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Indoor radon concentrations and radon doses at three districts of Ankara, Turkey and raising public awareness on the issue

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Abstract Indoor radon concentrations at METU, CIGDEM and DOSTLAR in Ankara were measured using electrets. The statistical analysis of the data indicated a lognormal distribution of radon concentrations, with no significant difference between CIGDEM and DOSTLAR with geometric means of GM = 87.5 and 54.5 Bq m^{-3}, respectively. Radon concentrations did not change seasonally at CIGDEM which contain modern buildings, but at the slum district DOSTLAR, with poor insulation of houses a seasonal variation was observed. Annual effective radon doses were estimated (0.4–8.4 mSv). Public awareness about indoor radon was raised.

Keywords Radon · Electrets · Lognormal · Dose · Awareness · Ankara

Introduction

Radon gas (^{222}Rn) and its progeny constitute a major source of human exposure to natural radiation [1]. ^{222}Rn has 3.8 days half-life and occurs in the decay chain of ^{238}U. Radon progeny are positively charged and they attach themselves to ambient aerosols and deposit in the lungs to deliver radiation dose. More than 95 % of total exposure of an individual to radon progeny is by inhalation of radon in the air [1, 2]. Since indoor "radon is the second cause of lung cancer after smoking", monitoring of indoor radon radioactivity in different environments is increasing worldwide. Health effects of exposure to radon are covered extensively in the Biological Effects of Ionizing Radiation, BEIR VI report [3]. The United Nations Report on ionizing radiation by United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR [4] discusses the sources and effects of ionizing radiation. Radon measurements done in different countries, for several years reveal indoor radon concentrations up to 100,000 Bq m^{-3}.

Radon moves from the soil into the houses by diffusion and advection [5]. "The particularities of its physical origin in rock and soil, transport through the soil and entrance into the buildings, controlled by many factors related to environment, house construction and life habits lead to temporal variability which can vary by orders of magnitude within days" [6]. The concentration of radon in a building depends on the concentration of uranium in the soil and rocks, the presence of cracks and leaks in the home or building structure, and air exchange within the dwelling [7] as well as soil porosity and permeability, how the buildings are constructed, the distance from the ground level, climate, humidity and temperature, level of ventilation, seasonal variations, insulation, cracks and basement type are some of the parameters that determine the final indoor radon concentrations. So, "radon concentrations can differ from region-to-region and from building-to-building within the same region, as well as within the same building from season-to-season or day-to-day" [8]. International Commission on Radiological Protection (ICRP) 65 discusses the protection against ^{222}Rn at home and at work place [9].

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In the US millions of indoor radon measurements were performed and several mitigation studies are under way. In Turkey, Turkish Atomic Energy Agency (TAEK) had initiated indoor radon measurements in 1984 [10]. Radon measurements were completed using alpha tract detectors in 53 localities in Turkey and reported by Köksal [11]. World Health Organization's (WHO) Recommended Reference Level for indoor radon concentration is 100 Bq m^{-3} [2]. Maximum allowed indoor radon concentration is 400 Bq m^{-3} in Turkey. In the US the intervention level is 148 Bq m^{-3} [12].

Radon dose gives energy deposition from radon and its progeny per unit mass of the absorber, such as human body or lung and it is expressed in the unit of mSv [13]. There are different categories of radon dose calculations: the dose from epidemiological assessment and that from physical dosimetry. ICRP 65 takes into account the epidemiological assessment. For 1 year exposure to radon concentration of 100 Bq m^{-3}, "annual effective dose" values are: 1.72 mSv according to ICRP [9], 2.5 mSv according to UNSCEAR 2000 Report [4, 13] and 6 mSv from dosimetric approach [13, 14].

In this study radon concentration in dwellings of three settlements, a university campus and two different districts, DOSTLAR and CIGDEM in Ankara covering a total area of about 8.4 km^2 and a population of less than 1 % of the city was considered. The electret detectors were used for the first time in Turkey. In order to investigate the behavior of the detectors and follow their stability, Middle East Technical University (METU) Campus was selected as the first location since the authors were faculty at METU. The buildings in METU were multistory and constructed with reinforced concrete structures following government standards. One of the districts CIGDEM, was next to METU, with houses built within the last 20–30 years, with modern techniques and good wall insulations, both multi-story and two-floor dwellings. The second district, DOSTLAR was located at Mamak, mostly with single story slum houses, with poor insulation. Furthermore, CIGDEM and METU have similar geological formations but DOSTLAR has a different geological formations. Radon concentrations for a given district and a given season constituted a data set. The comparison of radon concentrations between the districts and seasonal variation within each district were done using statistical methods. One of the motivations of doing this study was to raise awareness of local people to health effects of radon gas in dwellings. Locally elected state representatives of districts, muhtars, a local non-governmental organization (NGO) called the Cigdemim Neighborhood Association at CIGDEM, Chamber of Civil Engineers of Turkey and people living in these regions were informed about this study.

Experimental

Detector selection

Several different kinds of radon detectors are available for monitoring radon concentrations [15]. In this study, electret ion chamber detectors were used. An electret is a piece of dielectric material which responds to α-radiation emitted by isotopes within the ionization chamber, leading to the development of "Elecrets Passive Environmental ^{222}Rn Monitor" (E-PERM) for the measurement of domestic radon concentrations. The surface potential of electrets can be measured with a voltage reader in a few minutes, so there is no need to change the location of detector in the houses for seasonal monitoring. The electrets may be used repeatedly since they are easily recharged by the manufacturer and reused [16–19]. For this study, a batch of Short-Term (ST) and Long-Term (LT) electrets, together with *S* (50 mL volume) and *L* (200 mL volume) sampling chambers, and a dedicated RadElec Electret Reader Type SPER-1 were purchased through RadElec [20].

Sampling sites and placements of the detectors

The map of Turkey with location of Ankara, the capital of Turkey, and the sampling sites, METU and two districts, CIGDEM and DOSTLAR are shown in Fig. 1a, b, respectively. The sampling sites are marked by yellow polygons on Fig. 1b. The sampling sites METU and CIGDEM are located at South West of Ankara, whereas the DOSTLAR site is at the northeast part of Ankara. Area coverage of the three districts is 2.94, 5.64 and 1.78 km^2, respectively. The locations of sampling sites METU, CIGDEM and DOSTLAR are given on the geological map of Ankara in Fig. 1c. DOSTLAR district is located on an old volcanic activity region, Mamak formation, dated to late miocene period and its structure is composed of agglomerate, tuff, andesit and basalt. The other two radon sampling sites, METU and CIGDEM, are located on Elmadag formation that is composed of metaconglomerate, metasandstone, sandy limestone, sandstone, limestone, volcanogenic sandstone, agglomerate and metavolcanics. From the fossils found in sedimentation it is estimated that this geological formation was dated to lower and upper-middle triassic period. Due to volcanic activities in this period some volcanogenic stones were found in sedimentary rocks.

The detectors at METU were located as evenly as possible throughout the university on the basement levels of buildings. The buildings at CIGDEM and DOSTLAR were selected with the help of muhtars and the detectors were placed in the houses with the cooperation of muhtars. Since

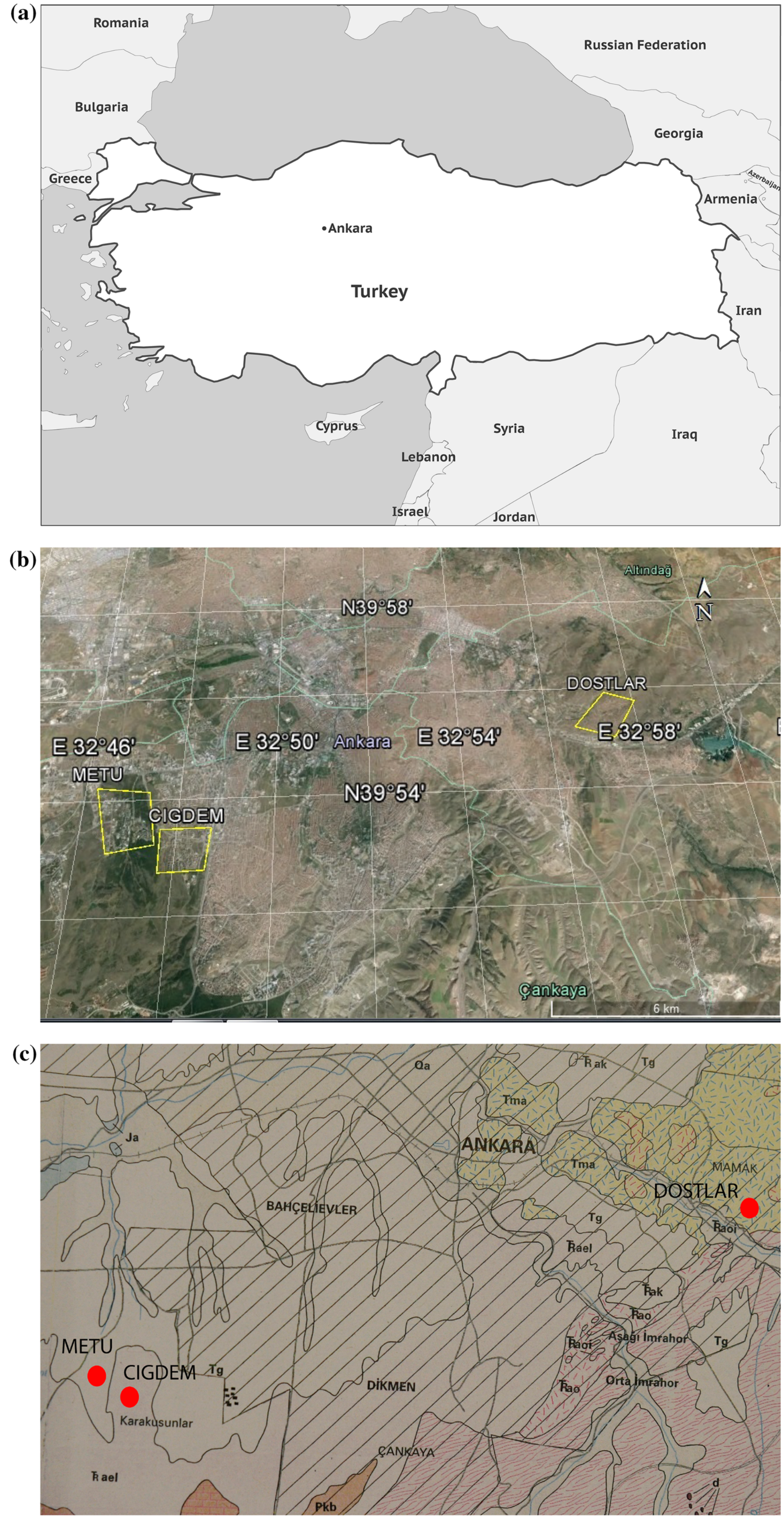

Fig. 1 **a** Map of Turkey with capital Ankara and its neighbour countries. **b** Location of sampling sites METU, CIGDEM and DOSTLAR on the map of Ankara. **c** Radon sampling sites METU, CIGDEM and DOSTLAR on the geological map of Ankara

the residents knew muhtars it did not require much effort to convince the residents to allow placement of the detectors into their households. Before placing detectors, the purpose of the experiment and the measurement protocol were explained and a questionnaire was filled with one of the residents of the household, often the mother. The initial potential of each electret was measured. The detectors were placed mostly on the lowest floor of the buildings, usually in the living room or the major bedroom of the residents, and away from the windows and out of the reach of the children. In order to achieve good detection levels over a medium-term measurement time, the *L* chambers with the ST electrets, LST, were located at CIGDEM and the *S* chambers with the LT electrets, SLT were placed at DOSTLAR. This combination yielded an appreciable change between initial and final potential readings to give radon concentration with low uncertainty within a few months period. With this medium-term measurement methodology, it was possible to do the measurements from a 1 month period up to a year. In order to check whether these combinations would give the similar results in the same conditions, one SLT and one LST type detectors were located side by side in the same house at CIGDEM. The radon concentrations of 392.2 ± 22.2 and 370.0 ± 18.5 Bq m^{-3} were measured and they were found to be not statistically different from each other at 95 % confidence level.

In this study 40-electret ion chamber detectors were employed. Firstly, twenty of them were distributed to the buildings of METU and kept for 9 days. After the completion of these measurements 40 detectors were distributed to the houses in two districts and a total of 161 indoor radon measurements were performed for all seasons (except CIGDEM's summer measurement) throughout a period of a year.

Indoor radon measurements using electrets

The initial potential readings of the electrets were around 700–750 V. The detectors can be efficiently used until the potential drops to nearly 250 V. After the detectors were kept in the houses for certain time period, the potential of the detectors were measured again. If the potentials on the detectors were higher than 250 V, they were placed back to the same locations for further measurements. If the potentials were close to 250 V, the lids were closed and they were brought back to the university.

The difference between the initial and final potential readings was multiplied by the calibration factor supplied by the manufacturer and divided by the duration of measurement to calculate the radon concentration in Bq m^{-3}. These results were further corrected for the average background gamma ray activity at the location to yield the net radon concentration. The gamma ray dose rate was measured using the LB 123 UMo counter with LB 6006 counter tube of EG&G Berthold and the average gamma ray dose rates at the specified locations were found as 0.14 ± 0.01 μSv h^{-1} at METU and CIGDEM and (0.14–0.28) ± 0.02 μSv h^{-1} at DOSTLAR, which was a volcanic site.

Due to the variations in the volume of the chambers, thickness of the electrets etc. 5 % uncertainty on radon concentration is expected [21, 22]. The calibration of the electret ion chambers were done at the sea level near New York at DOE/EML Laboratories. When the measurements are done above sea level, a correction is needed due to lower ionization of air by radon at higher altitudes [23]. As the altitude at these two districts was found as 975 ± 30 m using GP 12 global positioning system (GPS), a 14 % altitude correction for *L*-type chambers and no altitude correction for *S*-type chambers were applied. Electrets have been reported to be sensitive to relative humidity [24], but more extensive studies [25, 26] showed that there is little influence in the detection response to radon due to humidity. Hence, in this study the humidity was not monitored during the radon measurements.

At METU after 9 days of sampling, the potential drop of the electrets ranged between 24 and 88 V. Then the detectors were placed in the houses at CIGDEM and DOSTLAR in April 2007 for spring 2007 measurements. They were kept between 31 and 33 days in the houses at CIGDEM, and 51 days at DOSTLAR. At the end of these periods, potential differences of 20–151 V at CIGDEM and 12–65 V at DOSTLAR were measured. Due to a large potential drop of the detectors at CIGDEM their lids were closed and they were brought back to the laboratory in order to be able to use them for the fall and winter measurements. At DOSTLAR, at the end of each period, the potentials were measured and the detectors were left on the same houses. Sampling durations were 124 days for summer, 104 days for fall and 63 days for winter. At CIGDEM detectors were brought back to the site for fall measurements, which lasted 45 days, and two consecutive winter measurements were done, one for 41 days (winter-1), another for 21 days (winter-2). At the end of all these measurements a total of 161 indoor radon concentration measurements were performed.

Results and discussions

Radon concentrations and statistical analysis of the data

Indoor radon concentrations were monitored for a year, seasonally at CIGDEM and DOSTLAR. At CIGDEM the radon concentrations in two of the houses were found higher than the maximum allowed concentration for Turkey, 400 Bq m^{-3}. The radon concentration at METU was significantly lower than that of the houses at CIGDEM. The frequency distributions of all data sets (i.e., 4 sets in CIGDEM, 4 sets in DOSTLAR and 1 set in METU) have similar distribution patterns. The frequency distribution plots for two of the data sets, namely, CIGDEM (winter-1, 2008) and DOSTLAR (spring, 2007) were given in Fig. 2 a, b, respectively. Similar frequency distribution plots were observed for the other data sets.

CIGDEM spring 2007 data set has been analyzed by Minitab program to decide whether the distribution was normal or lognormal using Anderson–Darling test, and the results were given in Figs. 3, 4, respectively. In Fig. 3, normal distribution yielded a p value less than 0.005, but when it was plotted logarithmically in Fig. 4, a p value of 0.669 was found. Similar plots were drawn for all the data sets and it was observed that all the data sets were following lognormal distribution.

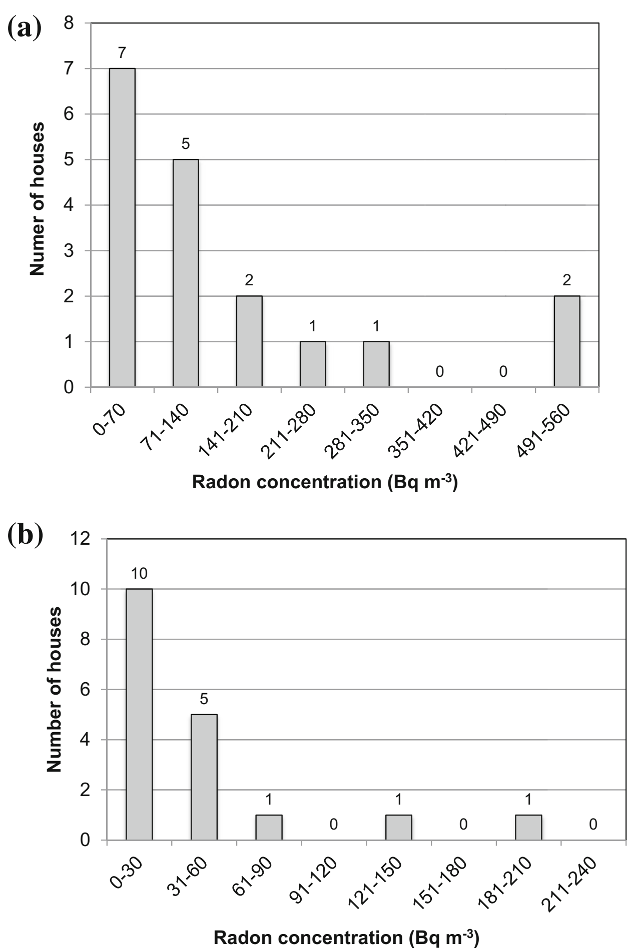

Fig. 2 **a** and **b** Frequency distribution plots of CIGDEM-winter1 2008 and DOSTLAR-spring 2007, respectively

In fall and winter, the indoor temperatures were kept higher than outside temperatures, and hence caused a negative pressure inside and this lower pressure generally results in the transport of radon from ground into the building [27], so radon concentration was expected to be higher on cold days. Moreover, ventilation in the houses were limited in fall and winter. The seasonal variation of indoor radon concentrations for each dwelling at DOSTLAR and CIGDEM are shown in Figs. 5, 6, respectively. At DOSTLAR radon concentrations in the fall seemed to be higher than other seasons. At CIGDEM no seasonal variation of radon concentration was observed.

In Table 1, the geometric mean (GM) and geometric standard deviation (GSD) of radon concentrations for three different sampling sites are given. In order to compare the results with the literature, the mean and standard deviations of radon concentrations are also given. The GM values for METU, CIGDEM and DOSTLAR are 24.1, 87.5, and 54.5 Bq m^{-3}, respectively.

The GM radon concentrations at three different sampling sites, in different seasons are given in Fig. 7. In fall, CIGDEM and DOSTLAR have nearly the same radon concentrations, however radon concentrations at CIGDEM seemed to be higher on spring and winter.

Statistical analysis of the data

The geometric standard score, t, for a sample population is defined as;

$$t = (\ln x - \ln \mu_G)/\ln \sigma_G \quad (1)$$

$$t = \log_{\sigma_G}(x/\mu_G) \quad (2)$$

Here, μ_G and σ_G represent the GM and GSD, respectively. Then, the confidence limits for a lognormal distribution is given by;

$$x = \mu_G \sigma_G^t \quad (3)$$

At a confidence level of 95 % and $t = 2.10$ for 18° of freedom, the confidence limit for lower and upper bound of METU data were 3, and 194, respectively for lognormal distribution. This showed a broad range of radon concentration extending 8 folds below and above the GM.

The natural log of radon concentrations were then analyzed using an SPSS (version 22) program. Using 2-way ANOVA, the logarithmic data sets for DOSTLAR and CIGDEM for spring, fall and winter were compared with each other. The test with $\alpha = 0.05$, yielded a significance value of 0.2203 indicating no significant difference on the overall data between the two districts DOSTLAR and CIGDEM. However, a significance value of 0.0030 for seasons and 0.0084 for interactions show

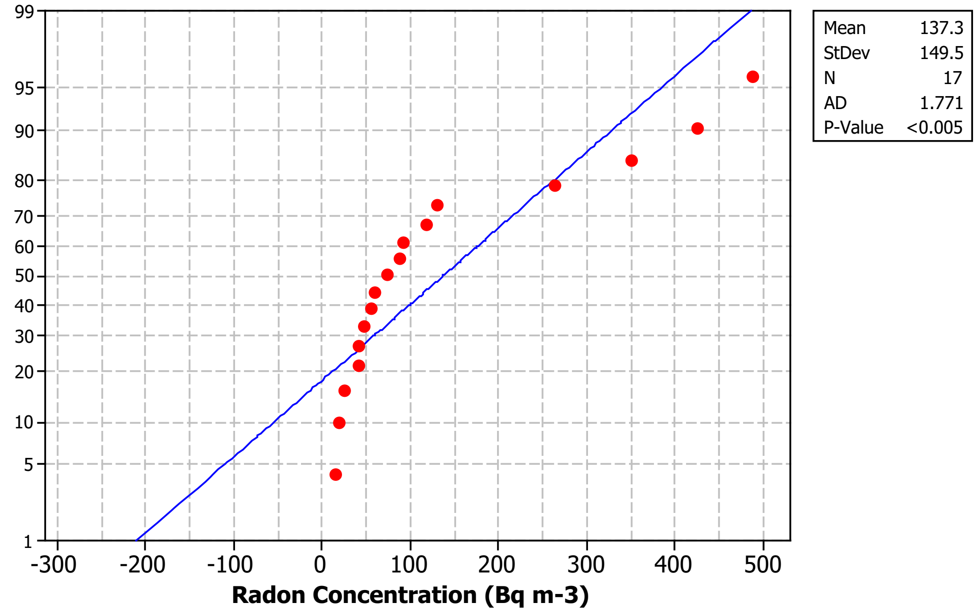

Fig. 3 Anderson–Darling test for normal distribution of CIGDEM spring 2007

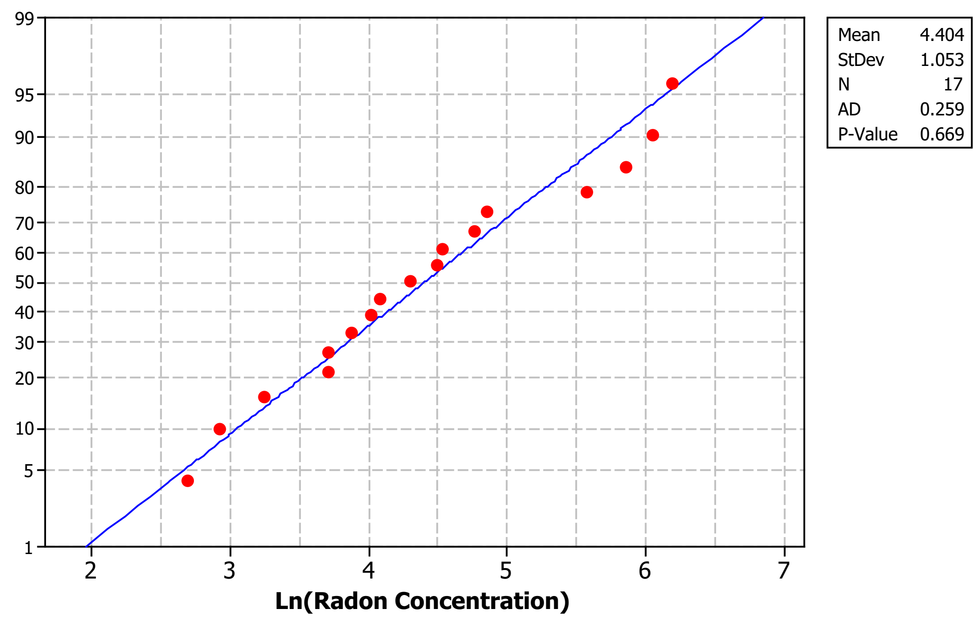

Fig. 4 Anderson–Darling test for lognormal distribution of CIGDEM spring 2007

that there was a significant difference between seasons and season-district interactions. Hence, multiple post hoc group comparisons were done using one-way ANOVA test to investigate the seasonal variations at DOSTLAR and CIGDEM.

The Levene test for logarithmic variances was found to be not homogeneous for DOSTLAR. The one-way ANOVA test yielded a significance value less than 0.05, suggesting that the radon concentrations varied with seasons. Hence, Tukey HSD post hoc test, which is independent of homogeneity of variances, was used for pair-wise comparisons of the results of different seasons. The radon concentrations at DOSTLAR were grouped in spring-summer and summer-fall-winter and no significant difference was found within a group, but there were significant differences between the groups. Hence, it was concluded that the spring radon concentration was different than those in fall, logarithmic variances were homogeneous and for CIGDEM there were no significant differences between seasons. Hence, no further post hoc tests were done. The radon concentrations at CIGDEM and DOSTLAR were compared pairwise in spring, fall and winter and a

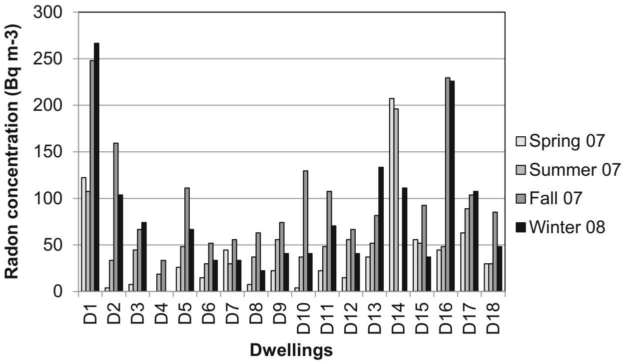

Fig. 5 The seasonal variation of indoor radon concentrations in dwellings at DOSTLAR

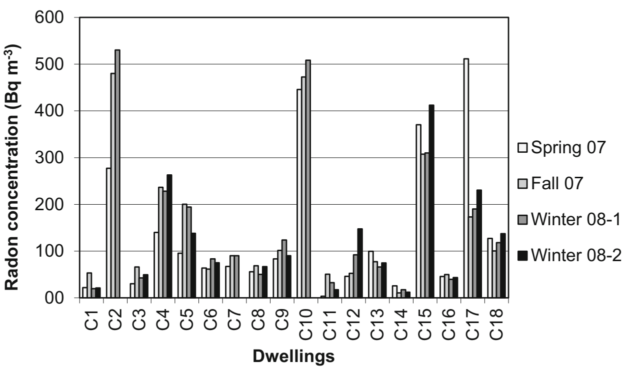

Fig. 6 The seasonal variation of indoor radon concentrations in dwellings at CIGDEM

Table 1 The GM and GSD and mean and standard deviation of indoor radon concentrations (Bq m^{-3}) at METU, CIGDEM and DOSTLAR, measured between spring 2007 and winter 2008

Location-season-(detectors)/days*	GM (GSD)	Mean ± SD
METU-spring-2007 (19)/9	24.1 (2.7)	37 ± 33
CIGDEM-spring 2007 (18)/32	77.5 (3.4)	141 ± 159
CIGDEM-fall-2007 (18)/45	99.5 (2.6)	148 ± 141
CIGDEM-winter1-2008 (18)/41	95.6 (2.7)	152 ± 155
CIGDEM-winter2-2008 (14)/21	77.5 (2.8)	118 ± 111
DOSTLAR spring 2007 (18)/51	27.1 (2.7)	44 ± 52
DOSTLAR-summer 2007 (18)/124	51.4 (1.7)	59 ± 41
DOSTLAR-fall 2007 (18)/104	99.5 (1.7)	115 ± 67
DOSTLAR-winter-2008 (18)/63	63.4 (2.7)	93 ± 74

* The numbers in parenthesis are the number of houses and the numbers following the parenthesis are the duration of the measurement periods in days

significant difference between two districts was found during spring, but there were no significant differences among fall and winter results.

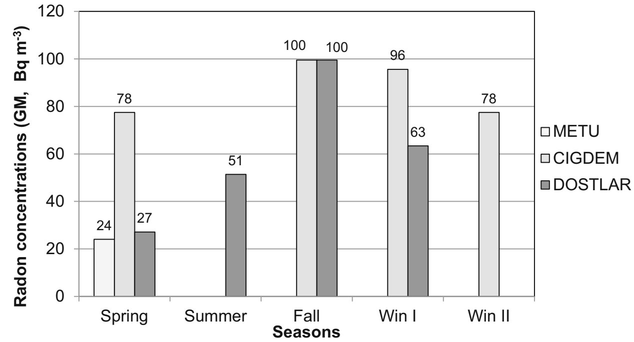

Fig. 7 GM radon concentrations at METU, DOSTLAR and CIGDEM on different seasons

As a summary of statistical analysis, it was concluded that there was no significant difference between CIGDEM and DOSTLAR during the 1-year period covering spring 2007–winter 2008, although the types of buildings and the geological formations were different at these sites. This conclusion deserves further research in the specified areas for understanding the correlations between radon concentrations, geological formations and building types as there are numerous other parameters affecting the indoor radon concentrations.

Annual radon doses

Radon doses (in mSv) calculated for mean and GM radon concentrations, using the estimates based on ICRP, UNSCEAR and physical dosimetry, at METU, CIGDEM and DOSTLAR, are given in Table 2. Indoor occupancy of 7000 h per year and an equilibrium factor of 0.4 were used in the dose calculations [4, 13, 14]. Due to larger mean values of radon concentrations, doses estimated from means were higher than those from GM's. Radon doses were found to be the highest at CIGDEM.

According to WHO "there is no known threshold concentration below which radon exposure presents no risk. Even low concentrations of radon can result in a small increase in the risk of lung cancer. The majority of radon-induced lung cancers are caused by low and moderate radon concentrations rather than by high radon concentrations, because in general less people are exposed to high indoor radon concentrations". The proportion of all lung cancers linked to radon is estimated to lie between 3 and 14 %. Radon is the second most important cause of lung cancer after smoking in many countries. It is the primary cause of lung cancer among people who have never smoked. Radon is much more likely to cause lung cancer in people who smoke, or who have smoked in the past, than in lifelong non-smokers [2]. In Turkey smoking is very

Table 2 Radon doses (in mSv) using mean and GM radon concentrations at METU, CIGDEM and DOSTLAR

Location	Distribution	ICRP "risk equivalent" radon dose	UNSCEAR recommended dose	Annual effective dose (dosimetric)
METU	Mean	0.6	0.9	2.2
	GM	0.4	0.6	1.4
CIGDEM	Mean	2.4	3.5	8.4
	GM	1.5	2.2	5.2
DOSTLAR	Mean	1.3	1.9	4.6
	GM	0.9	1.4	3.3

prevalent among adults. However, in this study smoking habits of the people living in the dwellings within the areas studied were not reported.

Comparison of indoor radon concentrations in literature

The indoor radon concentrations obtained in this study were compared with the other radon concentrations measured at different cities of Turkey in Table 3. It was observed that the results obtained in this study, using the electrets for the first time in Turkey were comparable with the results obtained using alpha tract detectors. In this study, most of the measurements were done at the lowest level of the buildings. Average radon concentration was found as 35 ± 12 Bq m^{-3} for 27 different locations in Turkey [11]. In the study done by Vaizoglu and Guler [28], only 38.1 % of the houses were measured at the lowest level of the buildings. In their study they found an average winter radon concentration of 93 ± 96 Bq m^{-3} for a region near DOSTLAR, which was in agreement with the average radon concentration of 77.1 ± 64.4 Bq m^{-3} obtained in this study. However, they had observed 26 ± 30 Bq m^{-3} for a district close to CIGDEM and

Table 3 Comparison of mean indoor radon concentrations with literature

Radon research*	Radon concentration (Bq m^{-3})**
METU-2007	37 (3.7–126)
CIGDEM-2007 to 2008	140 (3.7–529)
DOSTLAR-2007 to 2008	77 (3.7–270)
TAEK [10]	35
Turkey, Köksal [11]	35 (10–380)
Ankara, Vaizoğlu and Güler [28]	37 (1.9–407)
Isparta, Ulug [29]	163 (78–274)
İzmir, Erees and Yener [30]	(52–85)
Tekirdağ, Yarar and Kam [31]	89
Dikili, Yarar [32]	(30–281)
Manisa, Erees [33]	96 (48–148)
Kastamonu, Kam and Bozkurt [34]	89 (30–178)
Kars, Çelik [35]	115 (19–599)
Giresun, Çelik [36]	130 (52–359)
Adana-winter, Değerlier and Celebi [37]	48 (19–96)
Kilis, Can [38]	50
Antakya, Can [39]	40
Bursa, Güler [40]	42

* The radon concentrations at METU, DOSTLAR and CIGDEM were obtained in this study. TAEK and Koksal results were obtained for Turkey. For the other studies the location of the study and the authors were given

** The mean radon concentrations were given and the numbers given in parenthesis were the range of radon concentrations

METU, that was much lower than the average concentration observed in this study at CIGDEM, which was 140 ± 140 Bq m^{-3}, but comparable to the concentration at METU, which was 37 ± 33 Bq m^{-3}. In Turkey the building standards were improved extensively over the past several years, with better building materials, and better insulation of the windows, doors and walls. In the study by Vaizoglu and Guler [28] out of 191 houses studied, there were good window frame insulation only in seven of the houses, and 53 of the houses had double layer glasses on the windows. Yet, in this study at CIGDEM, all the houses had good insulated windows with double layer glasses. As expected, improvement in house insulation may result an increase in indoor radon concentration. In the houses where high radon concentrations were observed the floors were covered by wooden parquetry and there were cracks on the floor. So, radon was entering these houses easily and staying in the houses for longer periods because of the good wall and window insulation of these houses. At CIGDEM, the basement levels of all these multistory buildings were below the ground level and not ventilated properly and that might also have contributed to higher radon concentration. At METU with higher building standards, the radon could not enter the buildings as easily as it might have done at CIGDEM.

The worldwide average indoor radon concentration has been estimated at 39 Bq m^{-3} [2]. Radon concentrations measured at METU were comparable with the world average but at the two other districts concentrations were much higher than the world average. In some of the results reported in the Table 3 radon concentrations were higher than the world average radon concentration. A national reference level for radon represents the maximum accepted radon concentration in a residential dwelling and is an important component of a national programme. However, if this level cannot be attained under the prevailing country-specific conditions, the chosen reference level should not exceed 300 Bq m^{-3} which represents approximately 10 mSv dose per year according to recent calculations by the ICRP [2, 41].

Raising awareness

After the radon results were obtained, the residents at DOSTLAR and CIGDEM were informed about the radon concentrations in their homes. Firstly, a short report of research was submitted to the muhtar of the DOSTLAR district. Most recently, the slum houses of DOSTLAR were included in an urban renewal project by the metropolitan municipality of Ankara. Some of those slum houses have been abandoned for the construction of multistory buildings by TOKI, a state owned construction company building large scale multistory buildings. A report of this research will be given to the metropolitan municipality of Ankara and also to TOKI. A copy of the report has been sent to the muhtar of CIGDEM and Cigdemim Neighborhood Association, an NGO at the CIGDEM district and they have published the results of radon research of this study on their web page. A face-to-face meeting has been organized with the local people to raise their awareness on this public health issue. The Environmental Protection Agency (EPA) of the US developed standards for Radon Resistant New Construction (RRNC) and made suggestions for low cost radon gas mitigation for new buildings [42]. Chamber of Civil Engineers of Turkey will be informed about inclusion of radon prevention measures within the new building standards.

Conclusions

In this study, the electret ion chambers were used for the first time in Turkey and 161 indoor radon concentrations were measured at METU, and two districts of Ankara, CIGDEM and DOSTLAR. In multistory modern buildings of CIGDEM with good wall insulation, the radon entering the house seemed to be kept inside the house, yielding high radon concentrations, with no seasonal variations. At DOSTLAR (with poor insulated, slum houses), radon concentrations were lower in the spring, increased toward fall and winter. Electrets were found to be very practical to measure the radon, especially for seasonal monitoring of radon concentrations. It is important to consider mitigation studies in the houses with high radon concentrations. Some of the radon concentrations of modern houses at CIGDEM are above recommended reference level for indoor radon concentrations set by WHO, US and TAEK. Turkey's indoor radon reference level of 400 Bq m^{-3} seems to be higher than international reference level. Moreover, the indoor radon GM concentrations were found to be nearly half of the mean values. So it is important that the indoor radon reference levels to be lowered as low as reasonably achievable (ALARA) levels in Turkey. The results of radon measurements in dwellings were shared with all parties, local administrators, NGO's, municipalities and local people.

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References

1. Birchall A, Marsh JW (2005) Radon dosimetry and implication for risk. Int Congr Ser 1276:81–84
2. WHO (2009) WHO handbook on indoor radon-a public health perspective, edited by H. Zeeb, and F. Shannoun. http://apps.who.int/iris/bitstream/10665/44149/1/9789241547673_eng.pdf. Accessed May 2015
3. BEIR VI (1998) Health effects of exposure to radon. US National Research Council Report, National Academy Press, Washington, DC
4. UNSCEAR (2000) Sources and effects of ionizing radiation, Report to General Assembly of United Nations, New York, USA
5. Lindsay R, Newman RT, Speelman WJ (2008) A study of airborne radon levels in Paarl houses (South Africa) and associated source terms, using electret ion chambers and gamma–ray spectrometry. Appl Radiat Isot 66:1611–1614
6. Bossew P, Lettner H (2007) Investigation of radon in Austria, Part 1: seasonality of indoor radon concentration. J Environ Radioact 98:329–345
7. Tung TCW, Niu JL, Burnett J, Lau JOW (2005) Methodology for determination of radon-222 production rate of residential building and experimental verification. Radiat Meas 40(1):110–117
8. National Collaborative Center for Environmental Health (NCCEH) (2008) Effective interventions to reduce indoor radon levels, Canada
9. ICRP (1993) Protection against radon-222 at home and at work. A report of the International Commission on Radiological Protection. ICRP Publication 65 Pergamon Press, New York
10. Turkish Atomic Energy Authority (TAEK) (2012) Kapali ortamlarda Radon Gazi 2012. http://www.taek.gov.tr. Accessed May 2015
11. Koksal EM, Celebi N, Ataksor BA, Ulug M, Tasdelen Kopuz G, Akar B, Karabulut MT (2004) A survey of ^{222}Rn concentrations in dwellings of Turkey. J Radioanal Nucl Chem 259(2):213–216
12. USEPA (2012) A citizen's guide to radon. The guide to protecting yourself and your family from radon. US Government Printing Office, Washington. www.epa.gov/radon/pdfs/citizensguide.pdf. Accessed May 2015
13. Chen J (2005) A review of radon doses. Radiat Prot Manag 22:27–31
14. ICRP (1991) Recommendations of the International Commission on Radiological Protection. ICRP Publication 60 Annals of the ICRP 21
15. Gökmen A, Gökmen IG, Hung YT (2005) Radon pollution control. In: Advanced air and noise pollution control, handbook of environmental engineering, vol 2. Humana Press, New York, pp 335–357
16. Kotrappa P, Dempsey JC, Hickey JR, Stieff LR (1988) An electret passive environmental ^{222}Rn monitor based on ionization measurement. Health Phys 54:47–56
17. Sessler GM (1980) Electrets. In: Topics in applied physics, vol 33. Springer, Berlin
18. Denman AR, Groves-Kirkby CJ, Phillips PS, Crockett RGM, Woolridge A, Gillmore GK (2005) The practical use of electrets in public health radon remediation campaign. J Environ Radioact 84(3):375–391
19. Denman AR, Groves-Kirkby CJ, Phillips PS, Crockett RGM, Woolridge AC (2004) Domestic radon monitoring with electrets—practical experiences of large-scale use. In: Proceedings of the 11th international congress of the international radiation protection association, Madrid, Spain, 23–28 May 2004
20. RadElec Inc E-perm System Manual, June 2005. RadElec Inc. 5714-C Industry Lane Frederick, MD 21704 USA
21. Kotrappa P (2008) Long-term stability of electrets used in electrets ion chambers. J Electrostat 66:407–409
22. Kotrappa P, Dempsey JC, Ramsey RW, Stieff LR (1990) A practical E-PERM™ (electret passive environmental radon monitor) system for indoor ^{222}Rn measurement. Health Phys 58:461–467
23. Kotrappa P, Stieff LR (1992) Elevation correction factors for E-PERM® radon monitors. Health Phys 62:82–86
24. Mahat RH, Bradley DA, Amin YM, Wong CY, Su LD (2001) Radiat Phys Chem 61:489–490
25. Gervino G, Bonetti R, Cigolini C, Marino C, Prati P, Pruiti L (2004) Environmental radon monitoring: camparing drawbacks and performances of charcoal canisters, alpha- track and E-PERM detectors. Nucl Inst Methods Phys Res A518:452–455
26. Sorimachi A, Takahashi H, Tokonami S (2009) Influence of the presence of humidity, ambient aerosols and thoron on the detection responses of electrets radon monitors. Radiat Meas 44:111–115
27. Gunby JA, Darby SC, Mıles JCH, Green BMR, Cox DR (1993) Factors affecting indoor radon concentrations in United Kingdom. Health Phys 64:2–12
28. Vaizoglu SA, Guler C (1999) Indoor radon concentrations in Ankara dwellings. Indoor Built Environ 8:327–331
29. Ulug A, Karabulut MT, Celebi N (2004) Radon measurements in specific locations Turkey using CR-39 track detector. Nucl Technol Radiat Prot 19(1):46–49
30. Erees FS, Yener G (1999) Fundamentals for the assessment of risks from environmental radiation. Kluver Academic Publishers, The Netherlands, pp 65–68
31. Yarar Y, Kam E (2005) Environmental radioactivity concentrations of Tekirdag. Int Congr Ser 1276:387–389
32. Yarar Y, Gunaldı T, Kam E (2005) Environmental radioactivity concentrations of Tekirdag. Int Congr Series 1276:385–386
33. Erees FS, Akozcan S, Parlak Y, Cam S (2006) Assessment of dose rates around Manisa (Turkey). Radiat Meas 41:598–601
34. Kam E, Bozkurt A (2007) Environmental radioactivity measurements in Kastamonu region of northern Turkey. Appl Radiat Isot 65(4):440–444
35. Kapdan E, Taskin H, Kam E, Osmanlioglu AE, Karahan G, Bozkurt A (2012) A Study of environmental radioactivity measurements for Cankiri, Turkey. Radiat Prot Dosim 150(3):398–404
36. Celik N, Poffijn A, Cevik U, Schepens L (2007) Indoor radon survey in dwellings of the Kars province, Turkey. Radiat Prot Dosim 128(4):432–436
37. Celik N, Cevik U, Celik A, Kucukomeroglu B (2008) Determination of indoor radon and soil radioactivity in Giresun, Turkey. J Environ Radioact 99:1349–1354
38. Degerlier M, Celebi N (2008) Indoor radon concentrations in Adana, Turkey. Radiat Prot Dosim 131:259–264
39. Can B, Canbazoglu C, Albayrak N, Celebi N, Dogru M (2012) Measurement of indoor radon concentration levels in Kilis, Osmaniye and Antakya, Turkey during spring season. J Radional Nucl Chem 292:1059–1063
40. Guler O, Tarım UA, Yalcin S (2013) Estimation of mean Rn-222 concentrations in water and indoor air of Karacabey, Bursa. Fresenius Environ Bull, 22(1a):247–251
41. ICRP (2009) http://www.icrp.org/docs/ICRP_Statement_on_Radon(November_2009).pdf. Accessed Nov 2009
42. http://www2.epa.gov/radon. Accessed Sept 2015