



Assessment of indoor radon concentration in residential homes and public places in south of Tehran, Iran

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Abstract

Radon as primary source of natural radiation, is the second leading environmental cause of lung cancer after tobacco smoke. Radon gas is important sources of natural radiation. The aim of this study was to measure the concentration of radon gas in residential homes and public places in Kahrizak city and in the buildings near faults. Totally, 37 residential homes (two detectors at each home), and 23 public places (one detector in each place) were studied. The indoor radon concentration in the ground floor of residential homes and public places was measured by a long-term passive method using CR-39 detector. Data were analyzed by SPSS and GIS software. In the residential homes, radon concentration range was $25.1\text{--}130.2 \pm 19.0$ with average of 60.3 Bq/m^3 and in public places, radon concentration range was $18.9\text{--}95.6 \pm 21.9$ with average of 55.8 Bq/m^3 . Majority of residential homes and public places had an effective annual dose of $0.8\text{--}1.6 \text{ mSv/y}$. 28.1% and 26.0% of the total measured concentration of residential homes and public places were in acceptable range based on the U.S.EPA, respectively.

Keywords Radon · Residential homes · Public places · Kahrizak · Iran

Introduction

Recently, there has been a growing concern regarding the health effects of indoor air pollutants. Exposure to pollutants in indoor air can be problematic or even detrimental if

the levels reach high concentrations (Dehghani et al. 2018). Radon gas is one of the important sources of natural radiation, which, on average, accounts for about 50% of the natural exposure of people worldwide (Khan et al. 2014; Kumar et al. 2014). Radon, a natural odorless, tasteless and colorless radioactive gas, is produced from the decay of uranium 238, thorium 232 and uranium 235 and is found in different quantities in most almost all rocks, soils and groundwater resources (Keramati et al. 2018; Moreno et al. 2018). Radon gas can transfer through soil or fragmented rock, absorb by groundwater due to it is high solubility in water, migrate over long distances within the earth from high pressure toward low or negative pressurized areas such as basements and the air as well as enter into buildings and accumulate in indoor spaces. When homes are heated and thermal stacking induces pressure changes, radon is actively drawn up through foundations to accumulate within indoor air.

Factors such as diffusion rate, soil effective permeability and half-life affect on the traveled distance. Radon decay products generate toxic and radioactive α and β particles which can potentially stick in the lungs after inhalation and induce more harm than the radon itself (Sharma et al. 2012). The concentration of radon gas varies widely from place to place. Radon in ambient air quickly dilutes to very

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low quantities and is generally not a health problem. But in the amount present indoor spaces become sometimes high due to accumulation. In general, the concentration of radon inside dwellings varies depending on habitats, standard and type of buildings and methods of ventilation (Chauhan et al. 2014). Major people exposure to radon gas is through indoor air. Since most of the radon escapes, leaving only low quantities in the water itself, the health risk from drinking water is considered negligible (Inácio et al. 2017).

Several studies have shown a significant relationship between soil uranium and increased indoor radon concentration (Cosma et al. 2013; Mehra et al. 2006; Singh et al. 2002; Sujo et al. 2004). The process of radon production and transfer through walls differs according to the type of building materials (Carneiro et al. 2013). Another reason is the release of radon from building materials, including construction stones, bricks, concrete, sand and marble and water (Casey et al. 2015; Jelle 2012; Singh et al. 2016). Proper ventilation can keep indoor radon concentrations below the recommended levels (Mowlavi et al. 2012; Yousefi et al. 2014).

Radon can have many impacts on people's health as it increases the probability of lung and hematologic malignant problems, melanoma, kidney cancers and certain types of cancers during childhood (Marsh and Bailey 2013; Teras et al. 2016). Presence of indoor radon with concentration at 200 Bq/m^3 increases the risk of death due to lung cancer up to 3–5% due to the genotoxicity of alpha particles to biological tissue in the lungs (Chauhan et al. 2014).

In recent years the concern about this risk has grown and numerous studies in the United States, Europe and Asia have been carried out to assess the number of lung cancer cases attributable to radon (Field et al. 2000; Rafique et al. 2012; Ramola and Choubey 2003; Veloso et al. 2012). According to the WHO, exposure of individuals to radon gas is the second leading cause of lung cancer after tobacco smoke in the world and causes between six and fifteen percent of all cases (Hazar et al. 2014). Due to effects of radon on human health, the guideline levels have been suggested by the WHO (World Health Organization) 100 Bq/m^3 (WHO 2009) and the U.S.EPA (United States Environmental Protection Agency) 148 Bq/m^3 (US EPA 2018). In this regard, many countries have set limits for radon concentrations in buildings indoor air, so they monitor it regularly to meet legal requirements (Cosma et al. 2013). In recent years, several studies have been conducted for indoor radon measurement in Iran (Bouzarjomehri and Ehrampoush 2008; Gillmore and Jabarivassal 2010; Hadad et al. 2011b; Mortazavi and Karam 2005; Mowlavi et al. 2012).

Owing to the lack of data regarding indoor radon in Kahrizak city, the aim of this study was to measure the concentration of radon gas in residential homes and public places, which are known as public places in this study. Kahrizak

is one of the most important cities in the south of Tehran province, and has been faced uncontrolled construction of residential settlements in recent years. In this study, variables such as age of building, wall and floor materials, type of heating system, condition of ventilation, average annual effective dose and radon gas concentration buildings near faults were studied. Because Kahrizak city is located near faults, the results are considered very important for public health. This study also provides a general picture of the radon radioactivity of buildings in the city.

Materials and methods

Study area description

Kahrizak city is selected for the purpose of this study because the area is situated on an important fault named Kahrizak fault. Kahrizak city is located in Ray County in South of Tehran province. It has a population of 40,000. It covers an area of 2005 ha. The condition climate of Kahrizak is mostly arid. Between months November and May rainfall of Kahrizak occur. Figure 1 shows the map of study area.

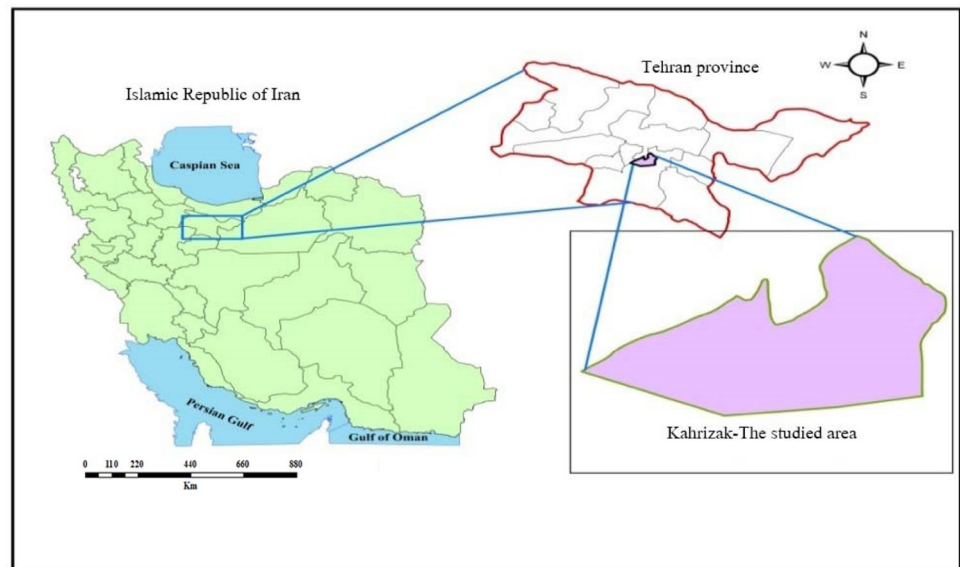
Kahrizak geological formation has different properties from layer to layer due to its heterogeneous, mechanical resistance and changeable porosity. Kahrizak Formation with 10–60 m of thickness contains pebble, gravel and sand. It is Middle Pleistocene in age. It also contains unconsolidated, heterogeneous and poorly sorted conglomerate (Khaksar and Tavassoli 2002). There are several faults in the study area based on the maps obtained from Iran National Cartographic Center (Fig. 6).

Data collection and analysis

Passive device was used in the current research to determine the radon concentrations in the ground floor of residential homes and public places (educational centers, health and medical centers). The methodology used in this study is described in detail in a previous study (Alqadi et al. 2016). CR-39 detector is extensively used for measurement of the radon due to its ability for the accumulation of the data over long period of time. This technology has a number of unique features such as light-weight, small, easy to use, contains simple materials, requires no power supply and often most importantly inexpensive.

The calibration was conducted in the radiation protection office of the Atomic Energy Organization of Iran based on the method described in a previous work (Al-Bataina et al. 1997). The accuracy of the measured data was also checked by determining unmeasured samples in the Atomic Energy Organization of Iran.

Fig. 1 Map of study area



Based on limitations in the study area and we considered 60 sampling points. Totally, 37 residential homes (two detectors at each home), and 23 public places (one detector in each place) were studied. Detectors were located for 3 months in autumn and winter seasons in the bedrooms and living rooms of residential homes in 2018. In this study autumn and winter are selected for the study, due to higher radon concentrations indoor in these seasons due to lack of ventilation. Generally, at public places one detector was placed at a height of 50–90 cm from the floor, away from windows and sunlight based on the standards of the US Environmental Protection Agency (U.S.EPA). At home, the detectors were placed at least 3 ft away from exterior doors or windows, at least 2 off the floor and 2 m from ground level.

Since there was no a separate bedroom in some of residential areas, two detectors were placed near each other in living room (one detector wrapped in a layer of aluminum foil as blank detector and another no wrapped). After 3 months from the time exposure, the detectors were wrapped in aluminum foil and transferred to the laboratory. Then the detectors were placed a 6.25 N sodium hydroxide solution for 3 h at constant temperature (85 °C). After that, the detectors were removed from the solution, washed several times with distilled water, and then counted using optical microscope. Finally, the average radon concentration was reported in Bq/m³. For homes with two detectors, the results of the two detectors were averaged.

The following formula was used to calculate the annual effective dose of radon concentration.

$$D_y = E_f \times C_f \times O_f \times Q_{Rn} \times T$$

where, Q_{Rn} radon 222 concentration (Bq/m³), E_f is balance factor (0.4 for indoor measurements), O_f is occupation factor (0.8 for indoor measurements), T is duration of residence

per 1 year ($T = 365 \times 24$ h is about 7008 h for 1 year stay at home), and C_f is the effective dose rate (9 nSv per Bq/m³ per hour).

We calculated the annual effective dose using the half year (autumn, winter) radon concentration and we assumed that in the Spring and Summer radon would be lower. Thus, we gave an upper estimation of the annual effective dose.

Finally, data were analyzed by SPSS software version 21 and used to compare the means, independent t test and variance analysis and Mann–Whitney test with statistical significance level of p value < 0.05. The map of radon gas concentration near faults was drawn by GIS software.

Results

Occurrence of radon concentration in Kahrizak

In the 37 residential homes, radon concentration range was 25.1–130.2 ± 19 with average of 60.3 Bq/m³ and in 23 public places, radon concentration range was 18.9–95.6 ± 21.9 with average of 55.8 Bq/m³. Table 1 shows the results of the study of the building age, wall type and floor materials, and the type of heating system in residential homes and public places. Box plots of radon concentration with building age, wall materials, floor materials and heating systems in residential homes and public places is shown in Figs. 2 and 3.

In the above table, statistical significance is the probability of finding a given deviation from the null hypothesis -or a more extreme one- in a sample. The p value or probability value or asymptotic significance is the probability for a given statistical model that, when the null hypothesis is true, the statistical summary would be greater than or equal to the actual observed results. The data regarding to the indoor

Table 1 Comparison of radon concentration between different age of the buildings; type of wall materials (1: cement block, 2: brick), type of floor materials (1: cement, 2: ceramic, 3: mosaic, 4: stone), and type of heating system (1: gas heater, 2: radiator)

Variable	Place	<i>p</i> value	Significance
Building age (new and old)	Residential homes	0.002	Significant
	Public places	0.232	Not significant
Wall materials (1 and 2)	Residential homes	0.148	Not significant
	Public places	0.198	Not significant
Floor materials (1, 2 and 3)	Residential homes	0.947	Not significant
	Public places	0.497	Not significant
Floor materials (3 and 4)			
Heating system (1 and 2)	Public places	0.043	Significant

radon concentration, building age and floor materials in residential homes was not normal. Thus, the median obtained values were studied. But for the other parameters both in residential and public places the data was normal and the average values we used.

The studied buildings were classified into two parts: less than 15 years (new) and more than 15 years (old). This classification was based on the Iranian national law which consider 15 years for buildings. There was a significant difference of average radon concentration between the two ages group of the residential homes. In contrast, there was no significant difference of average radon concentration between the two ages group of the public places.

The concentration of radon gas in buildings walls made from brick was higher than that of cement made walls in residential homes and public places, but in terms of statistical analysis, there was no significant difference between the average concentration of radon gas and the various types of wall materials (cement and brick block) in residential homes (*p* value 0.148) and public places (*p* value 0.198). The average concentration of radon in new and old buildings in public places was 50.9 and 61.6 Bq/m³, respectively. The type of wall materials in residential homes and public places was cement block and brick. Average radon concentration did not showed a significant difference between the two types of wall materials in residential homes (*p* value 0.148) and public places (*p* value 0.198). The average concentration of radon gas in residential homes with wall constructed from brick and cement block was 67.7 and 52.3 Bq/m³, respectively. For public places these values were 65.7 and 45.7 Bq/m³, respectively, for brick and cement block walls. In this study, cement, ceramics, and mosaics were the materials used in the floor of residential homes. Stone and mosaics were used in the floor of public places.

The data showed that residential homes covered with ceramics and public places covered with mosaic had the

higher concentrations of radon gas. Based on the results, there was no significant relationship between the average radon concentration of the different flooring materials (*p* value 0.947). The median value of radon gas concentration in ceramic flooring in residential areas (62.5 Bq/m³) was higher than that of cement flooring (56.5 Bq/m³) and mosaic flooring (48.9 Bq/m³).

Also, statistical analysis in the study of floor materials showed that the difference in average radon gas concentrations in residential homes (*p* value 0.947) and public places (*p* value 0.497) were not significant. However, the average concentration of radon gas in public places with mosaic flooring (59.7 Bq/m³) was higher than that those of stone flooring (51.8 Bq/m³).

The heating system in all the studied homes was gas heater and in public places gas heater and radiator. Statistical analyzes showed that there was a significant difference between the average concentration of radon gas in terms of the type of heating system (*p* value 0.043).

Radon concentration and ventilation conditions

The effect of ventilation conditions (weak and strong) on the average concentration of radon is given in Table 2.

The average concentration of radon gas in residential homes with more than one window and suitable ventilation for kitchen was 57.0 Bq/m³ and with one window and inappropriate kitchen ventilation was 76.7 Bq/m³ that this difference was significant (*p* value 0.02). The average concentration of radon gas in public places with more than one window was 47.8 Bq/m³ and with a single window was 56.6 Bq/m³, which the difference was not significant (*p* value 0.475).

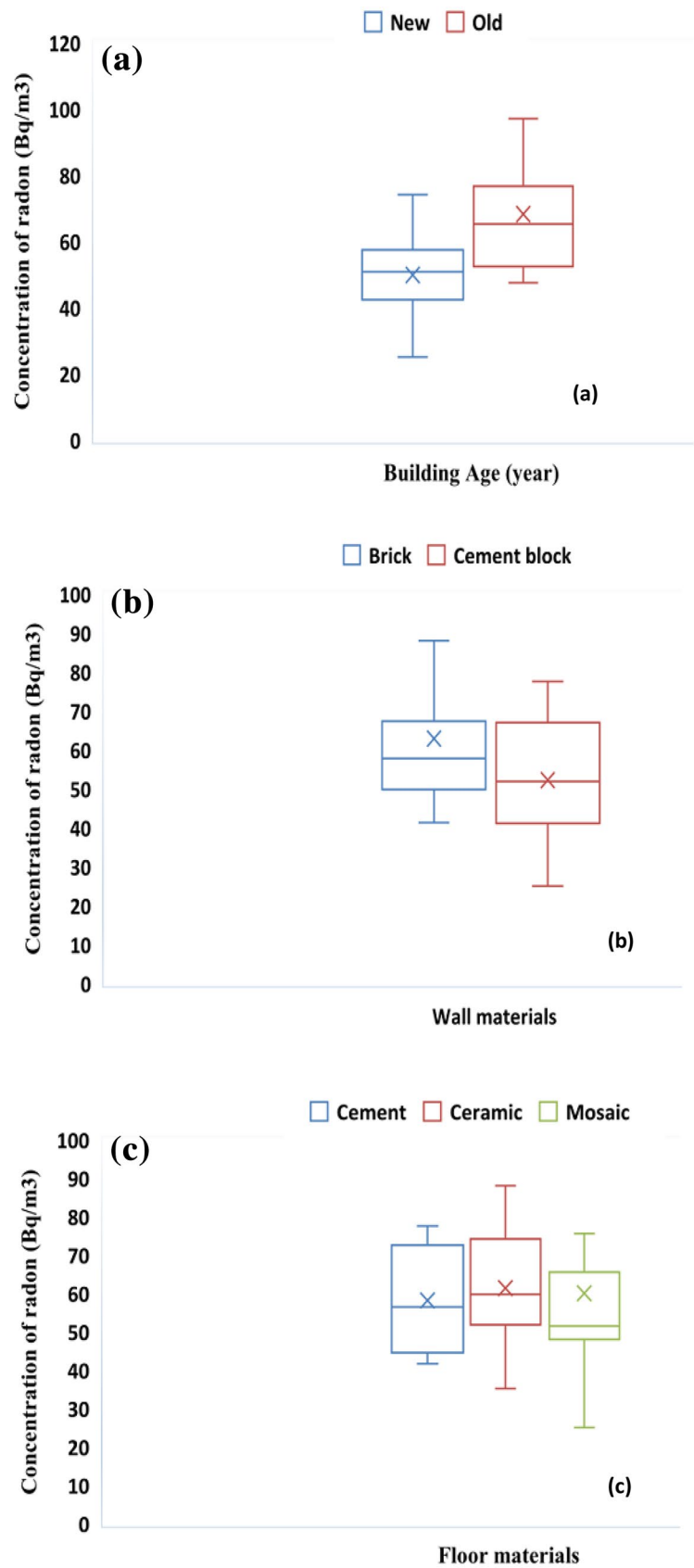
Estimation of annual dose of radon gas concentration

Figure 4 shows the annual effective dose of radon gas concentration and the number of residential homes and public places. According to the figure, majority of residential homes and public places had an effective annual dose of 0.8–1.6 mSv/y. The annual effective dose was below the action level of 3–10 mSv/y recommended by the International Commission on Radiation Protection (ICRP 1993) in all studied places.

Comparison of radon gas concentration with EPA and WHO standards

On average, 71.8% of the total measured concentration of residential homes is in a low level and 28.1% is in an acceptable level. Additionally, in public places, on average 73% of

Fig. 2 Box plot of indoor radon concentration and building age (a), wall materials (b), and floor materials (c) in residential homes



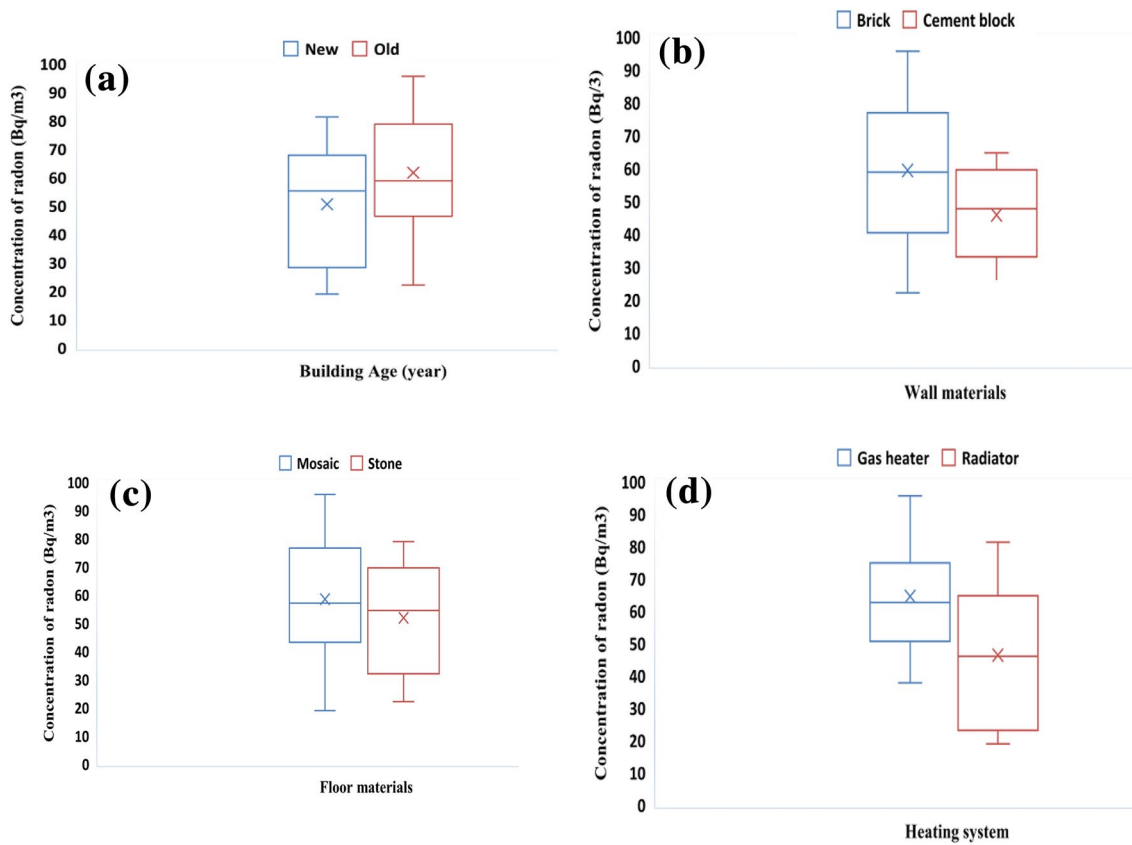


Fig. 3 Box plot of indoor radon concentration and building age (a), wall materials (b), floor materials (c) and heating system (d) in public places

Table 2 The concentration of radon gas in different situations in terms of the number of windows (in bed room and living rooms in residential homes and in the room of dictator in public places) and the existence of a suitable ventilation system (hood, ventilator and window in the kitchen of residential homes)

Place	Ventilation condition	Average radon gas concentration (Bq/m ³)
Residential homes	Strong	57.0
	Weak	76.7
Public places	Strong	47.8
	Weak	56.6

strong (more than one window and the presence of suitable ventilation in the kitchen of residential homes) weak (a window and the lack of suitable ventilation in the kitchen of residential homes)

the total radon concentration measured is in the low level and 26% is in the acceptable range (Fig. 5).

The maps of radon gas around faults

For better comparison radon of concentrations in in this study, the average concentrations were calculated in Kahrizak (Fig. 6). Totally 60 locations were analyzed for radon

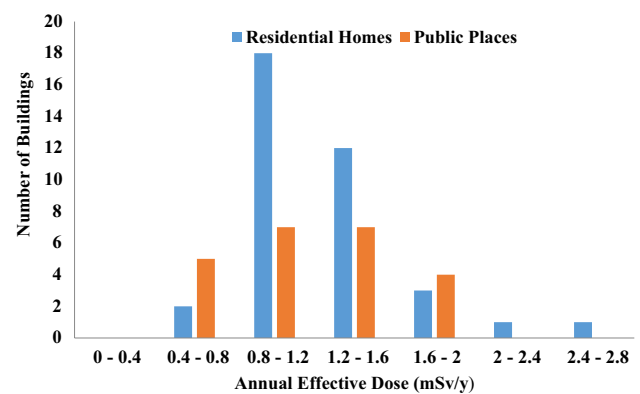


Fig. 4 Effective annual dose of radon in residential homes and public places

concentration indoors. The radon gas concentration shown in the map are the concentrations measured in the different sampling points in Kahrizak. As it was impossible to show all the sampling points in the map, the average concentrations were considered.

As shown in Fig. 6, the average radon concentration in residential homes and public places around the Kahrizak faults are classified into two groups; places with average

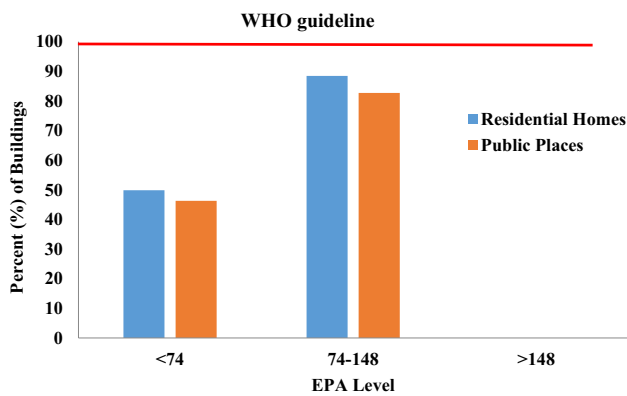


Fig. 5 Comparison of radon gas concentration with EPA standard (low level <74 Bq/m³, acceptable range between 74 and 148 Bq/m³ and dangerous level > 148 Bq/m³) and WHO guideline (100 Bq/m³) for indoor radon in residential homes and public places

radon concentration < 50 Bq/m³ and places with average radon concentration > 50 Bq/m³.

Discussion

In recent years, many studies have been done to measure the concentration of radon gas in residential homes in different countries. In these studies, the average concentration of radon gas was in range of 32–2200 Bq/m³ (Chauhan et al. 2016; Cosma et al. 2013; Cucos Dinu et al. 2017; Demoury et al. 2013; Fahiminia et al. 2016; Khan et al. 2014; Kumar et al. 2015; Marenny et al. 2005; Mowlavi et al. 2012; Sethi et al. 2012; Singh et al. 2005; Wanabongse et al. 2005). In the present study, the average concentration of radon gas in residential homes and public places was between 55.8 and 60.3 Bq/m³.

The amount of radon emissions in buildings depends on the type of material used in the construction (Hassanvand et al. 2018). Materials with higher porosity increase the rate and the quantity of radon transport and radon exhalation. For example, brick has a medium porosity compared to other materials such as concrete or cement block (Al-Ghamdi et al. 2011).

In this study, in residential home, maximum concentration of radon gas was in homes with ceramic floor, whereas, in public places, maximum concentration of radon gas was found in mosaic flooring. Reports have also shown that ceramic is the potential source of radon gas (Abd-Elzaher 2013), but because of the greater pores in mosaic than other materials, mosaic-covered buildings showed a higher concentration of radon gas (Yousefi et al. 2014).

In this study, the use of natural gas has increased the concentration of radon gas in indoor air compared to other heating systems (Table 2). Studies have shown that heaters using

natural gas increase radon gas indoors (Abd-Elzaher 2013). As homes are heated in winter and thermal stacking generates negative pressure, radon is actively drawn up through foundations to accumulate within indoor (Cuce and Riffat 2015). In another study, the authors reported that the concentration of radon gas in homes during the first 6 months of year (spring and summer) was low due to the openness of windows and natural ventilation. During the winter, residents use gas heater for warming and also the windows are closed which makes the pressure difference and increase the radon exhalation from the building material which lead to the accumulation and increase in the concentration of radon gas (Hadad et al. 2011a).

However, this study was conducted in the autumn and winter seasons (cold seasons) and closure of windows result in higher concentration of radon gas. Therefore, proper ventilation system can decrease the radon concentrations indoors. This statement is also confirmed by the other studies (Chauhan et al. 2014; Stabile et al. 2016).

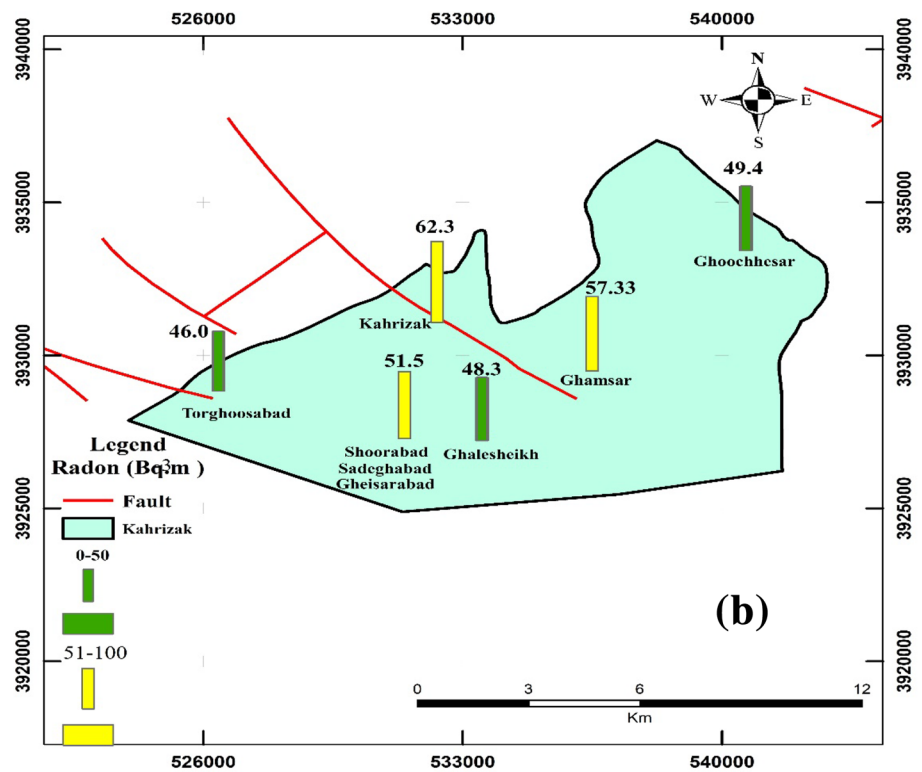
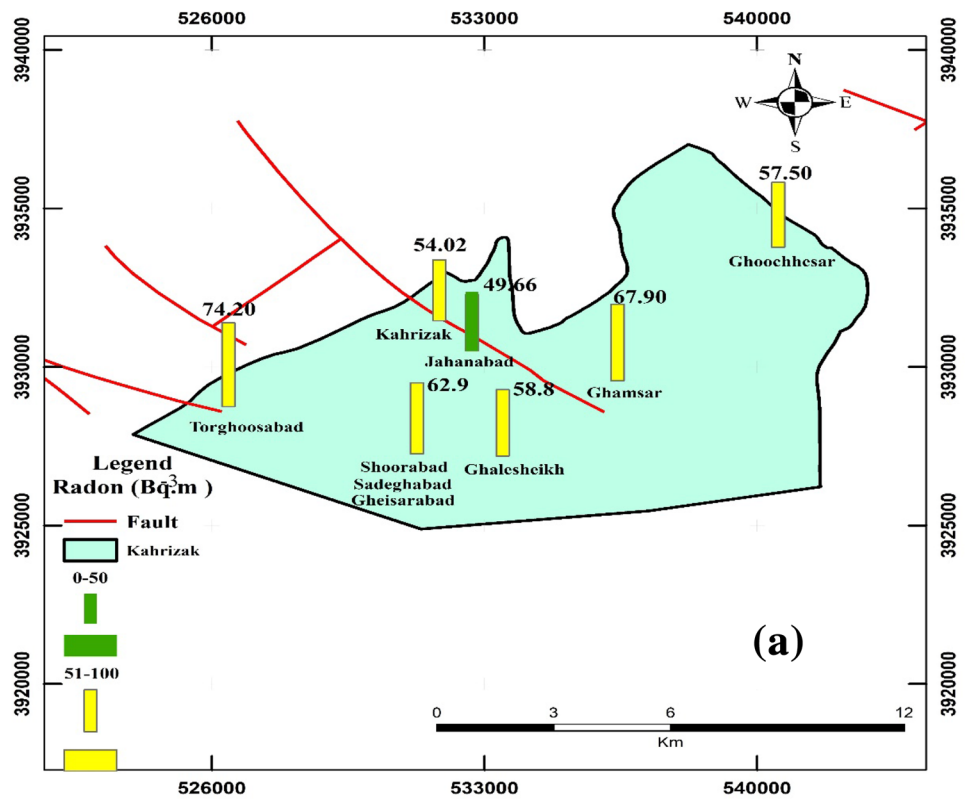
The International Commission on Radiation Protection (ICRP) has proposed a quantity of 300 Bq/m³ for radon gas [ICRP 115 (International Commission on Radiological Protection) 2019]. Therefore, the reference value should not exceed 300 Bq/m³, which is equivalent to 10 mSv/y based on the latest ICRP calculations. The U.S.EPA have categorized radon levels into 3 groups; dangerous level (> 148 Bq/m³), acceptable level (74–148 Bq/m³) and low level (74 Bq/m³) (Zdrojewicz and Strzelczyk 2006). It is important to note that there is no known threshold concentration below which radon exposure presents no hazard. Even low concentrations of radon can cause small increase in the hazard of lung cancer (Ting 2010). The average global concentration of radon gas in residential homes is estimated at 39 Bq/m³ (CFR 2009).

In this study, the annual effective dose in residential homes and public places did not exceed 10 mSv/y and was below the recommended dose of the ICRP. Additionally, concentration of radon gas in 97% of residential homes and all public places were lower than the WHO guidelines of 100 Bq/m³.

Radon may penetrate into residential homes from earth's faults. The earth faults in earthquake zones make up high concentrations of radon gas during activation (Kucukomerglu et al. 2016). In this study, some regions near the faults had higher radon concentrations. The low average concentration of radon gas in some areas near faults can be due to other parameters affecting the concentration of radon gas, such as ventilation conditions, the flooring and wall materials, etc.

Since indoor radon concentrations vary from location to location and is mainly dependent on differences in the geology of the subsoil, in the climatic parameters and in the building characteristics and materials and on the variations of the

Fig. 6 Average radon concentration in residential homes (a) and public places (b) around the Kahrizak faults (green bars are places with radon concentration < 50 Bq/m³, yellow bars are places with radon concentration > 50 Bq/m³)



ventilation conditions and air exchange between indoors, this study does not guarantee the safety of the studied places regarding indoor radon and show a general scheme of radon concentration in some residential homes and public places.

Conclusions

There is considerable public concern about radon concentration in indoor spaces. To address this concern, radon concentrations were determined 37 residential homes and 23 public places in Kahrizak. In the residential homes, radon concentration range was $25.1\text{--}130.2 \pm 19.0$ with average of 60.3 Bq/m^3 and in public places, radon concentration range was $18.9\text{--}95.6 \pm 21.9$ with average of 55.8 Bq/m^3 . Majority of residential homes and public places had an effective annual dose of $0.8\text{--}1.6 \text{ mSv/y}$. 28.1 and 26.0% of the total measured concentration of residential homes and public places were in acceptable range based on the U.S.EPA, respectively. Our findings showed that radon, an established carcinogen, is not of serious concern to public health in the studied houses and public places. The radon gas concentration was not high in residential homes and public places and was in the range of the U.S.EPA standard. The relationship between the building age, wall type and floor materials, and the type of heating system in residential homes and public places investigated. Although radon levels were low, but since there is no a safe threshold for carcinogens, preventive measures should be implemented to reduce even these levels as much as possible. Therefore, it is suggested use proper ventilation low radon emitting construction materials and to reduce the radon gas concentration. The study provides basic information for future researches on environmental health at a local level and for protecting the health of citizens against exposure to radon in residential areas and public places.

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Compliance with ethical standards

Conflict of interest The authors of this article declare that they have no conflict of interests.

References

Abd-Elzaher M (2013) Measurement of indoor radon concentration and assessment of doses in different districts of Alexandria city. *Environ Geochem Health* 35:299–309

- Al-Bataina B, Ismail A, Kullab M, Abumurad K, Mustafa H (1997) Radon measurements in different types of natural waters in Jordan. *Radiat Meas* 28:591–594
- Al-Ghamdi S, Al-Garawi M, Al-Mosa TM, Baig M (2011) Investigating indoor radon levels and influencing factors in primary schools of Zulfi city, Saudi Arabia. In: AIP conference proceedings, vol 1. AIP, pp 294–298
- Alqadi M, Alzoubi F, Jaber M (2016) Assessment of radon gas using passive dosimeter in Amman and Al-Rusaifa cities, Jordan. *Int J Radiat Res* 14:367–371
- Bouzarjomehri F, Ehrampoush M (2008) Radon level in dwellings basement of Yazd-Iran. *Iranian J Radiat Res* 6:141–144
- Carneiro G, Braz D, de Jesus E, Santos S, Cardoso K, Hecht A, Da Cunha MKD (2013) Radon in indoor concentrations and indoor concentrations of metal dust particles in museums and other public buildings. *Environ Geochem Health* 35:333–340
- Casey JA, Ogburn EL, Rasmussen SG, Irving JK, Pollak J, Locke PA, Schwartz BS (2015) Predictors of indoor radon concentrations in Pennsylvania, 1989–2013. *Environ Health Perspect* 123:1130
- CFR U (2009) Code of Federal Regulations Title 40: protection of Environment, Part 136–Guidelines establishing test procedures for the analyses of pollutants, Appendix B to Part 136–definition and procedure for the determination of Method Detection Limit Rev. 1.11
- Chauhan N, Chauhan R, Joshi M, Agarwal T, Aggarwal P, Sahoo B (2014) Study of indoor radon distribution using measurements and CFD modeling. *J Environ Radioact* 136:105–111
- Chauhan R, Kumar A, Chauhan N, Joshi M, Aggarwal P, Sahoo B (2016) Ventilation effect on indoor radon–thoron levels in dwellings and correlation with soil exhalation rates. *Indoor Built Environ* 25:203–212
- Cosma C, Cucos-Dinu A, Papp B, Begy R, Sainz C (2013) Soil and building material as main sources of indoor radon in Băița-Ștei radon prone area (Romania). *J Environ Radioact* 116:174–179
- Cuce PM, Riffat S (2015) A comprehensive review of heat recovery systems for building applications. *Renew Sust Energ Rev* 47:665–682
- Cucos Dinu A et al (2017) The distribution of indoor radon in Transylvania (Romania)-influence of the natural and anthropogenic factors. In: EGU general assembly conference abstracts. p 10278
- Dehghani MH et al (2018) Levels of formaldehyde in residential indoor air of Gonabad, Iran. *Hum Ecol Risk Assess* 24:1–9
- 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
- Fahiminia M, Fard RF, Ardani R, Naddafi K, Hassanvand M, Mohammadbeigi A (2016) Indoor radon measurements in residential dwellings in Qom, Iran. *Int J Radiat Res* 14:331–339
- Field RW et al (2000) Residential radon gas exposure and lung cancer: the Iowa Radon Lung Cancer Study. *Am J Epidemiol* 151:1091–1102
- Gillmore G, Jabarivasal N (2010) A reconnaissance study of radon concentrations in Hamadan city, Iran. *Nat Hazards Earth Syst Sci* 10:857–863
- Hadad K, Hakimdavoud M, Hashemi-Tilehnoe M (2011a) Indoor radon survey in Shiraz-Iran using developed passive measurement method, Iran. *J Radiat Res* 9:175–182
- Hadad K, Hakimdavoud M, Hashemi-Tilehnoe M (2011b) Indoor radon survey in Shiraz-Iran using developed passive measurement method. *Int J Radiat Res* 9:175
- Hassanvand H, Hassanvand MS, Birjandi M (2018) Indoor Radon measurement in dwellings of Khorramabad city, Iran. *J Med Phys* 15:19–27
- Hazar N, Karbakhsh M, Yunesian M, Nedjat S, Naddafi K (2014) Perceived risk of exposure to indoor residential radon and its

- relationship to willingness to test among health care providers in Tehran. *J Environ Health Sci Eng* 12:118
- ICRP (1993) Publication 65. Protection Against Radon 222 at home and at Work R protection—Ann. International commission on Radiation Protection, ICRP 23
- Inácio M, Soares S, Almeida P (2017) Radon concentration assessment in water sources of public drinking of Covilhã's county, Portugal. *J Radiat Res Appl Sci* 10:135–139
- Jelle BP (2012) Development of a model for radon concentration in indoor air. *Sci Total Environ* 416:343–350
- Keramati H et al (2018) Radon 222 in drinking water resources of Iran: a systematic review, meta-analysis and probabilistic risk assessment (Monte Carlo simulation). *Food Chem Toxicol* 115:460–469
- Khaksar K, Tavassoli A (2002) Geological characteristics of Tehran aquifer. XII Congresso Brasileiro de Águas Subterrâneas: São Paulo 1:1–7
- Khan F, Wazir Z, Tufail M, Nusrat M (2014) Variation of indoor radon concentrations in two-storey houses in Nowshera district, Pakistan. *Radiat Prot Dosim* 163:133–139
- Kucukomeroglu B et al (2016) Indoor radon and gamma spectrometric measurements for the Erzincan Basin on North Anatolian Fault Zone, Turkey. *Indoor Built Environ* 25:857–866
- Kumar A, Chauhan R, Joshi M, Sahoo B (2014) Modeling of indoor radon concentration from radon exhalation rates of building materials and validation through measurements. *J Environ Radioact* 127:50–55
- Kumar A, Sharma S, Kaur M (2015) Measurement of indoor radon concentration in some dwellings of Amritsar city. Punjab. 2013:1–9
- Marenny A, Shinkarev S, Penezhev A, Savkin M, Hoshi M (2005) Assessment of exposure to the population of Russia from radon. In: *International Congress Series, 2005*. Elsevier, pp 352–353
- Marsh J, Bailey M (2013) A review of lung-to-blood absorption rates for radon progeny. *Radiat Prot Dosimetry* 157:499–514
- Mehra R, Singh S, Singh K (2006) A study of uranium, radium, radon exhalation rate and indoor radon in the environs of some areas of the Malwa region, Punjab. *Indoor Built Environ* 15:499–505
- Moreno V, Bach J, Zarroca M, Font L, Roqué C, Linares R (2018) Characterization of radon levels in soil and groundwater in the North Maladeta Fault area (Central Pyrenees) and their effects on indoor radon concentration in a thermal spa. *J Environ Radioact* 189:1–13
- Mortazavi S, Karam P (2005) Apparent lack of radiation susceptibility among residents of the high background radiation area in Ramsar, Iran: can we relax our standards? *Radioact Environ* 7:1141–1147
- Mowlavi AA, Fornasier MR, Binesh A, De Denaro M (2012) Indoor radon measurement and effective dose assessment of 150 apartments in Mashhad, Iran. *Environ Monit Assess* 184:1085–1088
- Rafique M, Rahman SU, Akram M (2012) Estimation of concentration and exposure doses due to radon by using CR-39 plastic track detectors in the residences of Sudhnuti, Azad Kashmir, Pakistan. *Environ Earth Sci* 66:1225–1232
- Ramola R, Choubey V (2003) Measurement of radon exhalation rate from soil samples of Garhwal Himalaya, India. *J Radioanal Nucl Chem* 256:219–223
- Sethi TK, El-Ghamry MN, Kloecker GH (2012) Radon and lung cancer. *Clin Adv Hematol Oncol* 10:157–164
- Sharma J et al (2012) Comparative study of indoor radon, thoron with radon exhalation rate in soil samples in some historical places at Jaipur, Rajasthan, India. *Adv Appl Sci Res* 3:1085–1091
- Singh S, Kumar A, Singh B (2002) Radon level in dwellings and its correlation with uranium and radium content in some areas of Himachal Pradesh, India. *Environ Int* 28:97–101
- Singh S, Mehra R, Singh K (2005) Seasonal variation of indoor radon in dwellings of Malwa region, Punjab. *Atmos Environ* 39:7761–7767
- Singh P, Sahoo B, Bajwa B (2016) Theoretical modeling of indoor radon concentration and its validation through measurements in South-East Haryana, India. *J Environ Manag* 171:35–41
- Stabile L, Dell'Isola M, Frattolillo A, Massimo A, Russi A (2016) Effect of natural ventilation and manual airing on indoor air quality in naturally ventilated Italian classrooms. *Build Environ* 98:180–189
- Sujo LC et al (2004) Uranium-238 and thorium-232 series concentrations in soil, radon-222 indoor and drinking water concentrations and dose assessment in the city of Aldama, Chihuahua, Mexico. *J Environ Radioact* 77:205–219
- Teras LR, Diver WR, Turner MC, Krewski D, Sahar L, Ward E, Gapstur SM (2016) Residential radon exposure and risk of incident hematologic malignancies in the Cancer Prevention Study-II Nutrition Cohort. *Environ Res* 148:46–54
- Ting DSK (2010) WHO handbook on indoor radon: a public health perspective. Taylor & Francis, Roudledge
- US EPA, Health Risk of Radon [(accessed on 5 April 2018)]; 2016 Available online: <https://www.epa.gov/radon/health-risk-radon>
- Veloso B, Nogueira JR, Cardoso MF (2012) Lung cancer and indoor radon exposure in the north of Portugal—an ecological study. *Cancer Epidemiol* 36:e26–e32
- Wanabongse P, Tokonami S, Bovornkitti S (2005) Current studies on radon gas in Thailand. *Int Congr Ser* 1276:208–209
- WHO (2009) Guidelines for drinking-water quality: recommendations. World Health Organization, Geneva
- Yousefi Z, Naddafi K, Tahamtan M, Zazouli MA, Koushki Z (2014) Indoor radon concentration in Gorgan dwellings using CR-39 detector. *J Mazandaran Univ Med Sci (JMUMS)* 24:2–10
- Zdrojewicz Z, Strzelczyk J (2006) Radon treatment controversy. *Dose-Response* 4:106–118

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