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Measurement of indoor radon concentrations and doses assessment in the area of Tuzla Canton, Bosnia and Herzegovina

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Abstract
This paper presents the results of an indoor radon concentrations measured at the 15 locations in the area of Tuzla Canton, Bosnia and Herzegovina. Measurements were performed by using the AlphaE device in a continuous period of four to seven days at investigated locations. The results of measurements have shown that the mean values of radon activity concentrations were in the range from 18.38 ± 12.72 to 145.31 ± 52.74 Bq m^{-3}. One of the aims of this study was to assess the health hazard from indoor radon inhalation and therefore the annual effective dose and effective dose equivalent for different age groups were evaluated. The excess lifetime cancer risk was also estimated.

Keywords Radon · Radon activity concentration · Annual effective dose · Excess lifetime cancer risk

Introduction

The main exposure to radon originates from a radon gas inhalation in an indoor space. Therefore, an elevated radon activity concentration in an indoor space, where humans ordinarily habitat, may have a negative effect on their health. The half-life of radon is 3.825 days and the mean lifetime is 5.51 days. Radon is a noble and chemically inert gas with low reactivity. Radon is colorless, odorless and tasteless and generated in soil and rocks by radioactive decay of radium. Radioactive gas radon is formed during the decay of natural uranium in the soil and that seeps into homes [1, 2].

Natural radioactive sources are responsible for providing an annual average effective radiation dose in amount of 2.4 mSv, of which at least half is resulting from the inhalation of radon, thoron and its decays products and the other half originates from cosmic radiation, cosmogenic radionuclides and earth's gamma radiation [3]. Materials that containing uranium are sources of radon, considering that radon is formed by decay of radium, which is also product of uranium. Rocks that are releasing the highest concentrations of radon are granite and volcano rocks, but also an aluminum shale. Radioactive gas radon progress towards the earth's surface through the crust's cracks and mixes with an air in atmosphere. In a case of a permeable soil, such as sandstone, a radon gas formed in the rocks below easily penetrates the earth's surface. Moist clay or other kinds of impermeable soils are media which, more or less, prevent radon to move through the soil and to progress towards the earth's surface [2, 4, 5].

Daily radon activity concentration variations are in correlation with atmospheric changes. Maximum radon concentrations are mostly present around midnight and during early morning hours due to temperature inversion that prevents vertical airflow what creates an extremely stable atmosphere. Gradual soil heating starts early in the morning and it helps in raising the air off the soil surfaces, which reduce radon concentrations. The atmosphere becomes more stable late afternoon, which gradually raises radon concentrations. Depending on the meteorological conditions present, the temperature difference between outdoor and indoor air creates a pressure difference between the soil and the building foundation. Such difference increase radon enriched air flow from soil to higher parts of the building. The gradient of pressure moves the air and radon with it through the constructing materials due to the lower pressure constantly present in an enclosed spaces, so it could be stated that radon enters from soil into enclosed spaces by an advection process. Radon enters more intensively into the building if the pressure inside is lower than the outside

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one. Radon concentrations stabilizes or even decrease as soon as the pressure inside is the same or higher than the outside one. Besides that, radon from soil may enter into the building through different cracks on the construction itself [6]. Soil plays a dominant role in the radon concentration in an enclosed space to the second floor of building. Soil and rocks below or in the vicinity of the building are main source of radon inside. Also construction materials used to build floors and walls have a major impact on the radon concentration on upper floors. Seasonally, radon concentration peaks are during autumn and winter months, and radon level drops to minimum during spring months. During winter, the inside air is usually warmer than the outside air. Such difference in temperatures creates vacuum inside that pulls air from soil. However, radon concentration levels sometimes may increase even during warmer months. Besides meteorological, other important factors that may have a major impact on the radon activity concentration in enclosed spaces are quality of the building construction and ventilation of the space. Other factors are an actual way of individual's life, method of heating and smoking. Most of radon present in the building comes directly from soil, so its higher values are expected to be found in the basement and on the ground floor [1, 7, 8].

EU directive dated in 2013 (2013/59/Euratom) outlines the necessity to monitor radon activity concentration indoor, especially at homes and workplaces. The reference level for the annual average radon activity concentration indoor may not be higher than 300 Bqm^{-3} in every EU member state, except under specific circumstances [9].The main objective of this study was to measure the radon activity concentration in indoor air and based on that to assess the annual effective dose and effective dose equivalent for different age groups as well as the excess lifetime cancer risk.

Materials and methods

Study area

The indoor radon activity concentrations were measured at fifteen locations in Banovići and Živinice, in the area of Tuzla Canton, Bosnia and Herzegovina, as shown in Fig. 1. Those cities were selected because there were no data about radon levels as well as radon associated health risk for humans in these areas.

Municipality of Banovići is located at the north-eastern slopes of Konjuh Mountain, in depression south of Spreča River valley, being part of the south–southeaster Spreča river basin [10]. Continental and mild continental climate type is responsible for the warm summers with rain showers and harsh windy winters with lesser amount of snow falls in Banovići. Rain mostly falls during spring and autumn and air is rather humid. The oldest rocks are serpentine and their form a base for all other rocks. A lot wider prevalence belongs to marl clay and gravel types of rocks. The humus and loam covers a thin layer up to 1 m, which covers serpentine, but also marl and gravel rocks [11]. City of Živinice is located in the upper course of the Spreča river valley, bounded by the hilly and mountain areas of Konjuh, Majevica and Ozren Mountains. Territorially is located in the southeastern part of Tuzla Canton [10]. Mild continental climate is responsible for mildly cold winters and rather warm summers at Živinice. Maximum air humidity appears during winter period, with the peak during December. The lowest air humidity is registered during summer months, particularly during June and July. The northern part of Živinice is mostly flatland, and south and southwestern parts are mostly hilly mountainous areas, where automorphic soils prevail [12, 13].

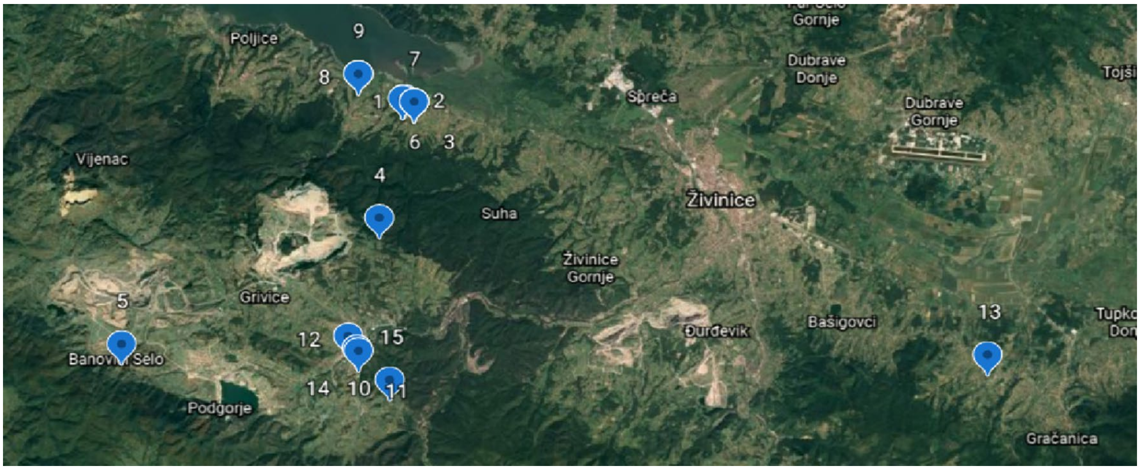

Fig. 1 Map of the investigated locations in Banovići and Živinice

Experimental setup and procedure

AlphaE radon meter (Saphymo GmbH, Germany) is an electronic handheld device for stationary short and long-term monitoring of radon in buildings, outdoors and in mines (Fig. 2.). AlphaE is an active measurement device for detecting and recording the radon concentration, exposure and dose. The detector provides a wide measurement range up to 10 MBqm^{-3} and is sufficiently sensitive for reliable measurements also below 100 Bqm^{-3}. According to the technical data of instrument the measurement range is from 20 Bqm^{-3} to 10 MBqm^{-3}. Based on the diffusion principle with silicon detector the radon gas diffuses through the entry holes of the case into the inner of the diffusion chamber. A Gore-Tex membrane that covers the entry holes ensure that only the radon gas can enter the chamber while the radon decay products are retained by the filter. The measurement of radon performs independently from fluctuating external parameters like aerosol concentration and air humidity. AlphaE is able to deliver precise and reliable measurement results after only 2 h, faster response time with higher radon levels. Low radon levels below 100 Bqm^{-3} can be measured as specified by the latest World Health Organization (WHO) recommendations (12% uncertainty at 1 sigma/24 h). Instrument calibrator error is 10% [14, 15].

The display of the device shows the floating mean of the radon concentration in kBqm^{-3} with related statistical error in %. According to the internal evaluation interval the display is updated every 10 s. For the conducted measurements the storing cycle of measurement data was set to the interval of 10 min, and in accordance with that the read values from instruments by software are the mean radon concentrations for every 10 min cycle and its associated errors.

Fig. 2 AlphaE radon meter placed in investigation location

During this study the measurements at location sites were performed continuously in a period of four to seven days. AlphaE radon meter was mounted in rooms at ground floor of the houses at height between 50 and 100 cm above the floor at places with no direct airflow and sunlight. During the measurements the device was not moved. The Communication Software Module was used for readout and export data from device to DataVIEW software for further data analyses.

Considering the storing data interval of 10 min and duration of measurement for each investigated location about 700 measurements data were recorded. Therefore, for every location the mean value of radon activity concentration and corresponding standard deviation were calculated.

Estimation of the annual effective dose, effective dose equivalent and excess lifetime cancer risk

Based on the measured values of the radon activity concentration, the annual effective dose received from inhalation of radon was estimated. The annual effective dose was calculated on the basis of the following Eq. (1):

$$AED = C_{\mathrm{Rn}} \cdot F \cdot T \cdot O \cdot D_{CF} \qquad (1)$$

where AED is the annual effective dose originated from the inhalation of radon indoors (mSv), C_{Rn} is the indoor radon activity concentration (Bq m^{-3}), F is the factor of radon equilibrium (0.4 for indoor), T is average number of hours per year, O is the indoor occupancy factor, that is 0.8 for adults above 20 years old, 0.9 for adolescents from 12 to 19 years old, 0.94 for infants below 1 year and 0.89 for children from 1 to 11 years old and D_{CF} is the dose conversion factor for radon (9 nSv Bq^{-1} h^{-1} m^3). Annually, in an enclosed space, adult person usually spend around 7000 h, children around 7800 h, adolescents around 7880 h, while infants spend around 8230 h [3].

The effective dose equivalent was estimated on the basis of the following Eq. (2):

$$E = AED \cdot w_R \cdot w_T \qquad (2)$$

where AED is the annual effective dose (mSv) according to Eq. (1), w_{R} is the radiation weighting factor (for alpha particle taking a value of 20) and w_{T} is the tissue weighting factor (for lung tissue the value of 0.12 was taken) [16, 17].

The excess lifetime cancer risk (ELCR) is calculated using Eq. (3):

$$\mathrm{ELCR} = AED \cdot DL \cdot RF \qquad (3)$$

where *AED* is the annual effective dose (mSv) according to Eq. (1), *DL* is the average duration of life (estimated to be 70 years) and *RF* is the risk factor (0.055)[18, 19].

Discussion and results

The results of the indoor radon activity concentration measurements, at all locations, are presented in Table 1. The maximum, minimum and mean values of the radon activity concentration with the corresponding standard deviations, as well as median values are presented. The values of the meteorological parameters at investigated locations and specific characteristics of the measurement locations are presented in Table 2. The maximum values were in the range 55.10–359.00 Bqm^{-3}, with the mean value of 182.23 ± 107.56 Bqm^{-3}. Maximum values of radon activity concentrations of 359.00 Bqm^{-3}, 303.00 Bqm^{-3}, 347.00 Bqm^{-3} and 307.00 Bqm^{-3} were found on the locations 2, 4, 13 and 14, respectively. These values are above the reference level of 300 Bqm^{-3} recommended by EU (Directive 2013/59/EURATOM) [9]. The space where measurements on location 4 are taken is a workroom, with infrequent numbers of entry/exit the room, which also affected on elevated values of radon activity concentration. Daily radon activity concentration variations on location 13 were observed, with daily maximum reached after midnight and during early morning hours, while radon activity concentration dropped after dorm. Room ventilation in morning hours brought the significant reduction in radon activity concentration with minimum in amount of 3.00 Bqm^{-3} reached on day 4. Room ventilation was not performed on day 6 what caused the maximum radon activity concentration of 347.00 Bqm^{-3} after midnight and exceeds the recommended value of 300 Bqm^{-3} [9]. Maximum values of radon activity concentrations at measured locations are highest after midnight during peak accumulation of radon in an enclosed investigated location and when ventilation of spaces reduced to minimum, while a sudden drop of the radon activity concentrations appears during morning hours.

The mean values of indoor radon activity concentration were in the range between 18.38 and 145.31 Bqm^{-3}. The mean value of radon activity concentration on investigated area of Banovići and Živinice was 68.61 ± 43.48 Bqm^{-3}, to be more specific at the area of Banovići was 61.71 Bqm^{-3} while at the area of Živinice was a bit higher, 74.65 Bqm^{-3}. These values are comparable with the indoor radon activity concentration in Croatia [20]. Obtained results are slightly higher than the values of radon activity concentration in Germany and Montenegro [20]. The mean value of radon activity concentration on location 1 was 88.94 ± 27.37 Bqm^{-3}, which is comparable with radon activity concentration in the area of Austria [21]. The measurements on the location 1 were taken during winter when radon activity concentrations are higher than any other season due to temperature differences between indoor and outdoor space, but also due to lower air ventilation during winter. The mean value of indoor radon activity concentration on location 2 is within allowed recommended concentration limits of 300 Bqm^{-3} (Directive 2013/59/EURATOM) [9]. The mean values on locations 5, 7 and 10 are comparable with the value of indoor

Table 1 Values of the indoor radon activity concentration at investigated locations

Location	Investigation area	C_{min} (Bqm^{-3})	C_{max} (Bqm^{-3})	C_{mean} (Bqm^{-3})	MED (Bqm^{-3})
1	Živinice	38.90	172.00	88.94 ± 27.37	84.50
2	Živinice	45.80	359.00	145.31 ± 52.74	140.75
3	Živinice	0.20	55.10	18.92 ± 11.66	17.80
4	Banovići	32.40	303.00	130.12 ± 56.37	123.15
5	Banovići	1.20	86.80	31.20 ± 18.19	27.95
6	Živinice	19.90	191.50	94.40 ± 35.58	91.30
7	Živinice	13.80	268.00	101.71 ± 52.33	90.50
8	Živinice	1.50	75.50	27.21 ± 16.00	28.35
9	Živinice	3.20	106.50	32.25 ± 20.07	28.35
10	Banovići	14.70	175.00	71.86 ± 35.78	66.30
11	Banovići	4.10	103.80	34.19 ± 17.16	31.35
12	Banovići	3.70	112.50	30.85 ± 18.06	27.85
13	Živinice	3.00	347.00	88.43 ± 59.20	69.90
14	Banovići	24.70	307.00	115.39 ± 46.62	111.15
15	Banovići	0.20	70.80	18.38 ± 12.72	16.65
Mean value				68.61 ± 43.48	
Median value		4.10	172		

Table 2 The mean values of the meteorological parameters at investigated locations and the specific characteristics of the measurement locations

Location	t (°C)	p (hPa)	r (%)	Duration of the measurements (days)	Season	Specific characteristics of the measurement locations	Ventilation of rooms
1	23	995	60	4	Winter	House/without basement/ground floor/living room	Low
2	26	988	60	5	Winter	House/without basement/ground floor/bedroom	Low
3	24	985	60	5	Winter	House/without basement/ ground floor/living room	Very frequent
4	24	968	50	5	Winter	House/without basement/ ground floor/living room	Rather infrequent
5	23	977	63	5	Spring	House/without basement/ ground floor/living room	Good
6	23	985	71	5	Spring	House/without basement/ ground floor/workroom	Infrequent
7	26	995	61	4	Spring	House/without basement/ ground floor/living room	Low
8	22	990	68	5	Spring	House/without basement/ground floor/living room	Very good
9	23	991	63	5	Spring	House/without basement/ground floor/workroom	Good
10	26	971	75	6	Spring	Building apartment/with basement/ ground floor/living room	Low
11	25	974	63	5	Spring	Building apartment/with basement/ground floor/ bedroom	Very good
12	27	971	69	7	Summer	Apartment building/without basement /ground floor/living room	Very frequent
13	23	978	66	7	Spring	House/without basement/ ground floor/living room	Low
14	23	978	72	7	Spring	House/with basement/ ground floor/living room	Low
15	23	970	76	5	Spring	House/with basement/ ground floor/living room	Very good
Mean value	25.60	981.10	65.10				

radon activity concentration at the area of Montenegro, Serbia and Croatia, respectively [20]. The mean value of radon activity concentration measured at the location 12 was 30.85 ± 18.06 Bqm^{-3}. The main reason for somewhat lower radon activity concentration values at this location was frequent room ventilation, since the measurement was taken during summer period when rooms are frequently ventilated during the whole day. The mean value of radon activity concentration measured at the location 11 was 34.19 ± 17.16 Bqm^{-3} and that value is comparable to the mean value of radon activity concentration measured in the Montenegro [20]. The mean values indicated that the indoor radon levels on investigated locations were not high when compared to indoor radon activity concentration in Austria [21].

The lowest values of indoor radon concentration at all investigated locations were in the range 0.20–45.80 Bqm^{-3}, with the mean and median values of 13.82 Bqm^{-3} and 4.10 Bqm^{-3}, respectively. The highest minimum value of 45.80 Bqm^{-3} was measured on the location 2, while on the locations 3 and 15 were measured the lowest value of radon activity concentration of 0.20 Bqm^{-3}.

The lowest values occurred in the morning hours when warming cause air to start rising from the ground and when ventilation of rooms is more intense. Also, the specific meteorological parameters were continuously measured and monitored during the radon activity concentration measurement. The mean values of meteorological parameters were in the range 970–995 hPa for atmospheric pressure, for air temperature 22–27 °C and for air humidity 50–76%.

Comparison of radon activity concentration of the present study with the similar studies in the other countries is presented in the Table 3.

According to the obtained radon concentrations at investigated locations it can be concluded that the frequency of the room ventilation has effect on radon levels. At locations where more frequent ventilation was present in room during the measurement the radon levels were lower and vice versa as well.

By using Pearson's correlation coefficient calculation between the mean value of radon activity concentration and the mean value of meteorological parameters at the

Table 3 Comparison of radon activity concentration of the present study with the similar studies in the other countries

Country	C_{mean} (Bqm^{-3})	References
Germany	43	[20]
Montenegro	32	[20]
Slovakia	48	[20]
Italy	109	[20]
Serbia	105	[20]
North Macedonia	105	[20]
Austria	97	[21]
Bosnia and Herzegovina	68.61	Present study

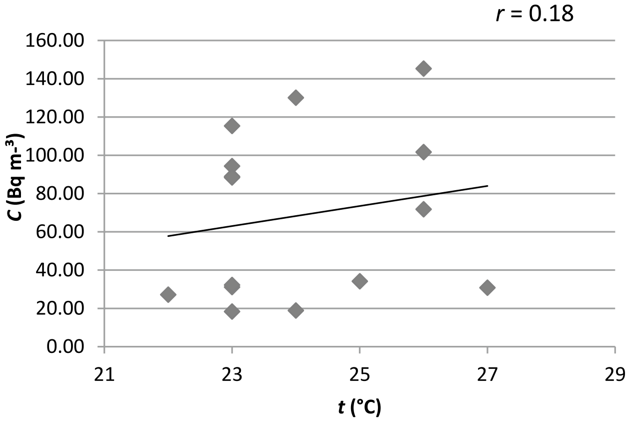

Fig. 3 Pearson's correlation coefficient between the mean value of radon activity concentration and temperature

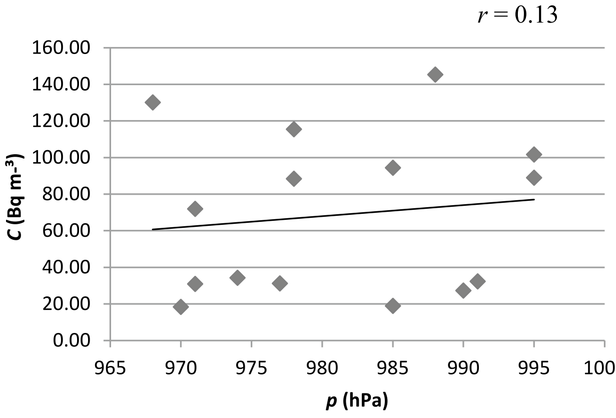

Fig. 4 Pearson's correlation coefficient between the mean value of radon activity concentration and air pressure

investigated locations, were obtained $r = 0.18$ for temperature and $r = 0.13$ for pressure (Figs. 3 and 4). After statistical correlation analyses, a weak negative correlation was observed between the radon activity concentration in indoor air values and air humidity (Pearson coefficient, $r = -0.33$, Fig. 5).

The results of the annual effective dose with the corresponding standard deviation for different age groups at investigated location are presented in Table 4. The results of the excess lifetime risk cancer and the dose equivalent are presented in Table 5. Also, the mean value of annual effective dose for an adult person at Banovići and Živinice is estimated to an amount of 1.73 ± 1.10 mSv. This value is a bit lower than the estimated mean annual effective dose value in the Europe of 1.96 mSv [22], but somewhat higher than the estimated mean annual effective dose worldwide value, of 1.15 mSv [3]. Infants, children and adolescents receive higher annual radiation dosages than adults due to longer inhabitation and exposure in enclosed spaces.

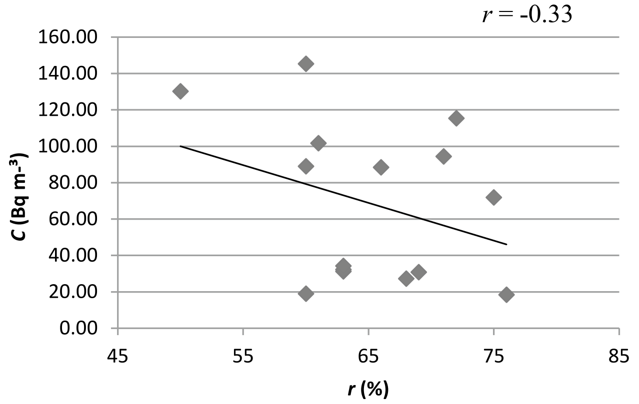

Fig. 5 Pearson's correlation coefficient between the mean value of radon activity concentration and air humidity

Table 4 Annual effective doses for differente age groups at investigated locations

Location	AED (mSv)			
	Infants (< 1 years)	Children (1–11 years)	Adolescents (12–19 years)	Adults (> 20 years)
1	2.64 ± 0.81	2.50 ± 0.77	2.52 ± 0.78	2.24 ± 0.69
2	4.31 ± 1.56	4.08 ± 1.48	4.12 ± 1.50	3.67 ± 1.33
3	0.56 ± 0.35	0.53 ± 0.33	0.54 ± 0.33	0.48 ± 0.29
4	3.86 ± 1.67	3.65 ± 1.58	3.69 ± 1.60	3.28 ± 1.42
5	0.92 ± 0.54	0.88 ± 0.51	0.89 ± 0.52	0.79 ± 0.46
6	2.8 ± 1.05	2.65 ± 1.00	2.68 ± 1.01	2.38 ± 0.90
7	3.02 ± 1.55	2.85 ± 1.47	2.89 ± 1.49	2.57 ± 1.32
8	0.81 ± 0.47	0.76 ± 0.45	0.77 ± 0.45	0.69 ± 0.40
9	0.96 ± 0.59	0.91 ± 0.56	0.92 ± 0.57	0.81 ± 0.51
10	2.13 ± 1.06	2.02 ± 1.00	2.04 ± 1.02	1.81 ± 0.90
11	1.01 ± 0.51	0.96 ± 0.48	0.97 ± 0.49	0.86 ± 0.43
12	0.91 ± 0.54	0.87 ± 0.51	0.88 ± 0.51	0.78 ± 0.46
13	2.62 ± 1.75	2.48 ± 1.66	2.51 ± 1.68	2.23 ± 1.49
14	3.42 ± 1.38	3.24 ± 1.31	3.28 ± 1.32	2.91 ± 1.18
15	0.54 ± 0.38	0.52 ± 0.36	0.52 ± 0.36	0.46 ± 0.32
Mean value	2.03 ± 1.29	1.93 ± 1.22	1.95 ± 1.23	1.73 ± 1.10

An estimated annual effective dose at the measuring locations for infants varies between 0.54 ± 0.06 mSv and 4.31 ± 0.47 mSv, with the mean value of 2.03 ± 1.29 mSv, for children is in the range 0.52–4.08 mSv, with the mean value of 1.93 ± 1.22 mSv, while for adolescents is in the range 0.52–4.12 mSv, with the mean value of 1.95 ± 1.23 mSv. The measurements were performed mostly in winter and spring period, thus it can be assumed that the estimated annual effective dose is slightly higher than it would be in case if the measurement period include also the summer and autumn period of the year. In the summer period the indoor radon levels are lower than in the winter [1].

Table 5 Values of the effective dose equivalent and excess life time cancer risk (ELCR)

Location	E (mSv)				ELCR ($\times 10^{-3}$)
	Infants (< 1 years)	Children (1–11 years)	Adolescents (12–19 years)	Adults (> 20 years)	
1	6.33 ± 1.95	5.99 ± 1.84	6.06 ± 1.86	5.39 ± 1.66	8.64 ± 2.66
2	10.34 ± 3.75	9.79 ± 3.55	9.90 ± 3.59	8.80 ± 3.19	14.11 ± 5.12
3	1.35 ± 0.83	1.27 ± 0.79	1.29 ± 0.79	1.15 ± 0.71	1.84 ± 1.13
4	9.26 ± 4.01	8.76 ± 3.80	8.86 ± 3.84	7.88 ± 3.41	12.64 ± 5.48
5	2.22 ± 1.29	2.10 ± 1.23	2.13 ± 1.24	1.89 ± 1.10	3.03 ± 1.77
6	6.72 ± 2.53	6.36 ± 2.40	6.43 ± 2.42	5.72 ± 2.15	9.17 ± 3.46
7	7.24 ± 3.72	6.85 ± 3.52	6.93 ± 3.56	6.16 ± 3.17	9.88 ± 5.08
8	1.94 ± 1.14	1.83 ± 1.08	1.85 ± 1.09	1.65 ± 0.97	2.64 ± 1.55
9	2.29 ± 1.43	2.17 ± 1.35	2.20 ± 1.37	1.95 ± 1.22	3.13 ± 1.95
10	5.11 ± 2.55	4.84 ± 2.41	4.89 ± 2.44	4.35 ± 2.17	6.98 ± 3.48
11	2.43 ± 1.22	2.30 ± 1.16	2.33 ± 1.17	2.07 ± 1.04	3.32 ± 1.67
12	2.19 ± 1.28	2.08 ± 1.22	2.10 ± 1.23	1.87 ± 1.09	3.00 ± 1.75
13	6.29 ± 4.21	5.96 ± 3.99	6.02 ± 4.03	5.35 ± 3.58	8.59 ± 5.75
14	8.21 ± 3.32	7.77 ± 3.14	7.86 ± 3.18	6.99 ± 2.82	11.21 ± 4.53
15	1.31 ± 0.90	1.24 ± 0.86	1.25 ± 0.87	1.11 ± 0.77	1.79 ± 1.24
Mean value	4.88 ± 3.09	4.62 ± 2.93	4.67 ± 2.96	4.15 ± 2.63	6.66 ± 4.22

The effective dose equivalent was in the range 1.31–10.34 mSv, 1.24–9.79 mSv and 1.25–9.90 mSv, 1.11–8.80 mSv for infants, children, adolescents and adults respectively. The values of excess lifetime risk cancer were in the range (1.79–14.11)$\times 10^{-3}$, with a mean value of (6.66 ± 4.22)$\times 10^{-3}$.

These values are still below the maximum risk of 10.3$\times 10^{-3}$ that yields from annual effective dose of 2.4 mSv [9]. The mean value of excess lifetime risk cancer is comparable with mean value on Neyriza and Shiraza in Iran in amount of 4.9 × 10^{-3} and 5.6 × 10^{-3}, respectively [19].

Conclusion

The results of these measurements indicate that the mean values of the indoor radon activity concentrations at the investigated locations are below the recommended concentration limits. These results do not exceed the value recommended by EU of 300 Bqm^{-3} (Directive 2013/59/ EURATOM) [9]. The radon activity concentration values in indoor air have weak negative correlation with air humidity at the investigated locations.

In this paper, the mean values of annual effective doses due to inhalation of radon and effective dose equivalent for different age groups at the investigated locations are presented. The mean value of excess lifetime risk cancer is higher than the recommended risk of 3.45 × 10^{-3}, but below of the maximum risk of 10.3 × 10^{-3} [9]. Indoor radon activity concentrations vary with the occupancy of the rooms and it is evident that the ventilation has significant effect on the reduction of concentration. The assessment results clearly indicate that reducing radon exposure in homes is the most important and most effective way for prevention of radon-induced health hazard effects.

Declarations

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

Data availability statement The authors declare that the data supporting the findings of this study are available within the paper. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request.

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