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Assessment of carcinogenic risk from indoor radon exposure influenced by geological structures in the mountains of southern Caspian Sea

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Indoor radon exposure is the main form of radon exposure that causes health consequences including lung cancer. The aim of this study was to investigate indoor radon concentration affected by different geological characteristics in a mountainous area. For this purpose, three areas close to each other in the mountains of northern Iran, which were different in terms of the presence of hot springs, were studied. Sampling and analysis of indoor radon concentration was done in twelve buildings in summer and winter. The results showed that the average concentration of radon in the studied buildings was 124.5 Bq m^{-3}, which was higher than the reference dose suggested by World Health Organization (WHO) (100 Bq m^{-3}) and lower than reference dose suggested by U.S. Environmental Protection Agency (EPA) (150 Bq m^{-3}). The average indoor radon concentration in areas with many hot springs, few hot springs, and no hot springs were 144.9 Bq m^{-3}, 130.45 Bq m^{-3}, and 98.06 Bq m^{-3}, respectively. The average Excess Lifetime Cancer Risk in the studied area was 9.700E−03, but Excess Lifetime Cancer Risk was 16.4% and 4.7% higher than the average in the areas that had many hot springs and few hot springs, respectively. High indoor radon concentration in hot spring areas and the carcinogenic risk caused by exposure to it should be controlled by concentration reduction techniques such as vent pipes and adequate ventilation, regular monitoring, and radon-resistant materials.

Keywords Indoor environment, Air pollution, Lung cancer, Health risk

As a result of urbanization, we are often in the indoor environment, which is estimated up to 90%[1,2]. In this situation, indoor air quality is known as an important factor in the health and well-being of citizens[3,4]. Indoor air quality is affected by indoor pollutant emission sources such as cooking, as well as pollutant infiltration from outdoor air[5]. Various pollutants including biological such as fungi and bacteria, particulate matter, and gases are important in indoor air quality[2,6]. These pollutants can be effective in the occurrence of Sick Building Syndrome (SBS) and have a negative impact on the health of residents[7]. As a result of these factors, morbidity and mortality caused by indoor air pollutants is a common phenomenon, so that three million premature deaths per year due to indoor air pollution reported in previous studies[8]. Radon is one of the most important indoor air pollutants, which is a serious health concern[9].

Radon is a carcinogenic gas that contributes the most to natural radioactive exposure. Radon is a colorless gas that has a high solubility in water[10,11]. Radon is the result of the natural decomposition of radium and uranium, which is naturally present in the structure of the earth, including soil and rocks[12]. Although several sources, including some industries, natural gas, oil, and coal, can emit radon, however, the majority of radon emissions are caused by natural sources[13]. Radioactive radon (Ra 222) is the result of uranium 238, uranium 235, and thorium 232 decay[14]. The most exposure to radon is caused by indoor radon, which includes more than 95% of all exposure to radon[15]. This exposure is one of the main threats caused by indoor air pollution because after cigarette smoke, indoor radon is the main cause of lung cancer in the world[13]. In addition, radon has a significant

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proportion in the total natural radioactive exposure. According to previous reports, the effective dose associated with exposure to natural radioactivity is 2.4 mSv/y, 52% of which is due to exposure to radon[14]. Some activities, such as mining, can contribute to increased radon emissions, as evidence has been reported of increased leakage of other pollutants, such as heavy metals, from mining into groundwater[16].

According to the definition provided by the WHO "Cancer is a large group of diseases that can start in almost any organ or tissue of the body when abnormal cells grow uncontrollably, go beyond their usual boundaries to invade adjoining parts of the body and/or spread to other organs". Also, this organization has reported that cancer is the second cause of death in the world, that one out of every six deaths is caused by various types of cancer. Lung, prostate, colorectal, stomach, and liver cancer are the most common cancers in men, while breast, colorectal, lung, cervical and thyroid cancer are the most common cancers in women (https://www.who.int/health-topics/cancer#tab=tab_1). Therefore, considering that radon is a known carcinogen and has an important effect on the occurrence of lung cancer[17,18], managing exposure to it is important. The WHO has proposed 100 Bq/m^3 as the reference level of radon in indoor air to reduce its health consequences[18], because exposure to radon increases the risk of lung cancer, one of the most common cancers in men and women[19].

Recent studies have well investigated the health consequences of indoor radon exposure, but assessing the impact of geographic characteristics on indoor radon concentrations, especially in Iran, is a research gap. Considering the effect of natural sources on indoor radon concentration[20], this study investigated the indoor radon concentration in residential buildings located in a mountainous area in Iran, in the Alborz Mountain ranges located in the southern Caspian Sea. The aim of this study was to investigate the effect of the geological conditions of this area on the indoor radon concentration and the carcinogenic risk of exposure to it. Therefore, the novelty of this study is the assessment of the carcinogenic risk of indoor radon exposure affected by different geographical characteristics.

Method

Study area and sampling

This study was conducted in Mazandaran province, Iran. Larijan region in Mazandaran province, located in the Alborz Mountain range in the south of the Caspian Sea, was the sampling site. As shown in Fig. 1, the residential buildings of Larijan were located in three separate areas and close to each other. 12 buildings were selected for sampling from each area. The reason for choosing this area was the presence of hot springs in two of the studied areas (A and B), which was a geological characteristic and the possibility of impact on natural radon emission. In each of the studied buildings, two locations were selected for sampling, which included the living room and the bedroom. Therefore, sampling in this study included 72 sampling points in 36 residential buildings. Due to the effect of heat on the radon concentration, sampling tools were installed at the highest distance from thermal devices and heating systems of buildings.

Indoor radon analysis

The sampling tool (Fig. 2), including the permeation chambers, was placed at a height of 1.5 m from the floor for one month. The permeation chambers consisted of a 250-cc cylindrical plastic container, a mesh door providing air flow into the chamber, and a filter for dust removal. The detector used in this chamber was polycarbonate. The

Fig. 1. Study area. This figure was created using the Google Earth/Pro version 7.3.4.8573 software (https://earth.google.com/).

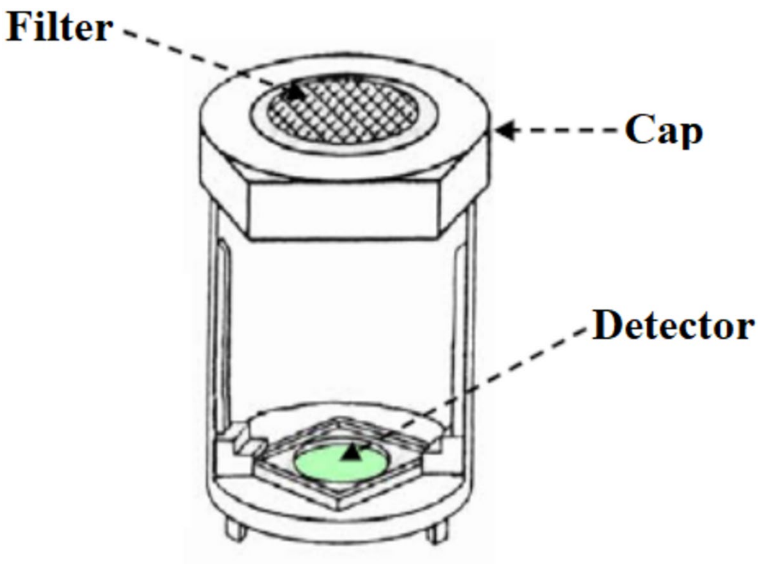

Fig. 2. Schematic of indoor radon sampler.

Parameter	Description	Unit
Aad	Annual absorbed dose	$mSv\ y^{-1}$
CR	Indoor radon concentration	$Bq\ m^{-3}$
DC	Dose conversion factor	9×10^{-6} mSv h^{-1}/Bq m^{-3}
OI	Indoor occupancy factor	0.4
EI	Indoor radon equilibrium factor	0.4
T	Hours in a year	8760 h/y
ELCR	Excess Lifetime Cancer Risk	–
DL	Mean duration of life	70 years
ER	Radon exposure	WLM/yr
FR	Risk coefficient for exposure to radon	5×10^{-4}

Table 1. Details of parameters used in risk assessment equations[13,18].

detector analysis was defined based on the investigation of the effect of physical destruction. The polycarbonate detector used in the sampler was transported to the laboratory and placed in a chemical solution containing 15% potassium hydroxide, 40% ethanol, and 45% water. This chemical solution led to the formation of traces in the detector, which were evaluated with an optical microscope. In this study, four detectors as the duplicate sample (10%) and four detectors as the blank sample (10%) of all the testing locations were used for quality assurance and quality control.

Risk assessment

Risk assessment due to indoor radon exposure in this study was defined based on Excess Lifetime Cancer Risk (ELCR)[13]. One of the effective factors in ELCR includes the radon exposure[18], which was considered as the annual radon effective dose. Therefore, the detected concentrations of indoor radon in 36 studied buildings were the basis of subsequent calculations according to following equations[13,18]. In addition to internal radon concentration, several variables were also effective in the calculations, which are explained in Table 1.

$$\mathrm{Aad} = \mathrm{CR} \times \mathrm{DC} \times \mathrm{OI} \times \mathrm{EI} \times \mathrm{T}\left(\mathrm{mSv} \cdot \mathrm{y}^{-1}\right) \tag{1}$$

$$\mathrm{ER} = \mathrm{OI} \times \mathrm{EI} \times \mathrm{CR} \times 2.7\mathrm{E} - 4 \times 51.53 \tag{2}$$

$$\mathrm{ELCR} = \mathrm{ER} \times \mathrm{DL} \times \mathrm{FR} \tag{3}$$

Results

The results of indoor radon concentration analysis in studied twenty buildings in summer and winter at two points including bedroom and living room are shown in Table 2. Indoor radon concentration in the studied buildings was in the range of 53.14–218.94 Bq m^{-3}. In summer, the highest concentration was 217.71 Bq m^{-3} and the lowest concentration was 53.14 Bq m^{-3}, while in winter, the highest concentration was 218.94 Bq m^{-3}

			Indoor radon concentration (Bq m^{-3})	
			Living room	Bed room
Aera A	Sp1[a]	Su[b]	194.83	126.20
		Wi[c]	132.84	120.54
	Sp2	Su	217.71	135.79
		Wi	114.4	97.17
	Sp3	Su	141.7	67.16
		Wi	–	–
	Sp4	Su	177.86	105.54
		Wi	167.28	218.94
	Sp5	Su	181.55	154.98
		Wi	–	–
Aera B	Sp6	Su	174.17	109.23
		Wi	90.41	85.49
	Sp7	Su	130.63	169.74
		Wi	–	–
	Sp8	Su	127.68	112.92
		Wi	91.64	72.57
	Sp9	Su	169.74	171.96
		Wi	–	–
	Sp10	Su	53.14	176.38
		Wi	142.7	88.56
Aera C	Sp11	Su	106.27	123.25
		Wi	110.7	85.49
	Sp12	Su	95.20	83.39
		Wi	106.4	73.8

Table 2. Indoor radon concentration in studied area. [a]Sample point, [b]Summer, [c]Winter.

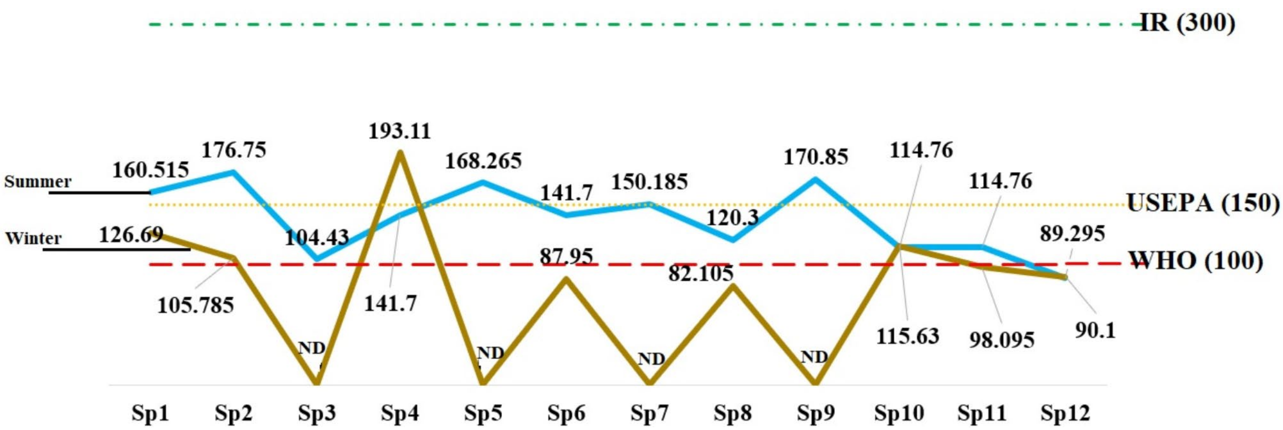

Fig. 3. Comparison of the detected indoor radon concentration with the suggested reference doses (Bq m^{-3}).

and the lowest concentration was 67.16 Bq m^{-3}. The average indoor radon concentration in the living room and bed room in summer was 152.3 Bq m^{-3} and 132.1 Bq m^{-3}, respectively, while in winter it was 119.54 and 105.32, respectively. The results showed that the average indoor radon concentration in the studied buildings was 124.5 Bq m^{-3}, while the concentration range was 89.69–170.85 Bq m^{-3}.

The comparison of detected indoor radon concentration in the studied points with the reference dose suggested by the World Health Organization (WHO), the Environmental Protection Agency (USEPA), and the national standard of Iran (IR) is shown in Fig. 3. None of the detected indoor radon concentrations were higher than the reference dose suggested by IR (300 Bq m^{-3}), while 25% of the detected indoor radon concentrations in the bedroom and 29.16% of the detected indoor radon concentrations in the living room were higher than the reference dose suggested by USEPA (150 Bq m^{-3}). Considering that the lowest reference dose is proposed by WHO (100 Bq m^{-3}), 60% and 66.6% of the detected indoor radon concentrations in the bedroom and living room were higher than this reference dose, respectively. In this situation, the definition of intervention plans

	CR	Aad	ER	ELCR	ELCR (%)
Sp1	143.6025	1.811E+00	3.197E−01	1.119E−02	1.119
Sp2	141.2675	1.782E+00	3.145E−01	1.101E−02	1.101
Sp3	104.43	1.317E+00	2.325E−01	8.136E−03	0.814
Sp4	167.405	2.112E+00	3.727E−01	1.304E−02	1.304
Sp5	168.265	2.123E+00	3.746E−01	1.311E−02	1.311
Sp6	114.825	1.448E+00	2.556E−01	8.946E−03	0.895
Sp7	150.185	1.894E+00	3.343E−01	1.170E−02	1.170
Sp8	101.2025	1.277E+00	2.253E−01	7.885E−03	0.789
Sp9	170.85	2.155E+00	3.803E−01	1.331E−02	1.331
Sp10	115.195	1.453E+00	2.564E−01	8.975E−03	0.898
Sp11	106.427	1.343E+00	2.369E−01	8.292E−03	0.829
Sp12	89.6975	1.131E+00	1.997E−01	6.989E−03	0.699
Area A	144.9	1.828E+00	3.226E−01	1.129E−02	1.129
Area B	130.45	1.646E+00	2.904E−01	1.016E−02	1.016
Area C	98.06	1.237E+00	2.183E−01	7.640E−03	0.764
Larijan area	124.5	1.570E+00	2.771E−01	9.700E−03	0.970

Table 3. Details of calculated risk in studied area.

Studied area		Location in Iran	Concentration	References
Tehran		North	54.11	[34]
Yazd		Center	66.77	[35]
Nourabad		South	42.4	[36]
Shabestar		Northwest	56.19	[37]
Isfahan		Center	28.57	[38]
Tarom		North	130.57	[39]
Minab		South	25	[40]
Hamedan		West	108	[41]
Gonabad		East	84	[42]
Larijan area	A	North	144.9	This study
	B	North	130.45	
	C	North	98.06	

Table 4. Comparison of indoor radon concentration in this study with some previous studies in Iran.

will be different based on each of the mentioned reference doses. Therefore, a solution to better interpret the situation and consequence of detected radon concentrations in the studied area is to assess the health risk caused by exposure to indoor radon.

The results of carcinogenic risk assessment due to indoor radon exposure in the three studied areas are shown in Table 3. The calculated ELCR in A and B areas were 47.77% and 32.98% higher than the calculated ELCR in C area, respectively. Also, the correlation between the number of spa springs and indoor radon concentration has been observed. The results showed that the average annual radon effective dose in areas A, B, and C was 1.82 mSv y^{-1}, 1.64 mSv y^{-1}, and 1.23 mSv y^{-1}, respectively. Therefore, the annual radon effective dose was 47.96% higher in the area A that had the highest number of spa springs compared to the area C had the lowest number of spa springs. The results showed that the number of excess lung cancers was equal to 11.29/10,000 people in the area A due to exposure to an average indoor radon concentration by 144.9 Bq m^{-3}. While in the area B, the average indoor radon concentration was 130.45 Bq m^{-3} and the excess lung cancer related to its exposure was 10.16/10,000 people. In these conditions, the lowest average indoor radon concentration was observed in the area C (98.06 Bq m^{-3}), which the excess lung cancer related to its exposure was estimated at 9.7/10,000 people.

Discussion

The results showed that the indoor radon concentration was very high in the sampling points and on average in the studied area. Comparing these results with previous studies in Iran and other countries showed high indoor radon concentration in Larijan area. In other cities of Iran, very different indoor radon concentrations have been reported, ranging from less than 40 Bq m^{-3} to more than 250 Bq m^{-3}[13]. For example, the highest indoor radon concentration was reported as 3235 Bq m^{-3} in one of the northern cities of Iran, while the lowest reported indoor radon concentration was 11 Bq m^{-3} in Tehran[21]. The comparison of indoor radon concentration in this study with some previous studies in Iran is shown in Table 4. In the compared studies, the indoor radon concentration was in the range of 25–130.57 Bq m^{-3}[13,22]. Although the detected concentrations in this study were higher compared to many other studies in Iran, however, very high indoor radon concentrations in some Iranian cities have caused the results of this study to be in the average range reported for Iran[13]. But the observed concentration in the studied areas was significantly higher than the average indoor radon concentration in the neighboring countries. As shown in Fig. 4, the average indoor radon concentration in studies of neighboring countries including Pakistan, Jordan, Iraq was close to the observed concentrations in our work, but reported concentration in Saudi Arabia, Oman, Lebanon, and Syria was much lower than the concentrations observed in our work[23–29]. Therefore, the indoor radon concentration is affected by factors that can be considered in the difference in reported concentrations in different studies[30,31]. The most important factors affecting indoor radon concentration can be classified into geological factors and building quality[32]. Factors such as meteorological parameters, geology, and soil are classified in the first group, and the type of floor, building material, ventilation quality, and the type of building (villa or apartment) are classified in the second group[13,33].

As shown in Fig. 3, indoor radon concentration was higher in summer than in winter. One of the reasons that can affect this difference is the accumulation of radon due to the reduction of outdoor air penetration[13]. Although in some other studies, indoor radon concentration was higher in winter, in others it was reported that the concentration was higher in summer[35,43], however, in both cases, the efforts of residents to reduce the penetration of outdoor air for prevent the penetration of cold air in the winter or saving the energy of the air conditioner system in the summer by keeping the windows closed, is reported as reason for seasonal indoor radon concentration[13]. In addition, the type of building and the distance from the surface are also effective in the indoor radon concentration[44]. According to the report of previous studies, the concentration of radon in villa buildings is higher than in apartments, as the distance from the surface increases, the concentration of indoor radon will decrease[45]. This condition can be caused by the higher density of radon compared to air, which leads to higher radon concentration near the surface[10]. In this study, most of the studied buildings were of the villa type, where the rooms were on the ground floor. Therefore, one of the reasons for the higher observed concentration in this study compared to other reports in Iran and neighboring countries could be this feature. Also, the location of sampling can be effective in the detected concentration of indoor radon, so that in the bedroom, due to the smaller size of the room and weaker ventilation, higher concentrations may be observed[13]. However, in our work, there was no significant difference in the concentration of indoor radon in the living room and bedroom. The average indoor radon concentration in the living room and bedroom was 136.3 Bq m^{-3} and 118.9 Bq m^{-3}, respectively, and their difference was less than 13%.

Exposure to high indoor radon concentrations in the studied areas is a serious concern for residents[46,47]. Considering that the average concentration was higher than the reference level suggested by WHO and USEPA, the carcinogenic risk of exposure to indoor radon is important[48]. According to previous reports, the average Aad in Iran is 0.5 mSv y^{-1}[13], while the average calculated Aad in this study was 1.65 mSv y^{-1}, which was 3.3 times more than the average of the country. The range of calculated Aad in this study was 1.13 mSv y^{-1} to 2.12 mSv y^{-1}, which showed that the annual absorbed dose was higher than the country's average even in minimal exposure. In this situation, the possibility of lung cancer due to exposure to a higher concentration of indoor radon increases. Yousefian et al. 2024, ranked different provinces of Iran were in terms of death due to lung cancer[13]. This ranking showed that Mazandaran province have a death rate equal to 8.73/10,000 people. As compared in Fig. 5, in our study, the average estimated risk for the studied area was 11% higher than this value. While the region A and

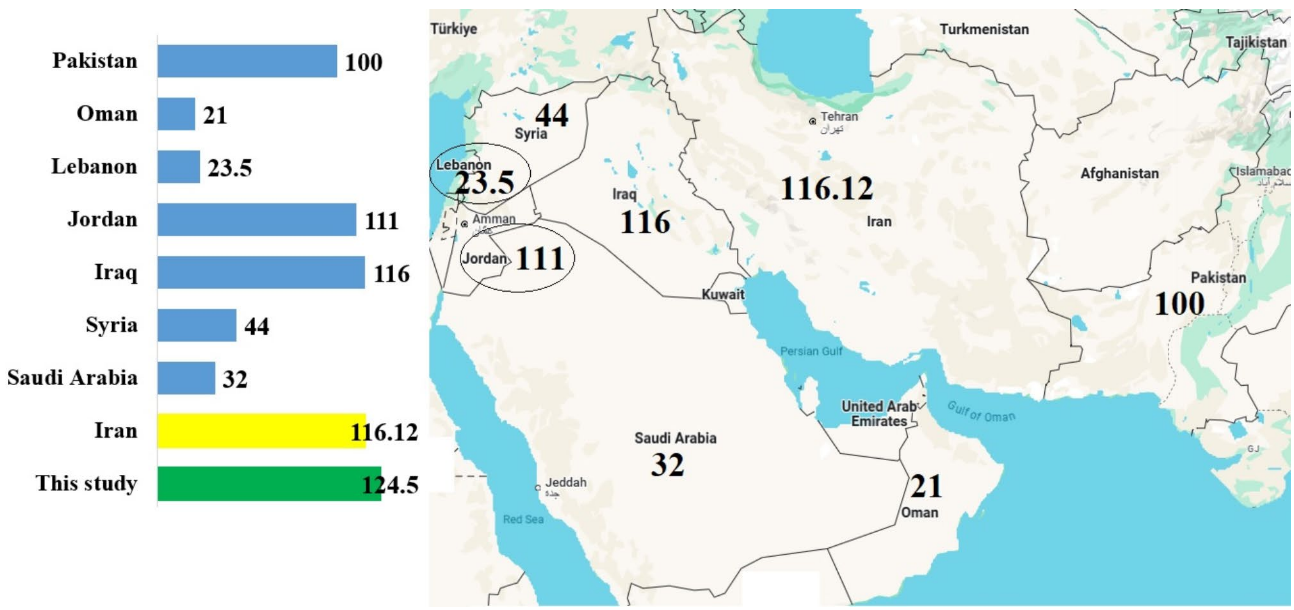

Fig. 4. Comparison of average indoor radon concentration in this study with reported in neighboring countries.

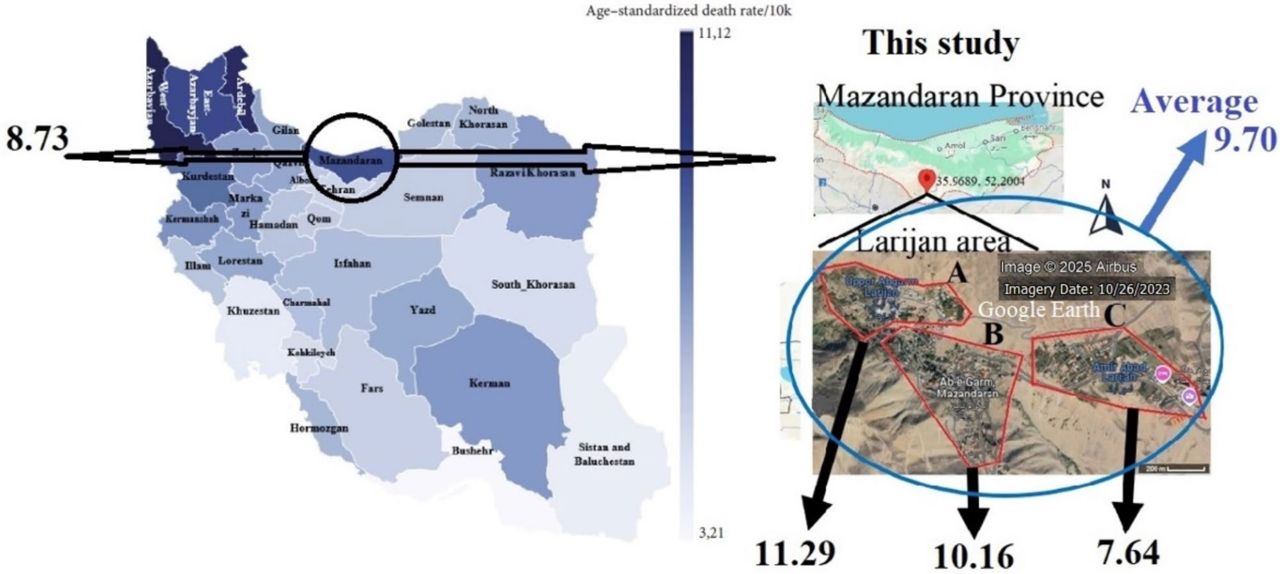

Fig. 5. Comparison of calculated ELCR in this study with age-standardized lung cancer death rate per 10,000 population in the 31 provinces of Iran due to residential radon exposure (adapted from[13]). This figure was created using the Google Earth/Pro version 7.3.4.8573 software (https://earth.google.com/).

region B had cancer risk more than the value reported in the study of Yousefian et al. 2024, by 29.3% and 16.4%, respectively[13].

As it can be compared in Fig. 4, the carcinogenic risk caused by indoor radon exposure is higher in area A and area B. Considering the insignificant change of other factors affecting indoor radon concentration in the three studied areas, the only effective factor in the significant difference in indoor radon concentration and the risk caused by it is the geological features. The presence of spa springs in areas A and B was important geological features in Larijan. However, more springs were observed in area A than in area B. Therefore, the presence of spa springs in the area increased the concentration of indoor radon, so that with the increase in the number of these springs, the concentration of radon also increased. Therefore, it is necessary to considering the conditions of the building and the solutions to reduce the concentration of indoor radon to reduce the risk of exposure to it in the studied areas, especially the parts that are located near the spa springs. This study had limitations and strengths. Although assessing changes in the carcinogenic risk of indoor radon exposure due to geographic characteristics was a strength, the lack of study of the effect of material type and changing the type of building floor on reducing carcinogenic risk was a limitation that could be considered in future studies.

Conclusion

The indoor radon concentration in a mountainous area that have numerous hot springs in the north of Iran and the health risk associated with its exposure were studied. The results showed that the average indoor radon concentration in the studied area was higher than the average reported in the country. The average indoor radon concentration in the area with many spa springs, few spa springs, and no spa springs was 144.9, 130.45, and 98.09 Bq m^{-3}, respectively. The calculated Excess Lifetime Cancer Risk in these areas was 1.129E−02, 1.016E−02, and 7.640E−03, respectively, which was 29%, 16%, and 11% higher than the average reported for the studied province. Exposure to indoor radon concentration in the studied areas due to higher radon emission and also features such as the type of building (villa) in the studied area was higher than the reference dose suggested by WHO and USEPA. In this situation, it is necessary to increase public awareness and consider equipment such as a vent pipe to reduce indoor radon concentration and its health consequences including lung cancer. Local decision makers, public health agencies, and residents of these areas should plan to reduce radon exposure based on factors affecting indoor radon concentrations. Based on this, the following solutions are suggested:

- Using radon-resistant materials to reduce the radon penetration into the indoor environment.
- Appropriate ventilation to prevent the accumulation of radon and increase its concentration in the indoor environment.
- Creating a distance from the surface in the building by constructing multi-story buildings instead of single-story buildings.
- Regular measurement of indoor radon concentration.
- The use of vent pipes in buildings with a high concentration of radon inside.
- Increasing public awareness and educating strategies to reduce indoor radon concentration.

Data availability

The datasets generated and analyzed during the current study were available from the corresponding author on reasonable request.

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Somayeh Dadashpoor: Conceptualization, Methodology, Investigation, Formal analysis, Writing–original draft. Parvin Nassiri, Nabiollah Mansouri, Zahra Azizi: Methodology, Writing–review & editing. Alireza Mirzahosseini: Methodology, Writing–review & editing, Supervision.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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