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Systematic grid-based radon concentration measurements in the urban areas of Cyprus

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ABSTRACT

A comprehensive grid-based study of indoor Rn concentration in all accessible urban areas of the Republic of Cyprus, where 67.3% of the population resides, is presented. During the years 2004–2012, a total of 407 measurements of indoor Rn in the four highly-populated urbanised areas of Lefkosia, Lemesos, Larnaka, and Pafos districts were conducted, using high-sensitivity active Rn portable detectors. The four districts were subdivided into 189 grid cells, each of 1 km^2 in area. The grid cell mean indoor Rn concentration is in the range of 1.7 to 86.4 Bq/m^3, with an overall geometrical mean of 14.3 ± 10.0 Bq/m^3, and a median of 14.3 ± 3.9. The Rn mean in Cyprus is almost two-and-a-half times lower than the estimated world average of 39 Bq/m^3. The equivalent annual effective dose rate for each measurement was also calculated and compared to the corresponding world value. The spatial distribution and variation of Rn concentration values are also shown on maps of the urban areas of these districts. The conclusion of the present extensive and systematic Rn survey is that the Rn risk in the highly populated areas of Cyprus is low.

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1. Introduction

Radon (^{222}Rn) is a naturally occurring radioactive inert gas that is found in homes all over the world. Indoor Rn concentrations depend on a number of factors, including the geological characteristics of the ground underneath buildings, details of construction, and the habits of the occupants (e.g., USEPA, 1993; Appleton, 1995; Miles et al., 2007; Quindós et al., 2008; Demoury et al., 2013; Szabó et al., 2014). It is the decay product of the naturally occurring uranium-238 (^{238}U) decay series, which is present throughout the earth's crust. The half-life of Rn-222 is only 3.8 days and it directly decays into Polonium-218 (^{218}Po) by emitting alpha particles with an energy of about 5.5 MeV. Daughter nuclides following Rn decay, attached to microscopic dust particles, are inhaled and emit alpha particles, which effectively cause biological damage to the lung cells. Inhalation of air with high Rn concentration over a long period of time increases the risk of lung cancer (Field, 2001; Darby et al., 2005; Field et al., 2006). According to the World Health Organisation (WHO) the risk of lung cancer increases by 16% per 100 Bq/m^3 increase in long time average Rn concentration; the dose–response relation is linear, i.e., the risk of lung cancer increases proportionally with increasing Rn exposure (Zeeb and Shannoun, 2009). According to WHO, Rn is much more likely, however, to cause lung cancer in people who smoke. In fact, smokers are estimated to be 25 times more at risk from Rn than non-smokers.

The International Commission on Radiological Protection (ICRP, 2009), the International Atomic Energy Agency (IAEA, 2003), the European Commission (EC, 1997), and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2000a,b) refer to the health hazards due to Rn inhalation and emphasise the need for each country to define upper limits for Rn concentration in old and new buildings. The World Health Organisation recommends a national annual average concentration reference level of 100 Bq/m^3, but if this level cannot be reached under the prevailing country-specific conditions, the reference level should not exceed 300 Bq/m^3 (Zeeb and Shannoun, 2009).

The rock and soil mineral composition under a house affects the indoor Rn concentration. Atmospheric pressure differences between house and ground (rock or soil) can cause a slight under-pressure in a house that can draw up Rn gas from the soil or rock into the building. Radon moves more rapidly and further through permeable overburden, such as coarse sand and gravel, than through less permeable material, such as clay. Fractures in bedrock allow Rn to move more quickly (Otton, 1992; Appleton, 1995).

Radon gas can enter a house through cracks in concrete floors and walls, floor drains, sump pumps and construction joints (Appleton, 1995). Radon levels are generally higher in basements and ground floor rooms that are in direct contact with the rock or soil. The ability of Rn to be drawn into a house from the subsurface is influenced by the building design, construction quality, and ventilation preferences

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Fig. 1. Map of Cyprus showing the main towns and the location of Lefkosia (or Nicosia), Lemesos (or Limassol), Larnaka and Pafos (Source: Department of Lands and Surveys, Cyprus).

of the occupants. Building materials within the home environment are another source of indoor Rn gas (Abari et al., 2013; Cosma et al., 2013).

The concentration of uranium in the underlying rock or soil is the main factor that determines Rn levels. The investigated four urban areas of Lefkosia, Lemesos, Larnaka and Pafos (Fig. 1) are located on a sedimentary formation containing alluvium deposits, calcarenite, gravel, sand, marl and marly chalk (GSD, 1995; Tzortzis and Tsertos, 2004). The elemental uranium concentration measured in samples of surface soil from this formation is 0.78 ± 0.58 ppm (A.M. ± S.D.), and 1.69 ± 0.44 ppm in representative rock samples from the four sedimentary formations occurring in the accessible part of Cyprus, while the corresponding worldwide value is 2.8 ppm (Tzortzis and Tsertos, 2004; Tzortzis et al., 2003a).

In 1993, Christofides and Christodoulides (1993) from the Lefkosia General Hospital presented the results of the first indoor ^{222}Rn concentration measurements in Cypriot houses using alpha-track (CR-39) detectors. In 2001, the newly established Nuclear Physics Laboratory of the Department of Physics, University of Cyprus, began the "*Cyprus Radioisotopes*" project, aiming to measure indoor ^{222}Rn concentration in Cypriot public buildings and dwellings (Anastasiou et al., 2003), using high-sensitivity portable active Rn monitors of the type "RADIM3A" (Plch, 2001). Other research parts of the project included extensive and systematic measurements of naturally occurring radioisotopes in samples from different types of rock and soil, and building materials by means of standalone and in-situ high-resolution gamma-ray spectroscopy (Tzortzis et al., 2003a,b, 2004; Tzortzis and Tsertos, 2004, 2005; Michael et al., 2011; Svoukis and Tsertos, 2007). To date, only a few sporadic measurements of Rn concentration levels in Cyprus were reported (Sarrou and Pashalidis, 2003).

As a next step, our Laboratory has started systematic grid-based measurements on indoor Rn concentration throughout the main urbanised areas of Cyprus (Lefkosia, Lemesos, Larnaka and Paphos), using a constant grid cell of 1 km^2 in area, and high-sensitivity Rn portable detectors. The methodology and dose rate calculations are described by Theodoulou et al. (2012), together with the results in the densely-populated Lefkosia area. In the present study, besides the Lefkosia Rn data, the indoor Rn concentration grid-based measurements for the other three main residential areas of Lemesos, Larnaka and Pafos districts, together with the associated annual effective dose rates, are presented and compared to world average values. The measured Rn concentration in these four highly-populated districts is also presented on maps.

2. Methodology

2.1. Portable Rn detector

Indoor Rn measurements were obtained by two high-sensitivity portable monitors. The RADIM3A (Jiří Plch — SMM company) is a

Table 1
The population distribution in the accessible urban areas of the Republic of Cyprus (Statistical service, 2012). The number of measured grid cells and the corresponding number of measurements (N) in each district, the grid cell geometrical mean and standard deviation (SD) of the Rn concentration measurements (Rn), the annual effective dose rates (D) in each district, and the grid cell median and median absolute deviation (MAD) in each district.

Location	Population	No. of grid cells	N	Grid cell Rn (Bq/m^3)		Grid cell geometrical mean (±SD)		Grid cell median (±MAD)	
				Min.	Max.	Rn (Bq/m^3)	D (mSv/y)	Rn (Bq/m^3)	D (mSv/y)
Lefkosia*	245,900	54	108	6.4	86.4	17.9 ± 13.2	0.451 ± 0.333	18.8 ± 5.9	0.474 ± 0.149
Lemesos	184,600	33	66	6.3	51.6	11.8 ± 9.3	0.303 ± 0.235	10.4 ± 2.6	0.262 ± 0.066
Larnaka	86,400	57	143	1.7	47.8	12.7 ± 9.5	0.320 ± 0.240	12.5 ± 4.2	0.315 ± 0.106
Pafos	63,900	45	90	10.5	18.7	14.6 ± 2.1	0.368 ± 0.053	15.0 ± 1.3	0.379 ± 0.033
Total	580,800	189	407						
Grand geometric mean (±SD)						14.3 ± 9.97	0.360 ± 0.251		
Grand median (±MAD)								14.3 ± 3.9	0.361 ± 0.098

* Source: Theodoulou et al. (2012).

compact and dedicated detector system designed to directly monitor Rn concentration, to determine the Rn entry rate and ventilation coefficient. It also incorporates additional sensors to simultaneously measure the detector critical quantities, such as pressure, temperature, and relative humidity. The sampling time interval can be adjusted from 0.5 to 24 hours (h) and, therefore, the fluctuations in all the measured quantities during the detection time (one record per sampling time for every measured quantity) can be observed graphically. An important feature of this detector type is the automatic correction of Rn measurements with respect to the effect of humidity within each sampling time interval. The data could be read either in counts per sampling time or Bq/m^3, and displayed on the instrument screen or transferred and displayed on a computer monitor. The instrument calculates the mean, and displays the maximum and minimum Rn concentration over the adjusted time intervals.

Details on the detection system and the measuring technique are presented and discussed by Anastasiou et al. (2003) and Theodoulou et al. (2012).

2.2. Site selection and Rn measurements

In total, 66, 143 and 90 indoor Rn concentration measurements were conducted in the urban areas of Lemesos, Larnaka, and Pafos districts, respectively (Fig. 1). Thus, together with the Rn concentrations of the urban area of the Lefkosia district (N = 108); Theodoulou et al. (2012), the indoor Rn concentration in all accessible[1] urban areas of the Republic of Cyprus was surveyed, where 67.3% of the population resides (see Table 1), using a grid cell of 1 km^2 in area.

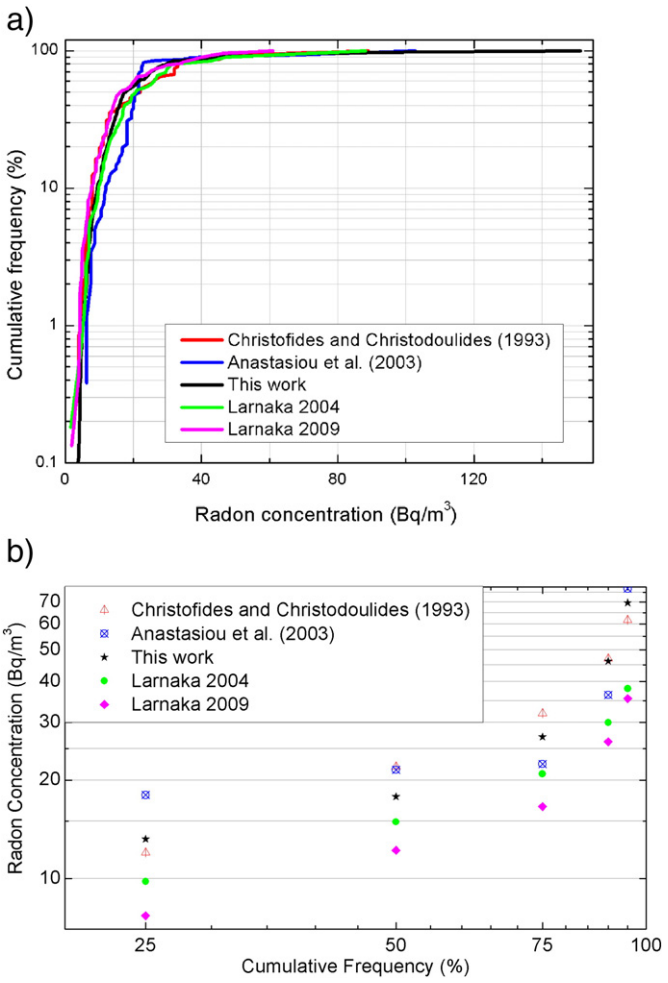

Fig. 2. Comparison plots of (a) cumulative frequency (%) of Rn concentrations, and (b) the 25th, 50th, 75th, 90th and 95th percentiles of the Rn measurements from Christofides and Christodoulides (1993), Anastasiou et al. (2003), this work, and the 2004 and 2009 measurements from Larnaka (see also Table 3). The geometrical mean of the Rn measurements of this work, Christofides and Christodoulides (1993) and Anastasiou et al. (2003) is 14.3 ± 10.0, 12.8 ± 16.0 and 16.3 ± 14.7 Bq/m^3 (GM ± SD), respectively.

Table 2
Basic statistics of the Rn surveys carried out in the Lefkosia, Lemesos, Larnaka and Pafos urban areas (Rn concentration in Bq/m^3). These values were used to define the class intervals of the plotted proportional dot maps.

Statistics	Lefkosia	Lemesos	Larnaka (2004)	Larnaka (2009)	Larnaka (All)	Pafos
N	108.0	66.0	49.0	94.0	143.0	90.0
Minimum	4.5	4.5	1.6	1.8	1.6	6.9
25th percentile	11.6	7.8	9.8	7.7	8.3	13.3
Median	17.8	9.9	14.9	12.2	12.8	15.1
75th percentile	24.6	13.5	20.9	16.6	19.4	16.2
90th percentile	28.7	24.5	30.0	26.2	29.3	17.4
95th percentile	30.7	38.6	38.1	35.5	36.9	18.7
Maximum	151.4	63.4	88.2	61.0	88.2	23.3

The four urban parts of Lefkosia, Lemesos, Larnaka, and Pafos districts were subdivided into 54, 33, 57 and 45 residential 1 km^2 area grid cells, respectively. Two to six measurements were conducted in each grid cell. For each measurement, the detector total counting time was set to 24 h, with the sampling time being adjusted to 2 h. The pressure, temperature, relative humidity, and Rn concentration were simultaneously measured every 2 h and saved in 12 independent memory records. Observing the measured quantities during the detection time or the automatically plotted graphs for the recorded parameters after each measurement, any possible diurnal variation could be clearly observed (see Fig. 4 in Theodoulou et al., 2012). Depending on the actual Rn concentration, the statistical accuracy for each of the 12 individual Rn concentration values was in the range of 5–20%. From the 12 records (12 × 2 h), the mean value of the Rn concentration and its standard deviation was then calculated automatically by the detector. In each 1 km^2 grid cell, two measurements were taken at the same or different sites. The two independent 24 h Rn measurements were combined to obtain the grid cell mean Rn concentration, and to estimate the corresponding standard deviation of the two measurements in each grid cell according to propagation of errors.

One measurement in each grid cell was conducted in the summer time, and another in the winter time of the same year to take into account possible seasonal variations, which may occur due to the specific climatic conditions at a certain location (see, e.g., Nazaroff, 1992; Neville and Hultquist, 2008 and references therein).

To test the precision of the Rn measurements, a more detailed investigation was carried out in the Larnaka district, where two different datasets were collected, not only in two different seasons, as in the other districts, but also in different years (2004 and 2009). Fig. 2 presents the cumulative frequency per cent of the Rn concentration from these two sets of measurements. No significant difference was observed (see also Table 2).

Before the start of the present survey, the Rn levels were measured at four sites in each district and compared with Rn levels measured previously by Christofides and Christodoulides (1993) and by Anastasiou et al. (2003). The measured Rn concentrations were within the levels of the previous two datasets. A comparison of the previous datasets with all measurements from this work is shown in Fig. 2 and Table 3.

A global positioning system (GARMIN, 2007) was utilised to obtain the geographical coordinates in decimal degrees of each site, which were subsequently used for plotting the Rn concentration on maps.

Priority for the site selection was given to schools and public workplaces, and then to old and new dwellings. In order to obtain the maximum possible Rn concentration, the detectors were placed in draught-free areas in the houses, preferably in occupied basements, if

[1] By accessible is meant the areas controlled by the Republic of Cyprus, excluding the northern part which is controlled by the Turkish army.

Table 3
Radon concentrations (Bq/m^3) at specific percentiles from the three datasets of Fig. 2, the maximum differences between the three datasets, the geometrical mean (standard deviation, SD) and the median value (median absolute deviation, MAD) of each dataset. Notation: N = number of measurements.

Percentile	Christofides and Christodoulides (1993); N = 89	Anastasiou et al. (2003); N = 84	This work; N = 407	Maximum difference
5	6.9	8.6	7.5	1.6
10	7.9	11.9	9.4	3.9
25	12.0	18.0	13.2	6.0
50	22.0	21.5	17.8	4.2
75	32.0	22.4	27.1	9.6
90	47.0	36.4	46.2	10.6
95	61.8	77.0	69.7	15.2
GM ± SD	12.8 ± 16.0	16.3 ± 14.7	14.3 ± 10.0	
Median ± MAD	22 ± 11	21.5 ± 3.3	17.8 ± 6.5	

available in the house, or in rooms that were closed for a long time, again if available, away from doors and windows. The detectors were always placed at a height of approximately 1 m.

The mean outdoor Rn concentration (background) measured at 4 sites of each district was 3.7 ± 0.7 Bq/m^3. This value agreed well with the corresponding outdoor Rn concentration of 3.9 ± 0.8 Bq/m^3, measured 10 years ago using the same method (Anastasiou et al., 2003). The outdoor Rn concentration value was not subtracted from the results obtained from the indoor measurements.

3. Results and discussion

Table 1 shows the population distribution in the accessible urban areas of the Republic of Cyprus and the averaged statistical parameters of indoor Rn measurements taken in each grid cell of 1 km^2 in area, while Fig. 3 portrays the statistical distribution of Rn in each grid cell (mean value and standard deviation) for Lefkosia, Lemesos, Larnaka and Pafos, respectively; for comparison the world average Rn value is plotted. In Table 2, the basic statistics of the individual site indoor Rn values are tabulated, which were also used as class limits in plotting the proportional dot maps (Fig. 4). Appendix A Tables A1, A2, A3 and A4 tabulate the indoor Rn measurements taken in the urban areas of Lefkosia, Lemesos, Larnaka and Pafos districts, respectively, and their basic statistics, as well as the corresponding annual effective dose rates.

The indoor Rn concentrations in the Lefkosia (Nicosia) urban area, the capital of Cyprus, vary from 4.50 to 151.4 Bq/m^3, with a mean and median of 20.6 and 17.8 Bq/m^3, respectively. The highest indoor Rn value of 151.4 Bq/m^3 was measured in a school in the Agios Dometios area of Lefkosia in grid cell number 4 (Dometio in Figs. 3 and 4; Table A1), which is situated to the west of Lefkosia centre. This measurement was recorded at the beginning of the year (September), where the room was closed during the summer vacation. The repeated measurement seven months later, in April of next year, has given a value of 96.2 ± 14.0 Bq/m^3. The Rn concentration in another room of the same school was at 14.4 ± 4.1 Bq/m^3. Only this particular room exhibited these relatively high values due to the low air exchange compared to the other rooms of the school. There are another three Rn concentrations that exceed the world average of 39 Bq/m^3 (UNSCEAR, 2000a,b), which is used here as a reference value for the comparison of the results of this study. These are in grid cell numbers 24 (89 Bq/m^3), 22 (67.7 Bq/m^3) and 45 (46.1 Bq/m^3), which are situated to the south (Aglantzia), south-west (Strovolos) and south-east (Geri) of Lefkosia centre, respectively, and all were recorded in schools.

The indoor Rn concentrations in the Lemesos (Limassol) urban area vary from 4.5 to 63.4 Bq/m^3, with a mean and median of 13.7 and 9.9 Bq/m^3, respectively. Four measurements exceed the world average

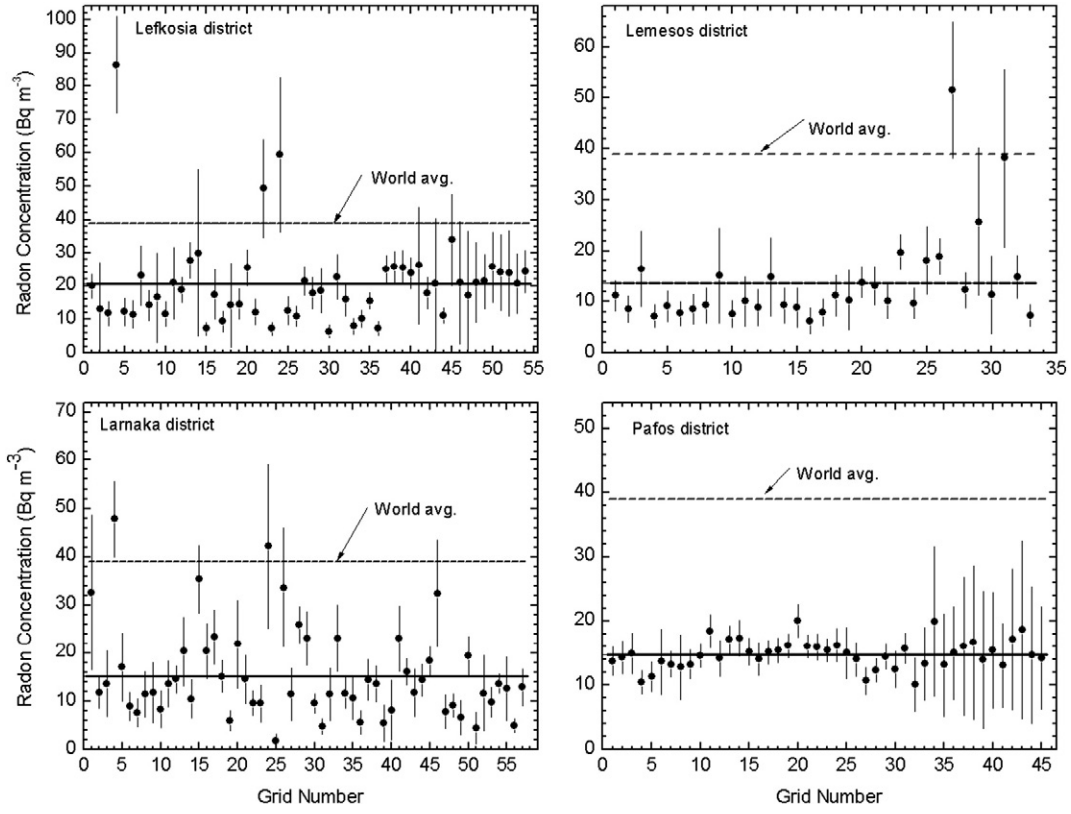

Fig. 3. The grid cell mean indoor airborne Rn concentration for each of the 54, 33, 57, 45 grid cells of the urban area of Lefkosia (Theodoulou et al., 2012), Lemesos, Larnaka, Pafos districts, respectively. The error bar denotes the mean standard deviation, calculated from the corresponding standard deviation of the two measurements in each grid cell according to propagation of errors law. The solid line represents the mean Rn concentration of 20.6, 13.7, 15.2, 14.7 Bq/m^3 for the measurements in the Lefkosia, Lemesos, Larnaka, and Pafos districts, respectively, and the dash line the corresponding world Rn average of 39 Bq/m^3 (UNSCEAR, 2000a, b).

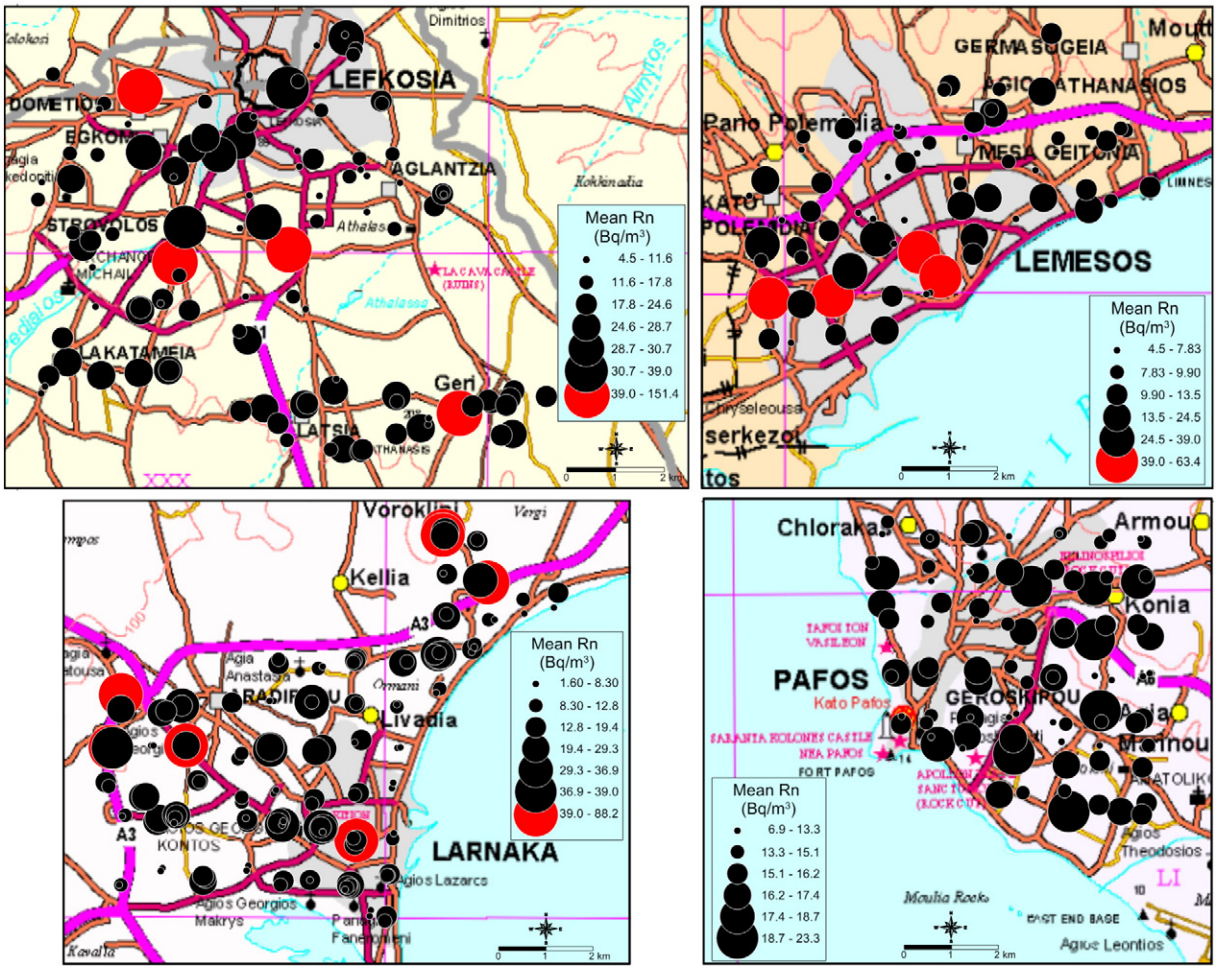

Fig. 4. Indoor Rn concentration distribution in the urban area of Lefkosia (N = 108; Source of measurements: Theodoulou et al., 2012), Lemesos (N = 66), Larnaka district (N = 143), and Pafos districts (N = 90), respectively. Radon measurements greater than the world average of 39 Bq/m^3 are displayed as red dots (Source of Administration and Road Map: Lands and Surveys Department, Ministry of Interior, 2007 version).

of 39 Bq/m^3 (Table A2; Figs. 3 and 4); two are in grid cell number 27, in the old central part of the town, with Rn values of 44.4 and 58.7 Bq/m^3, and the other to the west in grid cell numbers 31 and 29, with Rn values at 63.4 and 41 Bq/m^3, respectively. These measurements were conducted in windowless storage rooms and basements with little ventilation.

Larnaka was the district where indoor Rn measurements were taken in different years, 2004 and 2009, using the same grid, but the selected sites were different. The 2004 indoor Rn concentrations vary from 1.6 to 88.2 Bq/m^3, with a mean and median of 18.0 and 14.9 Bq/m^3, respectively (Table 2; Fig. 5). While, the 2009 indoor Rn measurements range from 1.8 to 61 Bq/m^3, with a mean and median of 14.4 and 12.2 Bq/m^3, respectively. Radon concentrations of the 2004 survey exceeding the world average of 39 Bq/m^3 occur in grid cells 46, 24 and 1, with values of 88.2, 47.1 and 42.7 Bq/m^3, respectively (Table A3; Fig. 5); these are situated in the north-western periphery of the older part of Larnaka, the north-west suburbs (Agios Georgios), and north-east suburbs (Voroklini). The 2009 Rn survey recorded four values above the world Rn average of 39 Bq/m^3 in three completely different grid cells, i.e., 4, 26 and 15, with values of 61.0, 46.3 and 42.3 Bq/m^3, respectively (Fig. 6), and with only one Rn value recorded in the same grid cell number 1, as the 2004 survey, with a value of 39.5 Bq/m^3. Two of the exceedance indoor Rn values occur in the north-east suburb (Voroklini; grid cells 1 and 4), and the other two in the north-west suburbs (Agios Georgios; grid cells 15 and 26) (Fig. 6). These comparatively elevated Rn

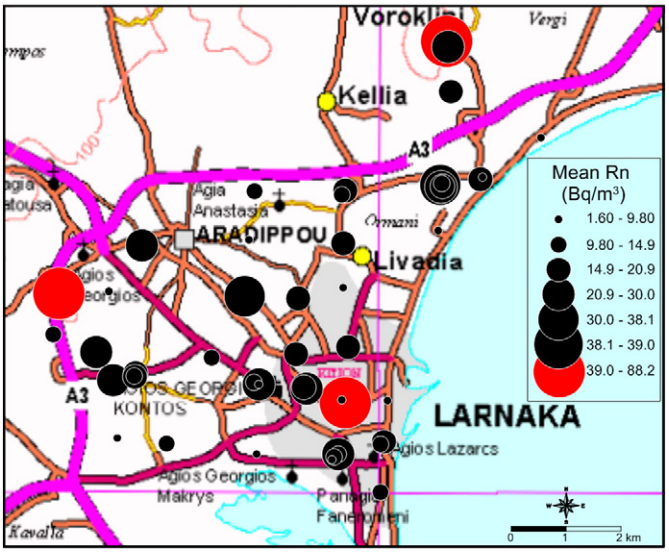

Fig. 5. Indoor Rn concentration distribution of the 2004 survey results in the urban area of the Larnaka district (N = 49). Radon measurements greater than the world average of 39 Bq/m^3 are displayed as red dots.

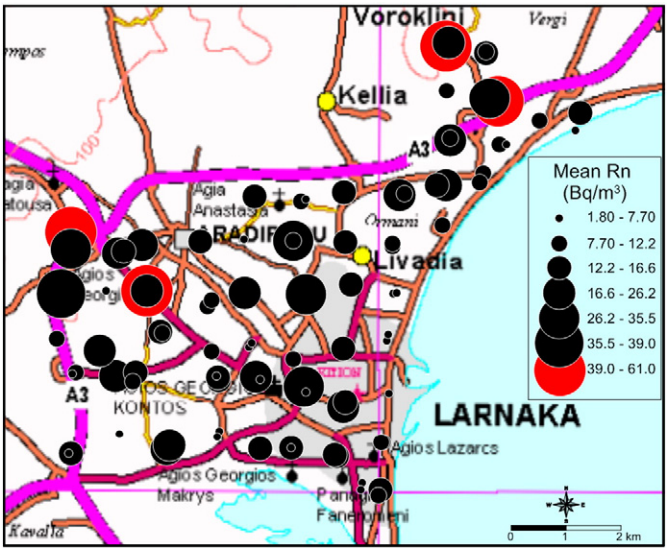

Fig. 6. Indoor Rn concentration distribution of the 2009 survey results in the urban area of the Larnaka district (N = 94). Radon measurements greater than the world average of 39 Bq/m^3 are displayed as red dots.

Table 4
Indoor Rn levels in dwellings of some European countries (WHO, 2000, Table 28, p. 210–211).

Country	Number of houses sampled	Radon concentration (Bq/m^3)			
		Period and duration of exposure	Average	Geometrical mean	±SD
Belgium	300	1984–1990	48	37	1.9
Czechoslovakia	1200	1982	140	–	–
Denmark	496	1985–1986	47	29	2.2
Finland	3074	1990–1991	123	84	2.1
France	1548	1982–1991	85	52	2.3
Germany	7500	1978–1984	50	40	–
Hellas	73	1988	52	–	–
Hungary	122	1985–1987	55	42	–
Ireland	1259	1985–1989	60	34	2.5
Italy	4866	1989–1994	75	62	2.0
Luxembourg	2500	1991	–	65	–
Netherlands	1000	1982–1984	29	24	1.6
Norway	7525	1987–1989	60	32	–
Portugal	4200	1989–1990	81	37	–
Spain	1555–2000	1988–1989	86	41–43	2.6–3.7
Sweden	1360	1982–1992	108	56	–
Switzerland	1540	1982–1990	70	–	–
United Kingdom	2093	1986–1987	20	15	2.2
Cyprus (this study)	407	2004–2012	16	14	10.0

concentrations were recorded in three basements with little ventilation, and in an old dwelling.

An overall view is given in Fig. 4, where the combined 2004 and 2009 Rn results are plotted; this map shows well the variation of Rn values in close proximity.

The indoor Rn concentrations in the Pafos urban area vary from 6.9 to 23.3 Bq/m^3, with a mean and median of 14.7 and 15.1 Bq/m^3, respectively (Tables 2 & A4; Figs. 3 and 4). All indoor Rn values are well below the world average of 39 Bq/m^3.

As the world average indoor Rn concentration is 39 Bq/m^3, the equivalent annual effective dose rate is 1 mSv/y. The grand geometric mean (±SD) and median (±MAD) are 0.360 (±0.251) and 0.361 (±0.098), respectively, which as expected are well below the world average annual effective dose rate (Table 1). The annual effective dose rate in Cyprus is only exceeded at the 4 Lefkosia, 4 Limassol and 6 Larnaka sites described above.

Fig. 2 shows the cumulative frequency per cent of Rn concentration from these measurements, and those of Christofides and Christodoulides (1993) and Anastasiou et al. (2003). Table 3 presents the Rn concentrations (Bq/m^3) at specific percentiles from the three datasets of Fig. 2. The maximum differences between the three datasets are within the estimated standard deviations and median absolute differences. The present Rn results (GM ± SD: 14.3 ± 10.0 Bq/m^3) are in agreement with those from Anastasiou et al. (2003; GM ± SD: 16.3 ± 14.7 Bq/m^3), utilising the same detectors in different seasonal periods with different sampling times, Also, the current results, 14.3 ± 10.0 Bq/m^3 (GM ± SD) are almost in agreement with those from Christofides and Christodoulides (1993; GM ± SD: 12.8 ± 16.0 Bq/m^3), conducted with passive (CR-39) detectors and a measuring time of 3–4 months.

4. Conclusions

A comprehensive grid-based survey of indoor Rn concentration measurements in all accessible urban areas of the Republic of Cyprus, where 67.3% of the population resides, was conducted. A total of 407 measurements in four districts, using 189 grid cells, each of 1 km^2 in area, gave an overall mean of 16.4 and a geometrical mean of 14.3 (±10.0) Bq/m^3. These values are almost two-and-half times lower than the corresponding world average of 39 Bq/m^3. An important feature in all measurements is the fact that the indoor Rn concentrations in Cyprus are below the values estimated in many other European countries (Table 4). Further, an extensive database on Rn concentrations and the maps depicting their spatial distribution in the urban areas of the Lemesos, Larnaka and Pafos districts are presented for the first time.

The rather low concentration of uranium in the underlying rock or soil in the urbanised areas of Cyprus results in reduced airborne Rn concentration levels. Even in the cases where there is a possibility for slightly elevated Rn concentrations in some home environments, the Mediterranean climatic conditions, and the daily practice to air the rooms throughout the whole year minimise this likelihood. It is finally concluded that the results of the present systematic investigation on indoor Rn concentrations show that there is a low risk from Rn in the highly populated areas of the accessible part of the Republic of Cyprus.

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Appendix A

Table A1
The Lefkosia district indoor Rn measurements in the 54 grid cells and their basic statistical parameters, the mean Rn concentration for each grid cell and corresponding grid cell mean annual effective dose rate. The standard deviation (SD) of the grid cell mean Rn concentration is calculated from the corresponding standard deviation of the two measurements in each grid cell according to the error propagation law.

Grid cell number	Coordinates		Radon concentration (Bq/m^3)						Annual effective dose rate (mSv/y)	
	Longitude (deg)	Latitude (deg)	Min.	Max.	Mean	SD	Grid cell mean	Grid cell average SD	Grid cell mean	Grid cell average SD
1	33.385907	35.187189	5.4	14.3	10.5	3.1	20.0	3.6	0.505	0.092
	33.386299	35.186486	23.7	40.2	29.4	6.6				
2	33.388948	35.184223	3.4	22.5	13.3	21.1	13.0	14.2	0.328	0.359
	33.388069	35.182921	4.2	24.9	12.7	19.1				
3	33.320247	35.170889	4.2	13.1	7.2	3.5	11.8	3.6	0.298	0.090
	33.322670	35.171861	11.9	27.5	16.3	6.2				
4	33.331330	35.175093	105.0	196.9	151.4	28.4	86.4	14.6	2.180	0.368
	33.359883	35.168383	15.2	29.4	21.4	6.6				
5	33.412419	35.152369	4.2	12.4	8.3	2.8	12.3	4.1	0.310	0.102
	33.348770	35.172660	5.9	29.0	16.3	7.6				
6	33.361815	35.169398	8.5	16.8	10.3	4.8	11.5	4.1	0.290	0.103
	33.348577	35.172666	4.2	21.5	12.7	6.6				
7	33.373496	35.177182	5.3	22.3	12.5	5.9	23.1	9.0	0.583	0.227
	33.370695	35.175726	12.8	55.7	33.7	17.0				
8	33.379598	35.170690	9.6	26.2	17.1	7.3	14.2	4.6	0.358	0.115
	33.378496	35.184880	7.8	20.1	11.2	5.5				
9	33.395708	35.172913	8.0	26.3	18.6	21.1	16.6	13.4	0.419	0.339
	33.395863	35.172230	4.9	21.1	14.6	16.6				
10	33.304852	35.155018	4.7	14.1	7.8	2.8	11.6	3.7	0.293	0.094
	33.322081	35.176177	11.2	32.1	15.3	6.9				
11	33.313066	35.161216	6.9	28.9	16.1	8.7	20.9	10.8	0.527	0.272
	33.312875	35.155491	5.7	55.5	25.6	19.7				
12	33.378496	35.184880	4.5	13.0	8.6	2.8	18.9	3.7	0.477	0.094
	33.332277	35.161626	22.3	40.7	29.1	6.9				
13	33.345058	35.162576	21.3	44.9	28.5	8.7	27.8	5.4	0.702	0.137
	33.348765	35.164634	20.2	38.1	27.1	6.6				
14	33.357358	35.163800	12.1	47.1	30.3	38.8	30.0	25.1	0.757	0.634
	33.352320	35.160993	17.3	43.7	29.6	31.9				
15	33.373794	35.158475	1.8	8.9	5.5	2.4	7.2	2.0	0.182	0.050
	33.373271	35.161893	5.2	14.1	8.8	3.1				
16	33.387142	35.156392	9.5	23.4	14.9	5.2	17.5	7.4	0.442	0.187
	33.377398	35.160087	6.5	58.6	20.0	13.9				
17	33.391910	35.156432	1.8	16.9	11.1	4.2	9.4	3.1	0.237	0.077
	33.390226	35.157938	1.7	14.4	7.6	4.5				
18	33.398779	35.161116	10.7	31.0	16.7	20.1	14.3	12.6	0.361	0.318
	33.389771	35.160174	6.2	21.3	11.9	15.2				
19	33.303998	35.151190	6.4	25.4	13.8	6.9	14.6	4.5	0.368	0.115
	33.319976	35.161059	8.2	22.0	15.4	5.9				
20	33.315993	35.141082	14.0	42.8	26.9	8.3	25.6	5.5	0.646	0.139
	33.318068	35.142287	16.3	35.8	24.3	7.3				
21	33.323492	35.143231	5.8	21.4	12.8	5.5	12.2	3.9	0.308	0.099
	33.313332	35.143930	7.9	18.7	11.6	5.5				
22	33.343248	35.145132	4.5	56.4	30.9	19.4	49.3	14.7	1.244	0.372
	33.340497	35.137680	35.8	93.9	67.7	22.2				
23	33.360428	35.152073	4.2	9.0	5.1	2.4	7.2	2.0	0.182	0.050
	33.357999	35.144990	6.3	16.3	9.2	3.1				
24	33.370898	35.140392	57.3	136.2	89.0	43.6	59.5	23.1	1.502	0.582
	33.364197	35.146394	9.3	56.9	29.9	14.9				
25	33.378594	35.146247	6.4	27.1	14.0	6.6	12.7	4.2	0.320	0.106
	33.379098	35.152092	4.8	19.5	11.4	5.2				
26	33.392545	35.148531	3.1	16.4	9.2	3.5	10.9	3.1	0.275	0.079
	33.399143	35.144886	4.7	16.7	12.5	5.2				
27	33.412207	35.152686	5.1	25.3	20.8	4.8	21.4	4.2	0.540	0.107
	33.410365	35.150042	6.2	28.5	22.0	6.9				
28	33.340486	35.156216	2.3	17.1	11.2	5.5	17.9	4.6	0.452	0.115
	33.340597	35.157486	6.4	28.9	24.6	7.3				
29	33.412217	35.152827	5.4	24.7	17.4	8.0	18.6	6.5	0.469	0.165
	33.310600	35.121094	6.6	26.2	19.8	10.4				
30	33.318816	35.136481	4.1	15.5	8.3	3.5	6.4	1.9	0.162	0.047
	33.319244	35.127837	4.1	7.3	4.5	1.4				
31	33.331401	35.127336	18.2	38.8	27.8	7.3	22.8	6.8	0.575	0.171
	33.331460	35.127744	10.1	35.1	17.8	11.4				
32	33.341799	35.134793	8.6	21.5	14.0	4.8	16.0	5.0	0.404	0.125
	33.344453	35.127288	9.1	28.3	17.9	8.7				
33	33.400813	35.154738	1.8	10.8	5.4	2.4	8.0	2.4	0.202	0.061
	33.359294	35.130227	4.3	19.2	10.5	4.2				
34	33.376303	35.127599	1.1	11.7	7.6	3.8	10.2	2.5	0.257	0.062

Table A1 (*continued*)

Grid cell number	Coordinates		Radon concentration (Bq/m^3)						Annual effective dose rate (mSv/y)	
	Longitude (deg)	Latitude (deg)	Min.	Max.	Mean	SD	Grid cell mean	Grid cell average SD	Grid cell mean	Grid cell average SD
	33.372089	35.130081	2.1	16.3	12.7	3.1				
35	33.336877	35.128718	4.1	12.6	9.5	2.4	15.6	2.3	0.394	0.057
	33.337199	35.129593	6.9	29.1	21.7	3.8				
36	33.305905	35.110441	1.3	13.4	7.4	2.1	7.3	2.0	0.184	0.051
	33.304708	35.109003	2.7	10.2	7.1	3.5				
37	33.306871	35.112823	6.2	31.1	24.3	7.3	25.1	4.3	0.633	0.108
	33.311775	35.115750	5.7	34.6	25.8	4.5				
38	33.320824	35.113075	3.8	31.9	26.5	9.0	25.7	4.7	0.649	0.119
	33.331013	35.113451	6.2	29.8	24.9	2.8				
39	33.339297	35.114227	5.7	33.4	27.8	8.3	25.5	5.2	0.644	0.131
	33.339248	35.114064	4.3	28.1	23.1	6.2				
40	33.364545	35.105666	5.6	28.8	24.6	7.3	23.9	4.8	0.603	0.121
	33.358126	35.105187	4.8	27.9	23.2	6.2				
41	33.375130	35.106686	16.9	38.9	28.0	25.6	26.2	17.6	0.661	0.445
	33.376125	35.106764	13.2	34.4	24.3	24.2				
42	33.358082	35.105118	8.4	20.1	11.2	5.5	17.9	4.6	0.452	0.115
	33.382775	35.109635	18.2	40.9	24.6	7.3				
43	33.399572	35.107273	3.0	33.0	14.3	33.6	20.7	19.7	0.522	0.496
	33.399694	35.108418	16.3	35.6	27.1	20.4				
44	33.408556	35.103445	5.3	14.8	10.9	2.4	11.2	2.3	0.283	0.057
	33.408344	35.102156	6.9	18.6	11.4	3.8				
45	33.416851	35.104485	12.3	93.9	46.1	27.4	33.9	13.8	0.856	0.349
	33.420331	35.106383	11.4	29.8	21.6	4.2				
46	33.357521	35.122550	6.5	27.7	17.1	25.6	21.0	18.4	0.530	0.464
	33.359916	35.120507	12.0	37.7	24.8	26.3				
47	33.368348	35.102444	15.7	35.1	21.3	14.5	17.2	19.3	0.434	0.486
	33.370431	35.098749	3.1	28.6	13.0	35.7				
48	33.385507	35.096853	15.5	35.1	26.3	19.7	21.1	12.0	0.532	0.302
	33.382070	35.096771	9.9	23.5	15.8	13.5				
49	33.389802	35.096509	17.3	31.6	22.1	14.9	21.4	8.1	0.540	0.205
	33.390597	35.096793	16.4	29.7	20.6	6.6				
50	33.406271	35.101365	19.0	34.8	27.2	6.6	25.7	10.6	0.649	0.267
	33.400504	35.100140	13.4	33.1	24.2	20.1				
51	33.424913	35.106968	6.4	55.8	24.5	15.6	24.2	11.4	0.611	0.288
	33.424141	35.107564	13.1	54.8	23.8	16.6				
52	33.430302	35.108405	9.9	50.2	23.2	23.2	23.9	12.8	0.603	0.323
	33.439524	35.107581	18.2	46.7	24.5	10.7				
53	33.427472	35.106506	9.3	24.9	17.8	6.9	20.7	9.0	0.522	0.227
	33.426662	35.099872	10.4	38.9	23.6	16.6				
54	33.429884	35.100167	14.8	44.2	24.6	9.7	24.3	6.4	0.613	0.161
	33.430736	35.109247	18.7	33.2	23.9	8.3				

Table A2
The Lemesos district indoor Rn measurements in the 33 grid cells and their basic statistical parameters, the mean Rn concentration for each grid cell and the corresponding grid cell mean annual effective dose rate.

Grid cell number	Coordinates		Radon concentration (Bq/m^3)						Annual effective dose rate (mSv/y)	
	Longitude (deg)	Latitude (deg)	Min.	Max.	Mean	SD	Grid cell mean	Grid cell average SD	Grid cell mean	Grid cell average SD
1	33.041697	34.714990	4.6	20.3	12.8	4.6	11.2	3.0	0.281	0.075
	33.040298	34.714093	5.2	15.9	9.5	3.8				
2	33.051699	34.710294	3.0	14.1	8.1	4.2	8.6	2.6	0.216	0.066
	33.053498	34.714195	4.2	13.9	9.0	3.1				
3	33.063952	34.713675	9.9	57.4	21.2	13.1	16.5	7.4	0.415	0.186
	33.066304	34.725027	4.9	25.3	11.7	6.8				
4	33.006196	34.702493	2.7	11.8	6.3	2.7	7.2	2.2	0.180	0.056
	33.006629	34.705144	2.6	14.8	8.0	3.5				
5	33.019053	34.703076	3.3	15.0	7.9	3.1	9.1	2.9	0.230	0.074
	33.016404	34.706777	2.6	18.9	10.3	5.0				
6	33.029198	34.706894	2.6	14.6	7.2	4.1	7.8	2.4	0.196	0.059
	33.029625	34.705849	3.9	13.2	8.3	2.3				
7	33.036798	34.703894	3.3	15.8	9.4	4.4	8.6	2.8	0.216	0.072
	33.033909	34.701665	2.7	14.3	7.7	3.6				
8	33.047498	34.707794	3.9	20.2	10.8	6.4	9.3	3.4	0.235	0.087
	33.045398	34.704890	4.1	13.0	7.8	2.5				
9	33.055798	34.700292	1.9	23.1	9.5	5.9	15.2	9.3	0.382	0.234
	33.052199	34.709746	6.2	55.4	20.8	17.6				
10	33.067218	34.702004	2.8	14.0	6.7	3.3	7.6	2.6	0.192	0.065
	33.067595	34.704680	3.6	15.8	8.5	4.0				
11	33.079316	34.704131	3.2	24.3	12.2	7.0	10.1	4.9	0.254	0.124

(*continued on next page*)

Table A2 (*continued*)

Grid cell number	Coordinates		Radon concentration (Bq/m^3)						Annual effective dose rate (mSv/y)	
	Longitude (deg)	Latitude (deg)	Min.	Max.	Mean	SD	Grid cell mean	Grid cell average SD	Grid cell mean	Grid cell average SD
	33.075797	34.705774	2.0	28.4	7.9	6.9				
12	33.083932	34.706212	2.8	22.3	9.1	5.5	8.9	3.5	0.223	0.089
	33.082692	34.706602	4.0	16.7	8.6	4.4				
13	32.997645	34.696724	4.3	47.0	23.3	14.5	14.9	7.7	0.376	0.194
	32.993698	34.693593	1.4	15.0	6.5	5.0				
14	33.008309	34.690679	3.8	20.4	11.7	5.7	9.3	3.4	0.235	0.086
	33.001400	34.688892	2.7	15.4	6.9	3.8				
15	33.010966	34.696267	4.0	24.2	11.1	7.3	8.9	3.9	0.223	0.097
	33.020047	34.690302	2.0	11.1	6.6	2.5				
16	33.023464	34.689314	2.6	14.1	6.8	3.9	6.3	2.5	0.158	0.064
	33.027020	34.697133	2.5	13.4	5.7	3.2				
17	33.030758	34.688887	0.7	7.2	4.5	1.9	7.9	2.6	0.199	0.065
	33.031152	34.699909	5.5	19.3	11.3	4.8				
18	33.044164	34.695980	2.5	15.4	8.8	3.1	11.2	4.0	0.283	0.100
	33.044594	34.691798	6.1	29.0	13.6	7.3				
19	33.050798	34.693294	5.4	46.4	14.4	11.4	10.4	5.9	0.261	0.148
	33.057610	34.688919	1.3	11.2	6.3	2.8				
20	33.064245	34.693316	9.3	27.1	20.3	5.5	13.8	3.0	0.348	0.075
	33.062155	34.698628	3.2	11.4	7.3	2.2				
21	33.074998	34.691082	12.9	30.0	16.0	4.6	13.2	3.7	0.332	0.092
	33.074446	34.694832	2.6	21.3	10.3	5.7				
22	33.089737	34.695282	4.5	23.6	12.1	5.5	10.2	3.4	0.256	0.087
	33.080448	34.692726	4.1	20.0	8.2	4.1				
23	32.996682	34.684193	21.9	42.1	31.3	6.0	19.8	3.4	0.498	0.086
	32.996737	34.684794	4.3	14.7	8.2	3.3				
24	33.004973	34.683594	5.1	15.4	11.1	3.6	9.7	3.0	0.245	0.076
	33.006018	34.681745	2.0	18.4	8.3	4.8				
25	33.017703	34.679099	13.7	56.1	25.6	12.5	18.2	6.6	0.458	0.168
	33.012811	34.687189	4.5	17.4	10.7	4.5				
26	33.024385	34.685263	23.6	42.3	31.0	6.4	19.0	3.5	0.479	0.089
	33.028253	34.684206	3.3	14.0	7.0	3.0				
27	33.039451	34.677982	34.0	56.0	44.4	6.0	51.6	13.3	1.301	0.337
	33.034399	34.682793	17.7	90.0	58.7	26.0				
28	33.047572	34.685433	6.4	22.7	13.8	5.5	12.3	3.4	0.309	0.086
	33.047298	34.682310	5.7	18.7	10.7	4.0				
29	32.998297	34.673890	11.7	87.3	41.0	28.6	25.8	14.4	0.650	0.364
	32.997870	34.666380	5.8	18.9	10.5	4.0				
30	33.006341	34.672535	2.5	43.1	16.4	15.0	11.4	7.6	0.288	0.193
	33.006722	34.672582	1.2	10.8	6.4	2.8				
31	33.014327	34.666983	7.5	21.9	13.0	5.0	38.2	17.5	0.964	0.441
	33.013749	34.674364	21.7	105.9	63.4	34.6				
32	33.026078	34.667882	7.7	33.8	17.0	7.3	14.9	4.2	0.376	0.107
	33.027839	34.674227	6.5	19.5	12.8	4.3				
33	33.036996	34.674991	3.0	12.6	7.6	3.2	7.3	2.1	0.184	0.052
	33.036222	34.674701	3.3	10.6	7.0	2.6				

Table A3
The Larnaka district indoor Rn measurements in each of the 57 grid cells and their basic statistical parameters, the mean Rn concentration for each grid cell and the corresponding grid cell mean annual effective dose rate. Two (up to six) measurements were conducted in each grid cell during two different periods, 2004 and 2009. In italics are the 2004 Rn measurements.

Grid cell number	Coordinates		Radon concentration (Bq/m^3)				Annual effective dose rate (mSv/y)	
	Longitude (deg)	Latitude (deg)	Mean	SD	Grid cell mean	Grid cell average SD	Grid cell mean	Grid cell average SD
1	*33.650802*	*34.988501*	*42.7*	*38.7*	32.5	30.1	0.820	0.758
	33.651209	*34.987511*	*23.7*	*21.9*				
	33.650616	34.987519	39.5	36.7				
	33.651184	34.988249	24.1	22.9				
2	33.659512	34.986400	15.0	4.8	11.7	4.5	0.295	0.114
	33.659746	34.986413	8.4	4.2				
3	*33.651697*	*34.979392*	19.0	12.0	13.6	9.1	0.343	0.231
	33.650698	34.979595	8.2	6.3				
4	33.662078	34.977577	61.0	10.6	47.8	11.0	1.206	0.278
	33.660294	34.978191	34.6	11.4				
5	33.648777	34.970958	23.6	11.1	17.1	10.0	0.432	0.252
	33.653986	34.971020	10.6	8.9				
6	33.662876	34.968993	11.1	4.3	8.9	4.1	0.225	0.103
	33.664110	34.968965	6.7	3.9				
7	*33.671561*	*34.970772*	*6.1*	*2.6*	7.6	3.9	0.192	0.098
	33.671307	34.974143	9.1	5.2				
8	33.678760	34.972686	6.6	2.4	11.4	5.8	0.288	0.148
	33.680158	34.975831	16.2	9.3				

Table A3 (*continued*)

Grid cell number	Coordinates		Radon concentration (Bq/m^3)				Annual effective dose rate (mSv/y)	
	Longitude (deg)	Latitude (deg)	Mean	SD	Grid cell mean	Grid cell average SD	Grid cell mean	Grid cell average SD
9	*33.606106*	*34.960384*	*10.5*	*7.4*	11.7	8.6	0.295	0.218
	33.606961	34.959330	12.9	9.9				
10	33.618577	34.959305	9.2	5.6	8.3	5.5	0.209	0.139
	33.619820	34.959039	7.4	5.4				
11	*33.628541*	*34.961200*	*16.0*	*11.1*	13.6	9.2	0.343	0.233
	33.628071	*34.960354*	*11.2*	*9.4*				
	33.628593	34.960754	12.4	8.1				
	33.628593	34.960754	14.8	8.3				
12	33.640333	34.960844	19.9	3.4	14.5	3.9	0.366	0.098
	33.641648	34.961017	9.1	4.4				
13	*33.650278*	*34.962631*	*11.2*	*8.5*	20.3	16.6	0.512	0.420
	33.650243	*34.962353*	*27.1*	*22.6*				
	33.650208	*34.962377*	*19.4*	*15.3*				
	33.650228	*34.962420*	*30.6*	*25.1*				
	33.650479	34.962563	20.3	17.1				
	33.650263	34.962392	13.2	11.2				
14	*33.659277*	*34.963471*	*7.4*	*5.9*	10.4	7.6	0.262	0.192
	33.659308	*34.963488*	*15.6*	*11.7*				
	33.659153	34.964193	10.4	6.9				
	33.657928	34.962953	8.2	6.0				
15	33.568152	34.954164	42.3	12.9	35.3	9.1	0.891	0.231
	33.569165	34.950620	28.3	5.4				
16	33.578466	34.950042	24.9	8.4	20.4	8.0	0.515	0.203
	33.579627	34.950679	15.9	7.7				
17	*33.583482*	*34.951627*	*29.8*	*8.8*	23.3	8.1	0.587	0.204
	33.583482	34.951627	16.7	7.4				
18	33.596246	34.952275	15.5	6.5	15.1	8.8	0.380	0.223
	33.596246	34.952275	14.6	11.2				
19	*33.607567*	*34.953009*	*6.9*	*3.4*	5.7	2.9	0.144	0.074
	33.605952	34.952545	4.5	2.5				
20	33.617392	34.952222	9.2	2.8	21.8	10.4	0.549	0.262
	33.617392	34.952221	34.3	18.0				
21	*33.627966*	*34.952185*	*16.8*	*7.3*	14.5	7.0	0.366	0.178
	33.628241	34.952203	12.2	6.8				
22	33.636743	34.950897	11.3	4.2	9.5	3.6	0.240	0.092
	33.637759	34.952659	7.7	3.1				
23	*33.648897*	*34.954391*	*6.9*	*6.5*	9.5	5.2	0.240	0.132
	33.649540	34.955075	12.1	4.0				
24	*33.565126*	*34.942424*	*47.1*	*25.7*	42.1	23.8	1.062	0.601
	33.565179	34.942419	37.1	21.9				
25	*33.577522*	*34.943120*	*1.6*	*1.5*	1.7	1.5	0.043	0.038
	33.577446	34.943209	1.8	1.5				
26	33.584680	34.943171	46.3	22.4	33.6	16.4	0.848	0.413
	33.584680	34.943171	20.9	10.3				
27	33.597962	34.940493	12.0	8.5	11.4	7.6	0.288	0.192
	33.598760	34.941465	10.8	6.7				
28	*33.606417*	*34.942831*	*31.3*	*5.7*	25.9	5.2	0.654	0.131
	33.606335	34.942990	20.5	4.7				
29	*33.618445*	*34.942082*	*19.4*	*8.9*	23.0	7.7	0.580	0.196
	33.619804	34.942683	26.6	6.6				
30	*33.627940*	*34.943769*	*5.6*	*1.4*	9.5	2.5	0.240	0.064
	33.629699	34.944497	13.4	3.7				
31	33.639287	34.942337	5.2	2.3	4.7	2.2	0.119	0.057
	33.639261	34.942345	4.2	2.2				
32	*33.566645*	*34.935296*	*12.8*	*7.9*	11.4	7.6	0.288	0.193
	33.566645	34.935296	10.0	7.4				
33	*33.573933*	*34.932567*	*26.6*	*9.9*	23.0	9.7	0.580	0.246
	33.574099	34.932783	19.4	9.6				
34	33.587580	34.936075	14.5	4.8	11.6	4.5	0.293	0.114
	33.587642	34.935656	8.7	4.2				
35	*33.598898*	*34.931393*	*12.1*	*6.2*	10.6	6.2	0.268	0.156
	33.598893	34.932391	9.1	6.2				
36	33.607290	34.933545	6.7	3.6	5.5	3.3	0.139	0.085
	33.607439	34.933804	4.3	3.1				
37	*33.617527*	*34.932129*	*16.8*	*6.0*	14.4	6.0	0.362	0.151
	33.616938	34.931146	11.9	6.0				
38	*33.629169*	*34.933423*	*14.9*	*4.9*	13.6	5.3	0.342	0.135
	33.627895	34.932988	12.2	5.8				
39	33.637623	34.934369	6.5	6.0	5.4	5.0	0.136	0.127
	33.637921	34.935511	4.3	4.1				
40	33.569394	34.928689	5.9	3.4	8.1	3.8	0.204	0.096
	33.569509	34.928734	10.3	4.2				
41	*33.577443*	*34.927759*	*25.2*	*9.8*	23.0	9.6	0.580	0.242
	33.577598	34.927995	20.8	9.4				

(continued on next page)

Table A3 (*continued*)

Grid cell number	Coordinates		Radon concentration (Bq/m^3)				Annual effective dose rate (mSv/y)	
	Longitude (deg)	Latitude (deg)	Mean	SD	Grid cell mean	Grid cell average SD	Grid cell mean	Grid cell average SD
42	*33.581786*	*34.927866*	*20.5*	*15.2*	14.0	10.6	0.353	0.268
	33.581808	*34.927878*	*10.6*	*8.6*				
	33.581976	*34.927862*	*17.4*	*13.9*				
	33.581786	34.927866	13.8	9.5				
	33.581546	34.927778	7.7	5.9				
43	33.599998	34.927991	6.3	9.3	11.7	7.8	0.295	0.197
	33.600346	34.927797	14.0	3.2				
	33.600501	34.927299	14.8	10.9				
44	*33.609270*	*34.926719*	*29.5*	*9.5*	14.3	6.3	0.361	0.159
	33.608337	*34.927135*	*4.7*	*2.3*				
	33.608205	*34.927167*	*14.6*	*5.8*				
	33.608830	34.927879	18.7	12.1				
	33.609699	34.927393	4.1	1.9				
45	*33.619188*	*34.926412*	*16.6*	*4.8*	18.3	5.1	0.462	0.130
	33.620149	*34.925898*	*20.9*	*9.5*				
	33.619188	34.926412	29.8	4.8				
	33.619792	34.925089	6.0	1.5				
46	*33.628485*	*34.923390*	*88.2*	*42.6*	32.3	15.4	0.816	0.389
	33.628046	*34.923869*	*8.7*	*5.4*				
	33.628485	34.922394	14.1	3.2				
	33.627995	34.922394	18.3	10.5				
47	*33.637798*	*34.923694*	*9.4*	*5.2*	7.8	4.9	0.197	0.125
	33.637973	34.924642	6.2	4.7				
48	33.583172	34.916442	5.6	3.3	9.0	3.4	0.227	0.086
	33.573705	34.915831	12.4	3.5				
49	*33.583847*	*34.916746*	*6.1*	*4.1*	6.6	5.0	0.167	0.126
	33.583892	34.916836	7.1	5.9				
50	*33.589315*	*34.916077*	*13.2*	*9.2*	19.3	6.9	0.487	0.174
	33.588997	34.914683	25.4	6.1				
	33.589837	34.915502	19.3	5.4				
51	33.600203	34.917001	4.0	3.9	4.4	4.1	0.111	0.103
	33.600863	34.917937	4.8	4.3				
52	*33.608850*	*34.914015*	*9.7*	*9.4*	11.6	10.9	0.293	0.275
	33.609545	34.914850	13.5	12.4				
53	33.616398	34.914994	5.0	1.5	9.6	3.7	0.244	0.095
	33.616398	34.914994	14.3	6.0				
54	*33.626792*	*34.913987*	26.0	*5.5*	13.6	4.6	0.343	0.117
	33.626792	*34.913987*	*11.7*	*4.4*				
	33.626155	*34.913605*	*9.8*	*3.8*				
	33.625749	*34.912846*	7.0	*1.7*				
	33.626684	34.913476	13.9	5.3				
	33.626096	34.913694	13.2	7.0				
55	*33.636431*	*34.915650*	*12.5*	*8.8*	12.5	8.3	0.315	0.211
	33.636905	*34.916350*	*17.1*	*10.9*				
	33.636361	34.916123	10.7	7.1				
	33.636361	34.916123	9.7	6.7				
56	33.632199	34.908737	5.0	1.8	4.9	2.0	0.124	0.050
	33.631908	34.907439	4.8	2.2				
57	*33.636099*	*34.907195*	*13.8*	*7.4*	12.8	6.7	0.323	0.169
	33.635779	34.906264	11.4	5.6				
	33.636197	34.907391	13.2	7.1				

Table A4
The Pafos district indoor Rn measurements in the 45 grid cells and their basic statistical parameters, the mean Rn concentration for each grid cell and the corresponding grid cell mean annual effective dose rate. See Table 1 for the estimation of standard deviation (SD).

Grid cell number	Coordinates		Radon concentration (Bq/m^3)						Annual effective dose rate (mSv/y)	
	Longitude (deg)	Latitude (deg)	Min.	Max.	Mean	SD	Grid cell mean	Grid cell average SD	Grid cell mean	Grid cell average SD
1	32.404385	34.799769	1.8	21.1	12.6	3.1	13.7	2.2	0.344	0.056
	32.405935	34.802227	5.5	20.7	14.7	3.1				
2	32.416122	34.798990	3.3	15.5	10.7	3.8	13.0	2.6	0.328	0.065
	32.416230	34.798685	11.3	33.7	15.3	3.4				
3	32.427236	34.800052	5.4	19.4	16.8	4.8	16.3	3.2	0.410	0.081
	32.425905	34.799872	9.3	18.4	15.7	4.1				
4	32.436205	34.800013	1.9	10.6	9.4	2.4	11.3	1.8	0.285	0.046

Table A4 (*continued*)

Grid cell number	Coordinates		Radon concentration (Bq/m^3)						Annual effective dose rate (mSv/y)	
	Longitude (deg)	Latitude (deg)	Min.	Max.	Mean	SD	Grid cell mean	Grid cell average SD	Grid cell mean	Grid cell average SD
	32.436167	34.799882	6.7	13.8	13.1	2.7				
5	32.447066	34.799840	4.0	9.7	8.1	1.3	11.6	2.4	0.291	0.059
	32.448139	34.799426	7.2	15.6	15.0	4.5				
6	32.461202	34.798715	2.6	20.4	13.3	9.7	13.9	5.1	0.351	0.130
	32.456093	34.798804	6.5	12.9	14.5	3.4				
7	32.469315	34.797923	4.2	9.3	6.9	2.7	10.5	2.0	0.265	0.049
	32.469315	34.797923	11.1	32.0	14.1	2.7				
8	32.405388	34.792045	6.3	35.9	18.2	9.0	16.0	5.0	0.403	0.127
	32.401819	34.795159	4.8	10.4	13.7	4.5				
9	32.416230	34.790236	10.7	20.9	11.0	3.1	12.6	2.2	0.317	0.056
	32.416129	34.793246	7.1	13.9	14.1	3.1				
10	32.425776	34.791851	5.9	22.4	10.1	2.7	12.8	1.8	0.322	0.046
	32.427768	34.792002	9.4	24.2	15.4	2.4				
11	32.435095	34.791751	10.3	33.7	16.7	3.8	17.9	2.6	0.450	0.065
	32.440944	34.789323	10.2	30.0	19.0	3.4				
12	32.446830	34.792621	5.8	27.3	15.9	4.1	15.6	2.8	0.392	0.071
	32.449953	34.790928	7.3	26.3	15.2	3.8				
13	32.458575	34.790501	6.1	22.0	14.6	3.1	16.4	2.1	0.414	0.053
	32.456235	34.788987	6.3	29.4	18.2	2.7				
14	32.468795	34.791492	5.2	29.3	13.8	4.1	16.1	2.8	0.406	0.071
	32.465469	34.790285	12.0	29.8	18.4	3.8				
15	32.406273	34.782833	7.9	23.3	15.8	3.1	16.0	2.1	0.404	0.053
	32.404992	34.786258	8.5	28.1	16.2	2.7				
16	32.415522	34.782304	10.5	24.7	14.7	3.8	15.0	2.6	0.377	0.065
	32.419338	34.786327	9.6	21.3	15.2	3.4				
17	32.427698	34.782644	6.9	22.1	12.6	2.7	14.4	1.8	0.362	0.046
	32.428024	34.784962	12.8	24.4	16.1	2.4				
18	32.435099	34.781911	7.9	23.0	14.2	3.1	15.3	2.0	0.386	0.050
	32.438976	34.780386	9.2	23.7	16.4	2.4				
19	32.447146	34.780635	10.5	29.8	15.8	2.7	16.2	1.8	0.409	0.046
	32.446836	34.779290	7.5	29.5	16.6	2.4				
20	32.458959	34.781512	11.3	31.0	15.7	3.8	18.7	2.6	0.472	0.065
	32.456377	34.778780	8.1	32.0	21.7	3.4				
21	32.465171	34.781738	5.0	26.6	15.9	2.7	16.5	1.8	0.415	0.046
	32.470220	34.778835	15.7	25.3	17.0	2.4				
22	32.406873	34.771586	5.9	20.4	14.7	3.1	15.9	2.1	0.400	0.053
	32.407091	34.772150	10.7	28.9	17.0	2.7				
23	32.415892	34.773185	5.9	22.4	15.2	2.7	15.8	1.8	0.399	0.046
	32.414898	34.771992	13.0	28.9	16.4	2.4				
24	32.427698	34.772694	11.1	28.1	16.5	3.1	16.9	2.6	0.426	0.066
	32.428099	34.770492	7.7	22.0	17.3	4.1				
25	32.439760	34.773249	8.1	23.6	14.3	6.5	14.2	4.0	0.357	0.101
	32.439249	34.769821	2.8	19.3	14.0	4.5				
26	32.446045	34.772042	11.6	27.3	16.7	3.1	15.9	2.6	0.400	0.066
	32.445797	34.772058	5.1	20.4	15.0	4.1				
27	32.457268	34.771751	5.2	29.3	10.9	3.1	11.1	2.1	0.280	0.053
	32.458216	34.771921	3.7	13.0	11.3	2.7				
28	32.471566	34.772170	8.0	23.3	9.4	2.7	11.3	1.8	0.285	0.046
	32.469786	34.770760	6.6	23.3	13.2	2.4				
29	32.410427	34.763712	10.5	24.7	12.1	2.7	13.8	2.0	0.347	0.049
	32.411256	34.761862	6.9	22.1	15.4	2.7				
30	32.416242	34.763130	7.9	20.0	13.3	4.1	13.3	2.8	0.336	0.071
	32.415196	34.762190	3.2	13.9	13.3	3.8				
31	32.425967	34.763356	4.6	24.5	12.8	3.4	14.5	2.3	0.366	0.059
	32.425996	34.763087	5.0	22.8	16.2	3.1				
32	32.437487	34.764410	5.8	11.8	10.6	7.2	10.7	4.2	0.269	0.106
	32.435399	34.763292	3.8	14.2	10.7	4.1				
33	32.446098	34.762285	5.0	24.4	11.5	5.2	13.3	5.7	0.334	0.143
	32.449156	34.761919	3.1	19.8	15.0	10.0				
34	32.457799	34.762394	10.3	36.1	13.9	12.4	18.0	11.7	0.454	0.295
	32.456176	34.764350	5.0	41.3	22.1	19.7				
35	32.468328	34.763092	8.5	26.0	15.7	5.8	15.5	8.0	0.390	0.202
	32.467083	34.762305	1.8	15.4	15.2	14.9				
36	32.416591	34.759319	6.6	19.9	7.4	7.9	12.6	7.3	0.318	0.183
	32.418098	34.757995	2.5	60.2	17.8	12.1				
37	32.425293	34.759714	6.0	17.4	16.2	17.6	14.5	10.8	0.365	0.273
	32.424040	34.757189	4.0	14.2	12.7	12.4				
38	32.434117	34.759630	10.1	34.6	16.4	13.1	18.7	12.0	0.471	0.303
	32.434007	34.758075	5.8	33.1	20.9	20.0				
39	32.448027	34.758685	4.4	15.2	10.6	10.3	13.7	10.7	0.346	0.270
	32.450322	34.753397	9.8	38.1	16.8	18.7				
40	32.457479	34.757812	6.5	18.3	10.6	10.3	13.3	9.1	0.334	0.229
	32.457754	34.754622	5.5	26.0	15.9	14.9				

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Table A4 (*continued*)

Grid cell number	Coordinates		Radon concentration (Bq/m^3)						Annual effective dose rate (mSv/y)	
	Longitude (deg)	Latitude (deg)	Min.	Max.	Mean	SD	Grid cell mean	Grid cell average SD	Grid cell mean	Grid cell average SD
41	32.467500	34.753982	4.0	26.4	14.6	10.3	15.4	6.5	0.387	0.165
	32.467561	34.753714	2.1	21.8	16.1	7.9				
42	32.438373	34.748193	6.0	27.4	13.6	18.0	14.9	11.0	0.376	0.276
	32.432997	34.748139	4.1	22.8	16.2	12.4				
43	32.449256	34.748768	11.3	39.1	13.3	16.3	18.3	13.9	0.462	0.350
	32.448612	34.745028	6.0	44.3	23.3	22.1				
44	32.457171	34.746741	9.5	29.0	15.1	12.4	15.8	10.7	0.397	0.269
	32.462497	34.745285	2.8	18.4	16.4	17.3				
45	32.468631	34.743795	7.1	27.6	15.2	5.8	15.2	8.0	0.382	0.202
	32.469888	34.747765	4.7	17.6	15.1	14.9				

References

Abari, K., Mahmoudi, J., Ghanbari, M., 2013. Influence of indoor air conditions on radon concentration in a detached house. J. Environ. Radioact. 116, 166–173.

Anastasiou, T., Tsertos, H., Christofides, S., Christodoulides, G., 2003. Indoor radon concentration measurements in Cyprus using high-sensitivity portable detectors. J. Environ. Radioact. 68, 159–169.

Appleton, J.D., 1995. Radon, methane, carbon dioxide, oil seeps and potentially harmful elements from natural sources and mining area: relevance to planning and development in Great Britain. Technical Report WP/95/4. British Geological Survey, Keyworth, U.K.

Christofides, S., Christodoulides, G., 1993. Airborne radon concentrations in Cypriot houses. Health Phys. 64 (4), 392–396.

Cosma, C., Cucoş-Dinu, A., Papp, B., Begy, R., Sainz, C., 2013. Soil and building material as main sources of indoor radon in Băiţa-Ştei radon prone area (Romania). J. Environ. Radioact. 116, 174–179.

Darby, S., Hill, D., Auvinen, A., Barros-Dios, J.M., Baysson, H., Bochicchio, F., Deo, H., Falk, R., Forastiere, F., Hakama, M., Heid, I., Kreienbrock, L., Kreuzer, M., Lagarde, F., Mäkeläinen, I., Muirhead, C., Oberaigner, W., Pershagen, G., Ruano-Ravina, A., Ruosteenoja, E., Rosario, A.S., Tirmarche, M., TomáBek, L., Whitley, E., Wichmann, H.E., Doll, R., 2005. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case–control studies. Br. Med. J. 330, 223. http://dx.doi.org/10.1136/bmj.38308.477650.63 (http://www.bmj.com/content/bmj/330/7485/223.full.pdf).

Demoury, C., Ielsch, G., Hemon, D., Laurent, O., Laurier, D., Clavel, J., Guillevic, J., 2013. A statistical evaluation of the influence of housing characteristics and geogenic radon potential on indoor radon concentrations in France. J. Environ. Radioact. 126, 216–225.

EC, 1997. Radiation Protection 88: recommendations for the implementation of Title VII of the European Basic Safety Standards Directive (BSS) concerning significant increase in exposure due to natural radiation sources. European Commission, Directorate-General Environment, Nuclear Safety and Civil Protection (33 pp., http://ec.europa.eu/energy/sites/ener/files/documents/088_en.pdf).

Field, R.W., 2001. A review of residential radon case–control epidemiologic studies performed in the United States. Rev. Environ. Health 16 (3), 151–167.

Field, R.W., Krewski, D., Lubin, J.H., Zielinski, J.M., Alavanja, M., Catalan, V.S., Klotz, J.B., Létourneau, E.G., Lynch, C.F., Lyon, J.L., Sandler, D.P., Schoenberg, J.B., Steck, D.J., Stolwijk, J.A., Weinberg, C., Wilcox, H.B., 2006. An overview of the North American residential radon and lung cancer case–control studies. J. Toxicol. Environ. Health 69 (7), 599–631.

GARMIN Ltd, 2007. GPSMAP 60CSx with Sensors and Maps Owner's Manual.

GSD, 1995. Geological Map of Cyprus. Geological Survey Department, Cyprus.

IAEA, 2003. Radiation Protection against Radon in Workplaces other than Mines. http://www-pub.iaea.org/MTCD/publications/PDF/Pub1168_web.pdf.

ICRP, 2009. ICRP Statement on Radon. http://www.icrp.org.

Michael, F., Parpottas, Y., Tsertos, H., 2011. Gamma radiation measurements and dose rates in commonly used building materials in Cyprus. Radiat. Prot. Dosim. 142 (2–4), 282–291.

Miles, J.C.H., Appleton, J.D., Rees, D.M., Green, B.M.R., Adlam, K.A.M., Myers, A.H., 2007. Indicative Atlas of Radon in England and Wales. Health Protection Agency & British Geological Survey Report HPA-RPD-033 (http://www.ukradon.org/cms/assets/gfx/content/resource_2686cs3a0844cee4.pdf).

Nazaroff, W.W., 1992. Radon transport from soil to air. Rev. Geophys. 30 (2), 137–160.

Neville, J.D., Hultquist, D.J., 2008. Seasonal radon variations in Utah testing results: short-term test results within 10% of the EPA threshold (4.0 PCI/L) should be repeated in a different season. Proceedings of the American Association of Radon Scientists and technologists, Las Vegas NV, 2008.

Otton, J.K., 1992. Radon in soil gas and soil radioactivity in Prince George's County, Maryland. U.S. Geological Survey Open-File, Report 11–92 (http://pubs.usgs.gov/of/1992/0011/report.pdf).

Plch, J., 2001. Radon Monitor Radim3. Instruction Manual (S.K. Neumanna, 18200 Prague 8).

Quindós, L.S., Fernández, P.L., Sainz, C., Fuente, I., Nicolás, J., Quindós, L., Arteche, J., 2008. Indoor radon in a Spanish region with different gamma exposure levels. J. Environ. Radioact. 99 (10), 1544–1547.

Sarrou, I., Pashalidis, I., 2003. Radon levels in Cyprus. J. Environ. Radioact. 68, 269–277.

Statistical service, 2012. Cyprus population by district. http://www.cystat.gov.cy/mof/cystat/statistics.nsf/populationcondition_22main_gr/populationcondition_22main_gr?OpenForm&sub=2&sel=2.

Svoukis, E., Tsertos, H., 2007. Indoor and outdoor in situ high-resolution gamma radiation measurements in urban areas of Cyprus. Radiat. Prot. Dosim. 123 (3), 384–390.

Szabó, K.Z., Jordan, G., Horváth, Á., Szabó, C., 2014. Mapping the geogenic radon potential: methodology and spatial analysis for central Hungary. J. Environ. Radioact. 129, 107–120.

Theodoulou, G., Parpottas, Y., Tsertos, H., 2012. Systematic grid-wise radon concentration measurements and first radon map in Cyprus. Radiat. Meas. 47, 451–460.

Tzortzis, M., Tsertos, H., 2004. Determination of thorium, uranium and potassium elemental concentrations in surface soils in Cyprus. J. Environ. Radioact. 77 (3), 325–338.

Tzortzis, M., Tsertos, H., 2005. Natural radioelement concentration in the Troodos Ophiolite Complex of Cyprus. J. Geochem. Explor. 85, 47–54.

Tzortzis, M., Tsertos, H., Christofides, S., Christodoulides, G., 2003a. Gamma-ray measurements of naturally occurring radioactive samples from Cyprus characteristic geological rocks. Radiat. Meas. 37, 221–229.

Tzortzis, M., Tsertos, H., Christofides, S., Christodoulides, G., 2003b. Gamma radiation measurements and dose rates in commercially-used natural tiling rocks (granites). J. Environ. Radioact. 70, 223–235.

Tzortzis, M., Svoukis, E., Tsertos, H., 2004. A comprehensive study of natural gamma radioactivity levels and associated dose rates from surface soils in Cyprus. Radiat. Prot. Dosim. 109 (3), 217–224.

UNSCEAR, 2000a. Sources and effects of ionizing radiation. Vol. I: SourcesUnited Nations Scientific Committee on the Effects of Atomic Radiation (http://www.unscear.org/unscear/en/publications/2000_1.html).

UNSCEAR, 2000b. Sources and effects of ionizing radiation. Vol. II: EffectsUnited Nations Scientific Committee on the Effects of Atomic Radiation (http://www.unscear.org/unscear/en/publications/2000_2.html).

USEPA, 1993. Geologic radon potential of EPA region 3: Delaware, Maryland, Pennsylvania, Virginia, West Virginia. Open-File Report 93-292-C. U.S. Department of the Interior, U.S. Geological Survey, U.S. Environmental Protection Agency (206 pp., http://pubs.usgs.gov/of/1993/0292c/report.pdf).

WHO, 2000. Air Quality Guidelines for Europe. Publication 91. World Health Organization, Regional Office for Europe, Copenhagen (273 pp., http://www.euro.who.int/__data/assets/pdf_file/0005/74732/E71922.pdf?ua=1).

Zeeb, H., Shannoun, F. (Eds.), 2009. WHO handbook on indoor radon: a public health perspective. World Health Organization, Geneva (94 pp., http://whqlibdoc.who.int/publications/2009/9789241547673_eng.pdf?ua=1).