Indoor radon concentrations in residential houses, processing factories, and mines in Neyriz, Iran

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Abstract

Purpose This study aimed to determine radon concentrations in mines, stone processing factories, residential houses, and public areas, as well as calculating its effective dose in Neyriz, Iran.

Method A total of 74 alpha Track detectors (CR-39 detector) were installed at the desired locations based on the US-EPA's protocol. After 3 months the detectors were collected and delivered to a Radon Reference Laboratory for analyzing.

Results Mean $\pm$ SD, minimum and maximum radon concentrations in the sampling buildings were 29.93 ± 12.63 , 10.33, and 66.76 Bq/m³, respectively. The effective annual dose was calculated to be 0.75 mSv/year, which was lower than the recommended value. Significant positive correlations were found between radon concentrations and some studied variables including smoking cigarettes, number of cigarettes smoked, duration of smoking, building's age, number of floors, having cracks, use of colors in the building, use of ceramic for flooring, use of stone for flooring, and gas consumption. The number of cigarettes smoked by the residents was the most important predictor of radon concentrations. Radon concentrations were lower than standard values in all sampling locations.

Conclusion It is necessary to conduct further studies in the field of regional geology and determine the sources that release radon in these areas to prevent further increases in radon concentration due to the proximity and plurality of mines and factories.

Keywords Air pollutants · Radioactive carcinogen · Chemicals and drugs · Inorganic chemicals · Gases · Radon

Introduction

In recent years, development of urbanization, technologies and various industries have led to increase serious environmental problems, including emission of air pollutants in indoor and outdoor environments [1, 2]. The levels and health effects of different environmental pollutants including PAHs [3, 4], bioaerosol [5], heavy metals [6], PM₁₀ [2], VOCs [7], and to some extent, radon [8] have been studied in various

environmental media by many researchers. Radon is known as the second factor causing lung cancer after cigarette smoking [9]. This gas is produced from natural decomposition of uranium [10, 11] and has the largest contribution to natural radiation [12]. It is a natural, odorless, colorless, and tasteless gas and is inert to most common chemical reactions [13]. Exposure to radon can cause a variety of health outcomes. Alpha radiation induced from radon decay can damage the gastrointestinal and respiratory systems [14]. Radon is produced by the radioactive decay of radium-226, which is found in uranium ores, phosphate rock, and igneous and metamorphic rocks. The main sources of radon production are usually earth, crustal rock, and groundwater [15]. It penetrates into buildings directly from the soil through the lowest level in the building that is in contact with the ground, building materials, invisible cracks in the walls, floor, and the environment's atmosphere [16].

According to the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the average annual human exposure (effective dose) from all natural radioactive sources has been estimated to be 2.4 mSv/year out of which, 1.25 mSv/year is due to inhalation and 1.15 mSv/year

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is related to other routes [17]. The maximum limit of radon concentration in indoor air has been suggested to be 148 Bq/m³ by the United States Environmental Protection Agency (USEPA) [18]. The permitted radon concentration in air has been also proposed to be 100 Bq/m³ by World Health Organization (WHO) [19].

Today, the concentration of this gas is routinely measured in most parts of the world, and its monitoring is increasing due to its destructive effects. The results of a study conducted by Firoozabadi et al. indicated that radon concentrations were 2068.2, 219.9, and 19.75 Bq/m³ in the workers' workplace, resort area, and rest area and outside the mines, respectively. Besides, the measured concentration was higher than the recommended maximum value in 25% of the cases [20]. Gang Song et al. also conducted a study to determine radon concentration in hotels near hot springs using the NR-667A method. The results showed that radon concentration was more than the allowed value [21]. In the same line, Celik et al. carried out a research to assess indoor radon concentrations and soil radioactivity levels in Turkey. The results indicated that radon concentration ranged from 52 to 360 Bq/m³ and its average value was 130 Bq/m³ [22]. The results of the study performed by Yarahmadi et al. in Shiraz in 2015 demonstrated that the mean radon concentration in residential houses was 57.6 ± 33.06 Bq/m³ and 5.4% of the houses had a concentration above the WHO's recommended value [13]. Vuckovic et al. also conducted a study in Serbia and reported that the average indoor radon concentration was 82 Bq/m³ [23]. Results of study conducted by Bektashi et al. showed that radon concentration ranged from 54 to 691 Bq/m³ in Trepça underground mines [24].

Measurement of radon concentration in residential buildings is very important in terms of its relevance to the inhabitants' radiation exposure. The aim of this study was to measure radon concentration in different public places including houses, processing factories, and mines, as well as to calculate its effective dose radiation in Neyriz, Fars province, Iran.

Materials and methods

Investigated area and geology

Neyriz is the capital of Neyriz County, Fars Province, Iran (29.1893° N and 54.3139° E, 1795 m above the sea level) with an area of about 55.5 km² has a population of 49,850 according to the 2016 census. This city has four active Chinese and marble mines and several stone processing factories with 50 ha area and 162 units related to stone cutting and processing located in 5 km away from the city. Considering the city's geographical situation and location of the mines and stone factories around the city, as the source of

radon emissions, as well as the carcinogenic effects of radon, this study aimed to determine radon concentrations in residential houses, processing factories, and mines in Neyriz, Iran. The locations of the sampling area have been depicted in Fig. 1.

Data collection

Totally 74 samples including 14 samples in mines, 8 samples in stone processing factories and 52 samples in residential houses and public areas were collected during the study. To increase the accuracy of sampling, 10% of the samples were placed repeatedly in the same places. Radon concentration was measured using Alpha Track (TAS Track UK). The detectors, which contained a small piece of the CR-39 polymer film and placed inside a small receptacle, were installed at the desired locations based on the USEPA's protocol. The detectors were placed in the sampling location at a height of 100–150 cm from the ground floor away from windows and sunlight [16]. The CR-39 detector is one of the best methods for measuring radon concentration for a long time due to their endurance, strength, availability, and ease of use [25]. Moisture and low temperatures are ineffective against these detectors. Due to the quality of the materials used in these detectors, there is no need for any source of energy to record alpha particles on it. The alpha particles emitted from radon leave some trails on the detectors film, which could be made visible using electrochemical methods and counted under a microscope [26].

CR-39 detector analysis

After being assembled in houses for at least three months, the detectors were completely covered with aluminum foil to prevent external radiation and were delivered to a Radon Reference Laboratory in Iran (Mazandaran University of Medical Sciences). At the laboratory, the aluminum covers were removed and the carved numbers were recorded on the detectors immediately. The detectors were kept in 6.25 M NaOH solution at a temperature of 90 °C for four hours and then washed with distilled water. Eventually, the alpha particle trails were read by an automatic counter and radon concentrations were determined in Bq/m³. A microscopic image was taken from each CR-39 detector via a counter equipped with a mechanical and electronic system and completely controlled by special software through a computer. All alpha particles of these images were calculated by the counting machine and the output table was recorded in terms of the number of traces per square centimeter based on the calibration coefficient and the conversion coefficient to Bq/m³. It should be noted that the calibration coefficient of the device was previously determined by the Iranian Atomic

Fig. 1 Map of the investigated places and sampling points in Neyriz

Energy Organization (IAEA). In addition, the accuracy of the results of radon laboratory at Mazandaran University of Medical Sciences was controlled and approved by the radiation protection unit of IAEA.

Calculation of the annual effective dose

The average annual effective dose (in mSv/year) for residents of Neyriz was calculated based on the UNSCEAR-2000 model and the following formula [27]:

$$E = C \times F \times H \times T \times D \quad (1)$$

- C the indoor radon concentration in Bq/m³ (the value of C in residential houses in Neyriz)
- F the adjustment factor (0.4 for indoor measurements)
- H the occupancy factor (0.8 for indoor measurements)
- T the number of hours in a year (8760 h for one year residence in the house)

- D the dose conversion factor for the whole body dose calculation (0.9 nSv per Bq/m³ h¹) [28].

Zoning of radon concentration

Interpolation method was used to map radon concentration using ArcGIS software, version 10.1.1. This method can estimate unknown values based on various mathematical and statistical models as well as known values in sampling points [29]. In this context, semi-variance of the variables and semi-variogram curves were prepared in order to select the best interpolation method. With regard to distribution of the sampling points, it was found that Inverse Distance Weight (IDW) was a more appropriate method. Thus, interpolation was conducted using quantitative data and radon concentration in Neyriz.

Statistical analysis

In this study, many parameters including the type of mines, mines antiquity, mineral texture, and detectors' locations (workers' workplace, resort place, resting place, and outdoors) in the mines, type of rock production, factory texture, factory's age, and factory area in the stone processing factories, and city texture, building's age, type of used materials, sample type, type of consumed gas, etc. in residential houses were collected by a detailed questionnaire and used as independent variables in statistical analyses. The data were analyzed by the SPSS statistical software, version 19 at the significant level of $p < 0.05$. Kolmogorov-Smirnov test was used to determine the normality of the data. Mann-Whitney U test and Spearman's correlation test were used to analyze the data. Finally, all data were processed using forward-mode regression. Comparison of the three study areas (residential buildings, mines, and factories) with respect to radon concentration was presented using a box plot.

Results and discussion

The average radon concentration in residential houses and public areas

The results of statistical analysis of the data in residential houses and public areas have been presented in Table 1. Accordingly, mean $\pm$ SD, minimum, and maximum radon concentrations in the sampling buildings were 29.93 ± 12.63 , 10.33, and 66.76 Bq/m³, respectively. In a study conducted in Tehran by Shahbazi et al., the maximum and minimum concentrations of radon were 460.2 (Shahid Baqeri in west) and 31 Bq/m³ (Shahid Araqi in north), respectively [30]. Radon concentrations were also estimated to be 57.60, 39, 43.99, 95.83, 108, 31.9, 137.36, 69.5, and 400 Bq/m³ in Shiraz [13], Tabriz [16], Gorgan [31], Qom [32], Hamedan [33], Mashhad [34], Yazd [35], Spain [36], and Germany [37], respectively. Considering the average global radon concentration in residential buildings; i.e., 39 Bq/m³ [19], the average radon concentration was lower than but near the global average value in Neyriz and higher than the global average value in Shiraz [13], Gorgan [31], Spain [36], and Germany [37].

In the present study, radon concentration in all measured sampling points was lower than the maximum permitted values proposed by EPA (148 Bq/m³) and WHO (100 Bq/m³ as the permitted values in indoor air). In the study conducted by Yarahmadi et al., radon concentration was less than the maximum limit, but higher the WHO's proposed value in 5.4% of the samples [13]. The results of a study conducted in Mashhad, Iran also showed that the concentration of radon in 5.3% of the samples was more than WHO's permitted value of 100 Bq/m³ [34]. The results of a study in Siberia showed

that the average radon concentration was 82 Bq/m³, however the concentrations were more than 100 Bq/m³ in 26.7% of the houses [23]. Barros-Dios et al. also conducted a study in Spain and reported that the concentration was higher than 148 Bq/m³ in 21.3% of the sampling points [36].

As shown in Table 1, radon concentration had a significant positive relationship with smoking cigarettes, number of cigarettes, duration of smoking, building's age, number of floors, having cracks, use of colors in the building, use of ceramic for flooring, use of stone for flooring, and gas consumption.

The results of multiple regression analysis also showed significant relationships between radon concentrations and dependent variables, such as number of cigarettes, duration of smoking, and use of stone for flooring. Among these variables, the number of cigarettes used by the residents had the greatest effect on radon concentration ($\beta = 0.769$) as presented in Table 2.

Relationship between radon concentration and variables collected by questionnaire

The results of the present study showed a significant positive relationship between radon concentrations and respiratory diseases. Similarly, some case-control studies have shown that the incidence of lung cancer was much higher among individuals living in houses with high radon concentrations [38]. It has been suggested that radon is the second most important factor causing lung cancer. Some studies reported a relationship between radon concentration and leukemia and skin and stomach cancers [36, 39]. Radon causes 21,000 deaths due to lung cancer in the United States every year, which is twice the death rate attributable to driving accidents [39].

In the present study, there was at least one smoker in 36.5% of the houses. Radon concentration was significantly higher in the houses with smokers compared to those with non-smokers ($p < 0.001$). Moreover, radon concentration was significantly associated with the number of cigarettes and duration of smoking. Studies have shown that when radon concentration in houses reach to 21 Bq/m³, the risk of lung cancer would be 30 times higher for smokers than for non-smokers [40]. The results of multiple regression analysis also showed a significant relationship between radon concentration and duration of smoking, number of cigarettes used by residents, and pulmonary disease. In this respect, the number of cigarettes had the greatest effect on radon concentration. In a study conducted in Shiraz [13], 26.4% of houses had at least one smoker and the radon levels were higher in those house.

Based on the results of this study, radon concentrations were higher in old foundations and old buildings (over 15 years old) compared to new foundations and new buildings (less than 15 years old), but the difference was not statistically significant. In the same vein, the results of the studies conducted in Yazd [20] and Spain [36] showed that radon

Table 1 Results of Mann–Whitney test and Spearman's correlation analyses of radon concentrations in residential houses and public areas regarding different variables in Neyriz

Variables		<i>N</i>	Mean (Bq/m ³)	<i>P</i> value ^a	<i>R</i> ^b
Smoking cigarettes in house	Yes	19	40.95	0.000	0.783
	No	33	18.18		
Number of cigarettes	–	–	–	0.000	0.778
Duration of smoking	–	–	–	0.000	0.778
Type of foundation	Old	16	27.09	0.851	–
	New	36	26.24		
Building' age	Newly-built (<15)	26	23.56	0.161	–
	Old-built (>15)	26	29.44		
Floors in the building	Ground floor	40	29.09	0.02	–
	2nd floor and higher	12	17.88		
Material used for building	Bricks	Yes	49	0.610	–
		No	3		
	Concrete	Yes	35	0.876	–
		No	17		
Having basement	Yes	9	33.06	0.154	–
	No	43	25.13		
Having cracks	Yes	7	37.21	0.044	–
	No	45	24.83		
Use of colors in the building	Yes	14	32.68	0.048	–
	No	37	23.47		
Use of ceramic for flooring (%)	–	–	–	0.026	0.309
Use of stone for flooring (%)	–	–	–	0.004	0.392
Gas consumption				0.002	0.416

^a Mann–Whitney analysis^b Spearman's correlation

concentration was significantly related to building's age. In these studies, radon concentrations were higher in older buildings than in new buildings, which is consistent with the results of the present study. This can be related to the type of materials used in buildings. Most new buildings are constructed with concrete, which is compact and does not allow radon to penetrate easily into the building environment. However, most old buildings are made with brick and clay, which have a lot of pores causing radon to be emitted to the buildings. In addition, walls of old buildings often contain gypsum, which contains a relatively large amount of radium as radon's parent [16].

Radon has a density of 9.73 g per liter (heavier than air) and, consequently, tends to move downward. Therefore, radon concentration is higher in underground and ground floor compared to other floors [16]. In this study, radon concentration was 29.09 Bq/m³ in the ground floor, which was significantly higher compared to the upper floors ($p < 0.05$). In the same line, Haddadi et al. showed that radon concentrations were 48 and 44 Bq/m³ in underground and the first floor, respectively. Besides, the concentration decreased in the upper floors, such a way that radon concentration was 43 Bq/m³ in the second and 25 Bq/m³ in the third floor. Moreover, increase in altitude results in a decrease in the concentration of this gas, which is justified due to its density. The results of the present study are

consistent with those of the studies conducted in Tabriz [16] and Shiraz [13]. However, the study results demonstrated that there was no significant difference between radon concentration in house with basement and those without basement, which is in agreement with the study performed by Vuckovic et al. [23]. The study of Hassanvand et al., in Khorramabad showed that radon concentration in the basement, ground floor, 1st floor and 2nd floor were 63.97, 42.99, 27.48 and 21.04 Bq/m³, respectively [41]. Another study in Shiraz showed that geometric mean of radon concentrations in the basement, ground floor, 1st floor and 2nd floor were 108.6, 87.2, 62.8, 60.5 Bq/m³ respectively [28]. The result of the study in Qom showed that geometric mean of radon concentration in basement, ground floor, 1st floor and 2nd floor were 115, 83, 56 and 34 respectively [32].

Construction materials are the main source of radon in buildings [42], while building materials are less important than earth crust and underground water [19]. Concrete has the highest [43] and brick has the lowest potential for releasing radon. In general, building materials can increase the amount of radon released in buildings by about 30–50% [19]. The results of the present study showed that radon concentrations were 26.77 and 26.27 Bq/m³ in brick and concrete buildings, respectively. It should be noted that the distribution of samples

Table 2 Multiple linear regression analysis between radon concentration and the factors affecting the increased concentration

Radon concentration	Unstandardized coefficients		<i>P</i> value	95% confidence interval for <i>B</i>	
	<i>B</i>	Std. error		Lower bound	Upper bound
(Constant)	31.64	5.29	0.000	20.981	42.299
Duration of smoking	0.098	0.032	0.003	0.034	0.162
Number of cigarettes	0.769	0.254	0.004	0.257	1.281
Use of stone for flooring	0.102	0.037	0.008	0.028	0.176
Pulmonary disease	−5.32	2.641	0.049	−10.645	−.012

was not the same in brick and concrete buildings. The results of a study in Tabriz showed that radon concentrations were 16, 29, and 70 Bq/m³ in concrete, brick, and clay buildings, respectively [16]. Furthermore, Duggal et al. performed a research in 2014 and reported that radon concentrations were higher in mud buildings than in concrete and cement buildings [44]. In a study in Shiraz [13], the highest concentrations were observed in the buildings that had used ceramic as the building material. The results of the study in Gorgan [31] also showed that radon concentrations were 34 and 56.76 Bq/m³ in ceramic and mosaic buildings, respectively. In the current study, a significant relationship was observed between radon concentration and the percentage of stone ($p = 0.026$) and ceramic ($p = 0.004$) used inside buildings. Consistently, the results of a study in Spain in 2007 [36] showed that the buildings that used stone as the main material had the highest radon concentrations.

The cracks in the walls and roofs of houses are one of the important ways for entrance of radon [16]. Radon gradually penetrates into the building through the building floor and walls cracks, connection of the walls to the floor, wells and drains, holes between the concrete blocks that are not filled, cracks that are intended for shrinkage and expansion, and holes around the sanitary services and inside the walls. This gas accumulates in the building depending on the flow, air pressure, and other structural conditions of the building [45]. The results of the present study indicated a correlation between the existence of cracks in the building and increased radon concentration. Accordingly, radon concentration was significantly higher in the buildings with cracks in their walls or roofs compared to the others.

The mean radon concentration was 32.68 and 23.47 Bq/m³ in the buildings with and without coloring, respectively. The results showed a significant relationship between use of color

on building walls and radon concentration ($p = 0.047$). However, Haddadi et al. conducted a study in Tabriz [16] and recommended that proper coloring and wallpaper reduced the residents' exposure. Thus, this issue is suggested to be assessed in further investigations.

The relationship between radon concentration and the amount of gas consumption was evaluated. The results revealed a significant correlation between radon concentration and the amount of urban gas consumption by residents. The results of a study conducted by Abdel-Ghany and Shabaan showed that radon concentration was significantly higher in dwellings supplied with natural gas consumption, where it was 252.30 versus 136.19 Bq/m³ in dwelling not supplied with natural gas ($P < 0.001$). Because natural gas is exclusively obtained from underground sources and found in deep underground natural formations or associated with other underground hydrocarbon reservoirs, it may hypothesize that it contains trace amounts of radon. These amounts may increase the levels of indoor radon [46].

Annual effective dose

The greatest human exposure to radon occurs in houses. Typically, radon enters the houses in a variety of ways, with soil, crustal soil, and stones in substructures being the main sources of radon generation and penetration. In fact, the first major source of radon is uranium followed by thorium in soil and stone [45]. It should be noted that radon does not cause any risks and dangers to human health in outdoor environments, but its high concentrations in houses and indoor environments can result in cancer and other problems due to excessive human exposure.

The annual effective dose was calculated based on average radon concentration in residential houses. The results

Table 3 Mean and standard deviation of radon concentration measured in mines and stone factories

Sampling location	<i>N</i>	Mean ± SD (Bq/m ³)	Recommended value by IAEA (Bq/m ³)	Recommended value by ICRP (Bq/m ³)	Recommender value by ICRP (max, Bq/m ³)
Mine	13	22.1 ± 10.4	1000	500	1500
Processing factory	7	22.4 ± 5.9	—	—	—

Fig. 2 The box plot of radon concentrations in residential areas, processing factories, and mines in Neyriz

indicated that the annual effective dose was 0.75 mSv/year for residents in Neyriz. The average annual effective doses were reported to be 2.45, 1.45, 0.97, 1.51, and 2.67 mSv/year in different studies in India [44], Shiraz [13], Tabriz [16], Saudi Arabia [9], and Kosovo [47], respectively. The recommended dose by ICRP is 3–10 mSv [13].

Investigation of radon concentration in mines and processing factories

In this study, all monitored mines and processing factories were marble stone mines and factories that had natural ventilation. The mean $\pm$ SD of radon concentrations in the studied mines and processing factories have been presented in Table 3. Radon concentration varied from 13.78 to 56.94 Bq/m³ and the mean $\pm$ SD concentration was 22.1 $\pm$ 10.4 Bq/m³ in the studied mines. The results of a study conducted by Hodolli et al. in Kosovo showed that radon

concentration ranged from 60 to 748 Bq/m³ in the mines despite the same geological layout. This could be due to the lack of proper ventilation in some mines [47]. The results obtained by Bekteshi et al. also indicated that radon concentration ranged from 54 to 691 Bq/m³ in Trepça underground mines [24]. The results of the study performed in lead and zinc mines of Yazd demonstrated that the average radon concentration was 0.0668 Bq/m³ at the workers' workplace, 219.29 Bq/m³ at the resort areas, and 19.75 Bq/m³ at the resting place and the environment outside the mines. Additionally, the measured concentrations were higher than the recommended maximum value in 25% of the cases [20]. However, the results of the current study showed that despite the large number of processing factories (162 units) and mines located near each other, radon concentration was less than the recommended values by ICRP [44] and IAEA [47]. This can be attributed to proper ventilation and suitable construction with large spaces for ventilation.

Fig. 3 Radon concentration zoning map in Neyriz in 2018

Comparison of the three study areas regarding radon concentration

The results of comparison of the three study areas (residential houses and areas, mines, and processing factories) regarding radon concentrations have been depicted in Fig. 2. Accordingly, there was no significant difference among the three studied areas concerning radon concentration. This may be due to this fact that the distance between Neyriz residential areas and processing factories is about five km and this small distance leads to similar concentrations in these areas.

Zoning of radon concentration in residential areas

The zoning and spatial distribution map of radon concentration in Neyriz in 2018 has been presented in Fig. 3. Accordingly, radon concentrations were lower than standard values in all residential areas. However, radon concentrations were higher in central and southern regions. This can be related to the small distance between these regions and processing factories.

Conclusion

The average concentrations of radon were 29.93 ± 12.63 , 22.18 ± 10.46 , and 22.39 ± 5.91 Bq/m³ in residential buildings, mines, and processing factories, respectively. The effective annual dose was 0.75 mSv/year, which was lower than the recommended value. The average radon concentration was also lower than the global average value. Moreover, radon concentration had a significant positive relationship with respiratory disease, pulmonary disease, smoking cigarettes, number of cigarettes, duration of smoking, building's age, number of floors, having cracks, use of colors in the building, use of ceramic for flooring (%), use of stone for flooring (%), and gas consumption in the building. Indeed, the number of cigarettes used by the residents had the greatest effect on radon concentration ($\beta = 0.769$). Furthermore, radon concentration was lower than the recommended value in all sampling mines and factories despite the large number of processing factories and mines located near each other. One of limitations of this study was that we could not measure radon in all mines due to the financial constraints. Besides the measurement of were not done in the villages around the mines and factories. Risk assessment and impact assessment on residents were not considered. All in all it is necessary to conduct further studies in the field of regional geology and determine the sources that release radon in these areas to prevent further increases in radon concentration due to the proximity and plurality of mines and factories.

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Compliance with ethical standards

Conflict of interest None declared.

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