in Fig. 3 are the mean values of the two detectors in each workplace. The radon distribution can be well described in general by a lognormal distribution (dashed line). However, the lognormal

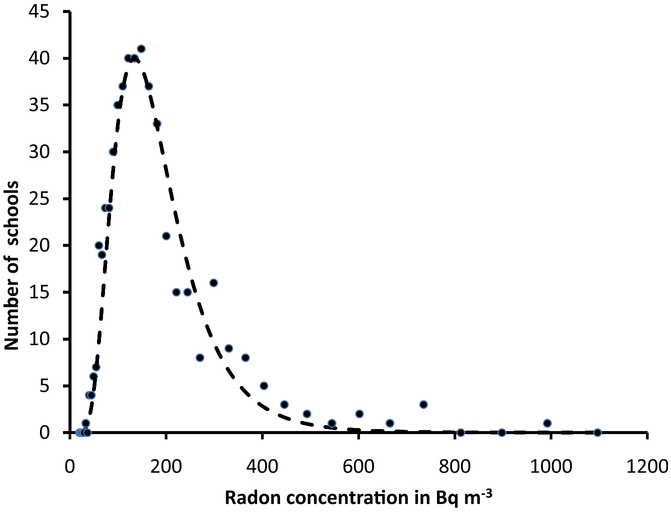

Fig. 3. Frequency distribution of the radon gas concentration (Bq m^{-3}) in the 512 schools. The radon distribution can be well described by a lognormal distribution (dashed line).

distribution seems to underestimate the number of schools with relatively high indoor radon concentrations. A possible reason is that the number of schools studied was not the same in all regions. Many of the measurements were performed in areas with high indoor radon concentrations. In particular, in the area of Xanthi which belongs to the region of East Macedonia and Thrace, there were measurements in 98 schools. About 45% of these schools had indoor radon concentrations more than 200 Bq m^{-3}.

Most (86%) of the radon concentrations presented in Fig. 3 were between 60 and 250 Bq m^{-3} with the most probable value of 135 Bq m^{-3}. The arithmetic (AM) and geometric (GM) means of the radon concentrations were 149 Bq m^{-3} and 126 Bq m^{-3} respectively. The maximum measured value of radon gas concentration was 958 Bq m^{-3}. The experimental uncertainty of radon concentration measurements using electret ionization chambers is less than 10% (Sun et al., 2006). The AM, GM, and range of the radon gas concentrations, as well as the number of workplaces with radon concentrations above 200 Bq m^{-3} and 400 Bq m^{-3}, for each of the 8 regions, are presented in Table 2. The values of 200 Bq m^{-3} and 400 Bq m^{-3} are the action levels proposed by the European Commission for new buildings and existing buildings respectively. The region of East Macedonia and Thrace (code number 1) had the relatively higher mean radon concentration (Table 2), the higher percentage of schools with radon concentration above 200 Bq m^{-3} and the higher mean indoor gamma dose rate. From soil sample gamma spectrometry analysis (Anagnostakis et al., 1996) and in situ gamma spectrometry measurements (Clouvas et al., 2001, 2004), this region is known to have relatively high natural radioactivity background. In general, Northern Greece has higher natural radioactivity than Southern Greece. In Table 3 are presented results from a number of radon surveys in schools that have been carried out in European countries. As is shown in this table the mean radon concentration measured in this work is similar to the mean radon concentration measured in other countries (e.g. Italy, Slovenia, Belgium). On the contrary, our results are much higher than those reported for schools in Patras in Southern Greece. This is not surprising, if one considers that the natural radioactivity (gamma radiation) in the Patras region is 2–3 times smaller than in Northern Greece (Clouvas et al., 2001).

The results of radon concentrations presented in Table 2 cannot be applied directly for the estimation of radon concentrations in homes. Two main differences exist between the measurements in houses and schools:

1. Most school offices studied in the present work are located on the ground floor. This is not the case for private lodgings, where at least in the big cities, most people stay in multi-storey buildings. It is well known that the radon concentration in the ground floor has the tendency to be higher than the upper floors.
2. The variations of the radon concentrations in a building are mainly dependent on the variations of the ventilation conditions and air exchange between rooms. These are caused by meteorological conditions (wind, barometric pressure, temperature) and by human activities, such as opening windows and doors. Human activities are definitively different between schools and homes. Schools in Greece are mainly operating from 8 h up to 14 h or 16 h. The rest of the day they are closed. In addition, with the exception of weekends, there are also long periods in the year where they are closed (summer, Easter and Christmas holidays). When schools are closed is expected there would be an increase in radon concentration due to poor ventilation. Therefore, in a given area, it is logical to expect higher mean value of radon concentration in schools than in homes.

Table 2

Results of the survey: No is the code number of the different regions. AM is the arithmetic mean and GM is the geometric mean of radon concentration. The radon range shows the minimum and maximum values of the radon concentration. The next two columns refer to the number of schools with radon concentrations above 200 Bq m^{-3} and 400 Bq m^{-3} respectively. The last column shows the mean indoor gamma dose rate (the error is the standard deviation).

No	AM (Bq m^{-3})	GM (Bq m^{-3})	Radon range (Bq m^{-3})	>200 Bq m^{-3}	>400 Bq m^{-3}	Gamma mean (nGy/h)
1	208	177	45–958	47 (36%)	10 (7.7%)	94 ± 30
2	141	123	32–386	22 (19%)	0	81 ± 33
3	120	110	49–364	6 (6%)	0	68 ± 28
5	130	122	51–288	5 (10%)	0	59 ± 15
8	75	69	38–131	0	0	30 ± 7
11	174	128	52–595	6 (19%)	4 (13%)	60 ± 31
12	112	102	51–357	3 (4.8%)	0	56 ± 27
13	96	87	38–153	0	0	40 ± 9
ALL	149	126	32–958	89 (17%)	14 (2.7%)	

Table 3

Indoor radon levels in schools from different European countries. AM and GM are the arithmetic and geometric mean radon concentrations.

Country	AM (Bq m^{-3})	GM (Bq m^{-3})	References
Ireland (national survey)	93		Synnott et al. (2006)
Slovenia (national survey)	168	82	Vaupotič et al. (2000)
Belgium	120		Poffin et al. (1992)
Croatia	93.4	70.6	Planinić et al. (1995)
Italy (Pordenone Province)	125		Giovani et al. (2005)
Italy (Neapolitan area)	144	86	Venoso et al. (2009)
Greece (Patras)	35	32	Papaefthymiou and Georgiou (2007)
Greece (Kalamata)	86	75	Geranios et al. (2001)
Greece	149	126	This work

It is a common practice in radon surveys to convert the radon concentration to dose, and in case of schools to calculate the annual effective dose for students and teachers. This is a straightforward calculation if one takes into account the annual mean radon concentration, the dose conversion factor, a mean equilibrium factor, and an occupancy factor for students and teachers. The problem is that the mean radon concentration takes also into account the radon concentration when the school is closed. According to Papaefthymiou and Georgiou (2007) the estimated effective doses may be a little overestimated as the classrooms are closed during nights, weekends and holidays. This statement is partially true. Indeed there is an overestimation, but it is not a little overestimation, it is a very important overestimation. As an example, in the school with the higher annual radon concentration (958 Bq m^{-3}), we (Clouvas et al., 2009) performed from 20 January 2009 up to 4 February 2009 radon measurements every 10 min. The AM radon concentrations when the school was in operation and when it was closed were 104 Bq m^{-3} and 866 Bq m^{-3} respectively. The AM radon concentration for that period was 700 Bq m^{-3}. In this example, the overestimation was a factor of 7. In order to check this result, we repeated this measurement in another school with much lower mean radon concentration. Radon concentration measurements every 10 min were performed (with the AlphaGuard 2000 radon detector) in a school for 48 h (Fig. 4). The AM radon concentrations when the school was in operation and when it was closed were 32 Bq m^{-3} and 145 Bq m^{-3} respectively. The AM radon concentration for the 48-h period was 121 Bq m^{-3}. Again, the overestimation was very important (almost a factor of 4). Despite the fact that the overestimation in the estimated effective dose for

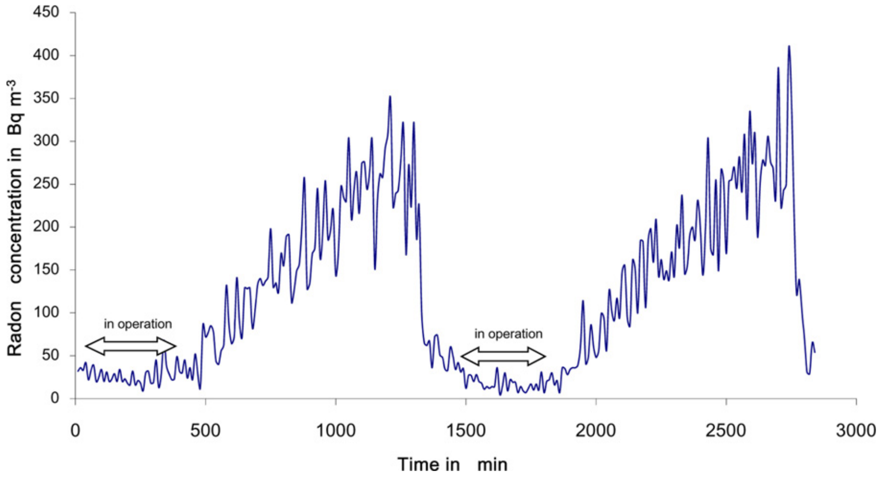

Fig. 4. Indoor radon concentration measurements every 10 min performed in a school for 48 h. The values of the arithmetic mean radon concentrations when the school was in operation and when it was closed were 32 Bq m^{-3} and 145 Bq m^{-3} respectively. The mean radon concentration for the 48 h period was 121 Bq m^{-3}.

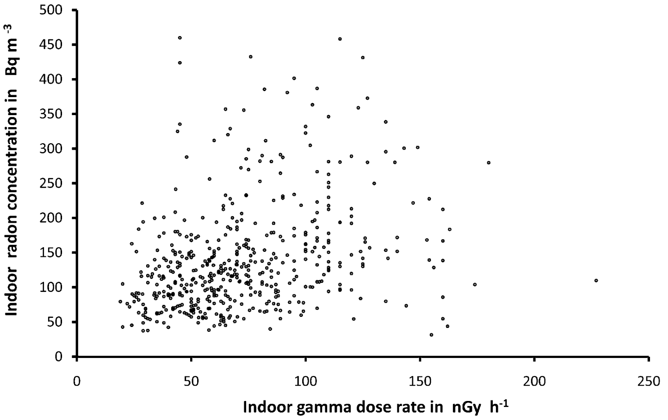

Fig. 5. Indoor radon concentration is plotted against indoor gamma dose rate for the whole data set of measurements.

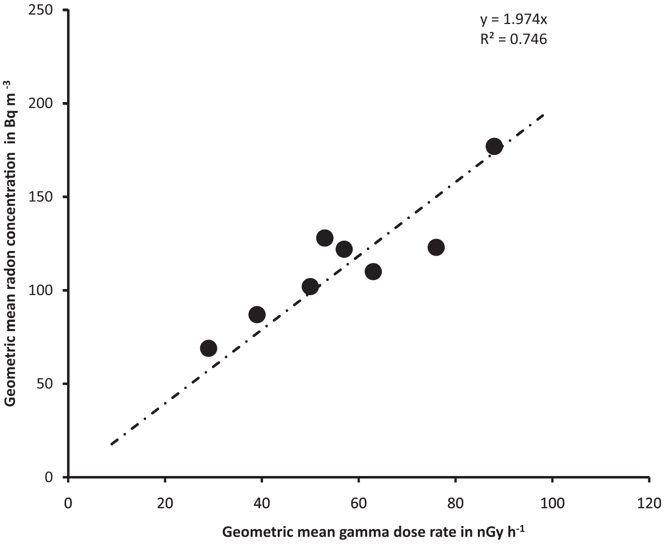

Fig. 6. Correlation between geometric mean region radon concentration and geometric mean region gamma dose rate values for the 8 regions (Table 2). The geometric mean standard deviations are within the dimensions of the points.

teachers (due to the overestimation of the radon concentration) is on the safe side from the radiation protection point of view, it is so important that we wish not to present in detail values of effective doses. Only as indication, the AM radon concentration 149 Bq m^{-3} for the 512 schools corresponds to a mean annual effective dose for teachers of 0.65 mSv, assuming an equilibrium factor of 0.4, an occupancy factor of 14% and a conversion factor of 9 nSv per Bq h m^{-3}.

The most important source for indoor radon concentration in low rise constructions is the subjacent earth. About 56% of the radon entry into the house is due to radon transport by advection and diffusion from soil to earth (UNSCEAR, 1993). About 21% is due to the diffusion from the building materials and 20% is due to infiltration from the outdoor air (UNSCEAR, 1993). In Fig. 5, indoor radon concentration is plotted against indoor gamma dose rate. No correlation is found between indoor gamma dose rate and indoor radon. The same result has been found previously (Clouvas et al., 2003) for ground and first floor apartments. This is not a surprising result due to the fact that radon concentration depends not only on the radon source term but also on the ventilation rate in the building and the exhalation rate of radon from the walls and floors, which depends very much on the way the surface has been covered with materials which let the radon pass through. In addition indoor gamma dose rate originates mostly from radionuclides in building materials and not from the outdoor environment, and as mentioned above, only a fraction of the radon concentration is due to the diffusion from the building materials.

Despite the fact that there is no correlation between indoor gamma dose rate and indoor radon for the whole data set of measurements (Fig. 5), it is remarkable to observe in Fig. 6 a linear correlation between the GM radon concentrations and the GM gamma dose rates presented in Table 2. Averaging of radon values can perhaps smooth the different variations of radon concentrations due to the different terms (ventilation rates, infiltration from outdoor air etc) and in this way revealed the correlation between radon concentration and gamma dose rate.

4. Conclusion

Radon and gamma dose rate measurements were performed from 1999 to 2010 in 512 schools in 8 of the 13 regions of Greece. The main conclusions are:

- The distribution of radon concentration was well described by a lognormal distribution. Most (86%) of the radon concentrations were between 60 and 250 Bq m^{-3} with a most probable value of 135 Bq m^{-3}. The AM and GM of the radon concentrations were 149 Bq m^{-3} and 126 Bq m^{-3} respectively. The maximum measured value of radon gas concentration was 958 Bq m^{-3}. These values are similar to those measured in other countries (e.g. Italy, Slovenia, and Belgium).
- Only in a small fraction (about 2.7%) of schools, the European Commission action level (400 Bq m^{-3}) was exceeded. The value of 200 Bq m^{-3} was exceeded at about 17% of the schools. These results must not be considered representative for the whole country. In this work, no measurements were done in Southern Greece which has low natural radioactivity background. In addition radon measurements were performed only in the teacher's or director's offices and not in the classrooms.
- Despite the fact that the results of radon concentration in schools cannot be applied directly for the estimation of radon concentration in homes, the results of the present survey indicate that it is necessary to perform an extended survey of indoor radon in homes of East Macedonia and Thrace.
- School is a special workplace due to the fact that it remains closed for many hours per day and many days per year (due to holidays), and consequently the "true" radon concentration (the radon concentration during the hours of occupation) is much smaller than the mean annual radon concentration. In the present work, a factor of 4 was measured between mean and "true" radon concentration in one school with a relatively low radon concentration. Previously, Clouvas et al. (2009) reported a factor of 7.
- As expected, no correlation between radon gas concentration and indoor gamma dose rate was observed. However, if mean values for each region are considered, a linear correlation between radon gas concentration and gamma dose rate was apparent.

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