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Gamma radiation and indoor radon concentrations in the western and southwestern regions of Saudi Arabia

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Abstract

The exposure of the population to natural gamma radiation in air and to indoor radon gas was investigated in Makkah, AlBaha, Assir, Jazan and Najran regions in the western and southwestern of Saudi Arabia. The survey was performed by using LiF:Mg,Cu,P thermoluminescence dosimeters (TLDs) for indoor and outdoor absorbed dose rates in air measurements in 885 locations, and a passive integrating ionizing system, equipped with an E-Perm Electret ion chamber, for radon concentration measurements in a total of 1119 dwellings. The ambient indoor rates vary from 54 to 191 nSv h^{-1}, while it is in the range of $42-112$ nSv h^{-1} for the outdoor. The indoor and outdoor rates of the directional dose equivalent ranged from 56 to 185 nSv h^{-1} and from 43 to 135 nSv h^{-1}, respectively. Makkah region showed the highest mean indoor ambient and directional rates, whereas Assir region showed the highest mean outdoor rates. The indoor and outdoor gamma dose rates were significantly correlated. On the other hand, the indoor radon concentrations ranged from 11 to 137 Bq m^{-3} with an overall mean of 32 Bq m^{-3} for all investigated houses. The overall annual

mean effective dose rate from radon and its decay progenies was estimated to be 0.76 mSv y^{-1}, which yields an excess lifetime cancer risk of around 2.3×10^{-3}.

Keywords: Ecology, Environmental science

1. Introduction

Human beings expose to ionizing radiation from several sources such as cosmic rays, terrestrial radionuclides and radon gas and its daughters. Besides, man-made sources such as medical and industrial exposures, and global fallout releases from nuclear weapon tests, accidents and puffs may also contribute to the human exposure. Among the natural sources, radon and terrestrial radiations are unavoidable as they can be considered the major contribution to the total daily effective dose of ionizing radiation to which human is exposed. In general, more than 60% of the natural radiation background comes from these two sources (UNSCEAR, 2000). The most significant terrestrial radiation originates from uranium and thorium decay series and potassium (^{40}K) radionuclide, which are nearly ubiquitously present in the earth's crust with different activities depending on the type and composition of the soil and rocks (UNSCEAR, 2000). The soil and rocks rich with ^{238}U lead to high release of radon gas, which is considered the largest source of internal exposure. Radon and its daughters have been confirmed through epidemiologic studies to be human carcinogen (UNSCEAR, 2000) and constitute the strongest source of airborne radioactivity because it can rise from the soil under houses and build up inside. By the same reasons, it was classified as a Group 1 carcinogen according to the classification used by the International Agency of Research in Cancer (IARC) and the World Health Organization (WHO/IARC, 1998) and by the Environmental Protection Agency (EPA, 1987), respectively.

The last few decades have witnessed a considerable interest in environmental radioactivity measurements in many countries, including Saudi Arabia. A number of studies have been conducted on natural radioactivity in various environmental components of Saudi Arabia. The internal and external doses from natural sources as well as indoor radon surveys have been the subject for some of these studies (Al-Saleh, 2007; Al-Ghorabie, 2005; Al-Jarallah et al., 2003). However, data on indoor radon and natural exposure to the population of various regions of Saudi Arabia are still very limited.

A national research project was launched in 2012 in order to build the national environmental radiation database in Saudi Arabia (Aleissa and Enany, 2012; Alghamdi and Aleissa, 2014). Within that project, Aleissa and Enany (2012) measured the environmental radiation doses due to natural sources in 31 sites in Riyadh region

by using 450 LiF:Mg,Cu,P (TLD-100H) dosemeters. The average ambient and directional dose equivalent were found to be 81 and 89 nSv h^{-1} for the indoor rates and 71 and 76 nSv h^{-1} for the outdoor rates, respectively. In the same project, Alghamdi and Aleissa (2014) have measured the indoor radon levels in 786 dwellings of the same region and found concentrations up to 195 Bq m^{-3} with a mean value of about 25 Bqm^{-3}. As part of this ongoing research project and a supplement of the previous works, the current study was conducted with the aim to investigate the distribution of indoor radon concentrations and exposure from natural radiation in the western and southwestern part of Saudi Arabia, namely, Makkah, AlBaha, Assir, Jazan and Najran regions.

The importance of the study areas arises from the fact that these regions of Saudi Arabia have no reference data to show the natural background or exposure dose. Therefore, this study comes in compliance with the importance of the surveillance of environmental radioactivity and in order to obtain a national baseline of the natural background radiation to estimate the total effective dose received by the population as well as a reference data in case of nuclear accident. Moreover, the inhabitants of the regions of study are around 12 millions, which represent about 40% of the total population of the kingdom. Therefore, knowing the radon concentrations and exposure rates in the surveyed regions is important from the point of view of protection against natural radiation. Such studies are also essential for providing baseline data that can be used to detect possible future changes. It is thus useful to evaluate if radon concentration levels and natural exposure rates in comparison with international recommended limits so as to check whether intervention actions must apply or not. Hopefully our findings will form a reference database in documenting potential changes to environmental radioactivity of this vital and populated regions of the country in future.

2. Study area

The western and southwestern parts of Saudi Arabia lie between latitudes (23°50′−16°10′) north and between longitude (41°10′−43°10′) east. Generally, Saudi Arabia is situated in a desert climatic region of the Arabian Peninsula, which characterized by extreme variations in temperature between day and night and between north and south. A map showing the five studied regions is presented in Fig. 1. Geologically, these regions are located within the Arabian Shield terrains comprising the Precambrian continental crust, which consists of a crystalline basement complex overlain by laterally extensive Cenozoic rocks. Specifically, the geological aspects of the five investigated regions can be summarized as follows:

Makkah region, the most populous province of western Saudi Arabia, is located in the northern part of the study area and extended from the western coastline of Saudi
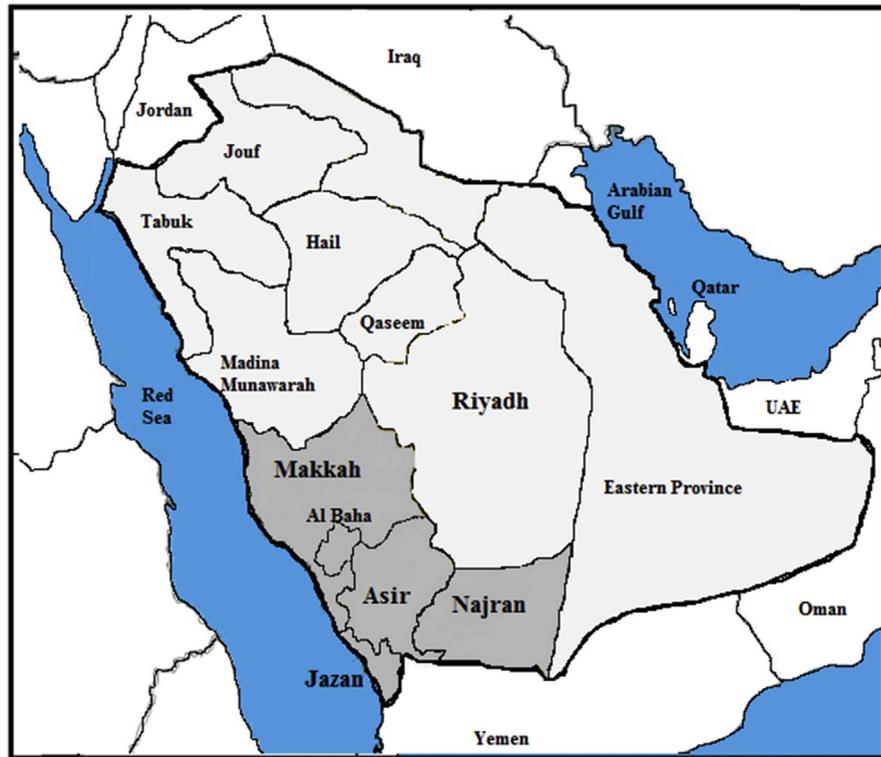
Fig. 1. Map of Saudi Arabia showing the five western and southwestern regions.

Arabia to about 500 km towards the east coastline with an area of 164,000 km^2 and altitudes varies from 250 to 560 m a.s.l. Its capital is the sacred city of Makkah and its largest city is Jeddah, which is also Saudi Arabia's main port city. The bedrock is mostly of igneous rocks composed of diorite and tonalite with some formations of sedimentary and metamorphic rocks (Moore and Al-Rehaili, 1989).

AlBaha region is located on the south of Makkah region along the Red Sea coast with an area of 151,990 km^2. In AlBaha outcrop mainly volcanic rocks of the Piech and AlBaha groups (theolitic basalt, dacite and rhyolite) but also metamorphic rocks in some parts (Cater and Johnson, 1987).

Assir region and its capital Abha are located in the southwest of the country, with an area of 81,000 km^2, and share a short border with Yemen. Asir geology consists also of volcanic rocks that belong to AlBaha and Jeddah groups including basalt, andesite and dacite rocks associated with some plutonic rocks, such as monzogranite, syenogranite and gabbro (Greenwood, 1985).

Najran region is situated in southwestern Saudi Arabia near the border of Yemen and its capital is Najran city. In Najran region, four main geological zones can be distinguished; the first zone, western part of Najra, belongs to the Proterozoic (Precambrian) of the Arabia shield and consists of sedimentary and volcanic

rocks. In the second zone, eastern part of Najran region, outcrop a the sedimentary cover composed of stratified rocks of Wajid sandstone of the Camporian-Ordovician age. The third one is the Tertiary bedrock in the southern part of Najran (Sable, 1985), and the fourth zone is the Quaternary surficial of alluvial deposits, sand dunes and gravel located between Wadi Najran and the Empty Quarter.

Finally, Jazan region is located on the country's west side, along the Red Sea coast and has an area of 151,990 km^2. Jazan geology consists of sedimentary rocks of Tertiary and Quaternary age, including deposits, sabkhas and dunes filling the valleys under the effective exchange of gravel, silt and sand system that spreads along the north and south coast of Jazan (Blank et al., 1985).

3. Methodology

3.1. Gamma dose rate measurements

The environmental gamma radiation in air has been carried out by determining two area monitoring operational quantities recommended by the ICRU Report 57 ((ICRU, 1998) to provide a reasonable estimate for the radiological protection. The ambient dose equivalent, H*(10), at a depth of 10 mm inside the ICRU sphere of tissue equivalent material with diameter of 300 mm, and the directional dose equivalent, H′(0.07), at a depth of 0.07 mm inside the ICRU sphere, that is skin dose. Both H*(10) and H′(0.07) gamma radiation dose rates have been measured indoor and outdoor by means of LiF:Mg,Cu,P dosemeters (TLD-100H) (Harshaw Chemical Co., Cleveland, OH,USA) over a two-month period (from March to April, 2011). The TLD-100H are commonly used for environmental dosimetry measurements because of their unique characteristics, such as high sensitivity and suitability to detect low doses, energy independence, low fading effect and cost (Shambon, 1972; Jain, 1982; Sivakumar et al., 2002; Miah, 2004).

Each TLD-100H package was consisting of four freshly annealed LiF:Mg,Cu,P chips placed in Aluminum casing with 43 mm × 31 mm dimensions. The calibration process of the dosemeters has been performed in the Secondary Standard Dosimetry Laboratory (SSDL) at the Nuclear Science Research Institute (NSRI) at KACST. The TLD-100H cards were calibrated under the same irradiation conditions to ensure that all dosimeters will give virtually the same response. The calibration procedure resulted in values of Element Correction Coefficient (ECC) that was specific to each TLD-100H chip to be used. The TLD-100H were read in the Harshaw TLD Reader 6600 system, which provided the charge accumulated in each chip in units of nC. These values were later converted to mGy using the calibration constants (mGy/nC) obtained before. The details of specification of the system, procedure of measurement and calibration can be found in Aleissa and Enany (2012).

In total, 885 TLDs were distributed in cities, towns and villages covering the most populated areas within the studied regions. 405 of these TLDs were distributed indoor and the remaining were distributed outdoor. At each location, between 5 and 10 TLDs were hung at a fixed height of 1 m above the ground. The dwellings chosen to distribute the TLDs were the most populated ones within the study regions. The distribution of the TLDs among the studied locations was also based on the area and activities of each location. The sacred city of Makkah has been provided with the biggest number of TLDs as it is the most populated city of the study area. The numbers of the distributed TLDs in each region are included in Table 1.

3.2. Radon measurements

The indoor radon concentrations were carried out using a time-integrated passive device from Electret Ion Chambers from E-PERM, Rad Elec. Inc., Frederick, MD 21701, USA. The device consists of a 210 mL plastic canister known as "S" chamber attached with one of the two types of different sensitivity detector (electret) placed at the bottom of the canister. Radon gas enters the canister via passive diffusion through a filtered inlet placed at the top of the canister (Kotrappa et al., 1996). This filter will not allow the radon daughters products (RDP) to enter and so all RDP are produced via radon decay inside the canister. When the disk is exposed, the positively charged electret collects the negative ions formed by the interaction of radiation emitted by radon and its daughters with the air inside the collection chamber. The resulting decrease in charge is related to the concentration of radon integrated over the period of measurement, according to Eq. (1) (Kotrappa et al., 1990):

$$C = \frac{V_i - V_f}{CF \times t} - BKG \tag{1}$$

where C (Bq m^{-3}) is the mean radon concentration, V_i and V_f (Volt) are, respectively, the voltage on electret before and after radon exposure, CF (Volt Bq m^{-3} d^{-1}) is the calibration factor calculated as:

$$CF = 5.1 \times 10^{-2} + 1.7 \times 10^{-5} \times (V_i + V_f)/2 \tag{2}$$

where t (days) is the exposure time, and BKG (= 8.7 Bq m^{-3} per μSv h^{-1}) is the gamma background correction.

The calibration of the electrets was done in the Rad Elec Inc. at which each electret was divided into 10 groups according to its previous response. For each of these groups, 3 electrets were selected and exposed to a ^{226}Ra radioactive standard source that was placed at the bottom side of the top cover of an accumulator jar of 3720 mL in size. To trap ^{222}Rn gas and its daughter products, the jar was covered by a radon leak-tight lid and then sealed hermetically for a one-month period to ensure secure equilibrium between the ^{226}Ra and its daughter ^{222}Rn. Moreover, 50 detectors were

Table 1. The rate of indoor local ambient, H*(10), and local directional, H′(0.07), gamma dose (nSv h^{-1}) for each of the five investigated regions.

		Makkah	AlBaha	Assir	Jazan	Najran
Indoor	No. of TLDs	138	56	83	59	69
H*(10)	Range	91.0−190.9	63.2−97.0	62.5−110.7	54.1−87.7	60.9−75.8
	Mean (SD)	126.2 (25.1)	81.4 (12.2)	85.1 (15.1)	67.9 (12.0)	66.9 (4.9)
	Geomean (SD)	123.9 (1.3)	80.6 (1.2)	83.8 (1.2)	67.0 (1.2)	66.7 (1.1)
	Skewness	0.8	−0.1	0.3	0.4	0.6
	Kurtosis	0.5	−1.7	−0.6	−1.2	−0.6
Indoor	Range	92.7−185.2	69.6−117.7	82.0−128.1	55.8−92.1	65.5−82.6
H′(0.07)	Mean (SD)	125.9 (24.9)	95.9 (15.6)	101.5 (15.4)	72.1 (12.7)	73.9 (5.4)
	Geomean (SD)	123.7 (1.3)	94.7 (1.2)	100.4 (1.1)	71.1 (1.2)	73.8 (1.1)
	Skewness	0.8	−0.4	0.7	0.2	0.1
	Kurtosis	0.1	−0.9	−0.7	−1.1	−0.9
Outdoor	No. of TLDs	169	57	84	81	89
H*(10)	Range	51.7−97.0	62.3−80.5	56.9−112.1	42.3−90.3	48.4−67.9
	Mean (SD)	69.4 (13.3)	68.6 (6.7)	77.5 (17.8)	54.9 (12.7)	58.0 (6.2)
	Geomean (SD)	68.2 (1.3)	68.4 (1.1)	75.6 (1.2)	53.8 (1.3)	57.7 (1.1)
	Skewness	0.8	1.1	0.6	2.1	0.3
	Kurtosis	−0.7	−0.2	−0.7	5.6	−0.9
Outdoor	Range	55.9−109.3	68.4−84.8	62.3−135.5	43.0−97.3	50.4−71.8
H′(0.07)	Mean (SD)	72.9 (15.4)	75.2 (5.5)	85.0 (21.7)	58.2 (14.6)	61.7 (6.8)
	Geomean (SD)	71.5 (1.3)	75.0 (1.1)	82.7 (1.3)	56.8 (1.3)	61.4 (1.1)
	Skewness	0.9	0.9	1.0	1.9	0.1
	Kurtosis	−0.4	0.2	0.5	4.5	−0.8

tested at the laboratories of KACST to ensure quality assurance. The reader device was tested by using the reference package (RT) from Rad Elec Inc. The uncertainty ($\pm\sigma$) in all calibration measurements was estimated to be less than 5% of the calculated values.

The optimum measurement period was estimated, based on preliminary lab trials made by Alghamdi and Aleissa (2014), to be about 20 days for the sensitive short-term (ST) electrets. Due to the relatively large number of surveyed dwellings, the ST electrets were re-used in this study several times depending on the remaining

charge on the electret. More details of the method can be found in Alghamdi and Aleissa (2014).

Radon concentrations were measured in 1119 dwellings, with focus on the most populated areas, and were assumed to be representative to all common types of houses in each of the five regions. Wide range of traditional houses and modern accommodation types (villas and apartments) were roughly chosen following to the distribution of the dwelling types provided by the Saudi Central Department of Statistics and Information (CDSI, 2009). Thus, the dwellings sample integrate 28% of traditional houses (such as town houses and mud brick houses), 20% of villas and 52% of apartments. Most of these dwellings used bricks, concrete and stones as building materials. In every house two E-PERM detectors were used placed in the rooms were the resident spent most of their time, generally the bedroom and the living room. The floor level, of room in which radon measurements were taken, was not exactly specified. However, it is usually the ground floor for traditional houses and villas, and the first or second floor for apartments. The detectors were let away from windows and doors, at about 1.0 m above the floor and 0.3 m distance from the walls.

4. Results and discussion

4.1. Gamma dose rate assessments

The results obtained from the 885 TLD-100H dosimeters, distributed in 79 selected locations in cities, towns and villages of the five investigated regions for the indoor and outdoor gamma radiation levels, have been statistically evaluated and presented in Tables 1 and 2. Table 1 lists the range, mean, geometric mean together with their respective standard deviations for the indoor and outdoor local ambient, H*(10), and directional, H′(0.07), dose rates in nSv h^{-1} in each

Table 2. Overall statistics on the rate of indoor and outdoor local ambient, H*(10), and directional, H′(0.07), dose rates (nSv h^{-1}) for all regions.

	Indoor		Outdoor	
	H*(10)	**H′(0.07)**	**H*(10)**	**H′(0.07)**
No. of TLDs	405		480	
Range	54.1−190.9	55.8−185.2	42.3−112.1	43.0−135.5
Mean (SD)	94.4 (30.3)	101.7 (27.6)	67.0 (14.8)	71.7 (17.3)
Median	87.3	96.9	62.7	66.5
Geomean (GSD)	90.1 (1.3)	98.2 (1.3)	65.5 (1.2)	69.9 (1.2)
Skewness	1.0	0.8	1.0	1.2
Kurtosis	0.7	0.5	0.6	1.8

region. Table 2 gives the overall statistical data for the same parameters and for the five investigated regions. The two tables give also the skewness (lack of symmetry) and kurtosis (pointiness) coefficients of the gamma radiation dose rates as combining these two parameters is a useful tool to test the deviation of the data from normality. The rates of outdoor H*(10) and H′(0.07) in Jazan region showed strong evidence of asymmetrical distributions with high skewness and kurtosis coefficients relative to those of the other regions that showed distributions of indoor and outdoor gamma dose rates much closer to the normality.

It can be seen from Table 1 that the indoor H*(10) and H′(0.07) gamma dose rates have their highest mean values in the most populated region of Makkah when compared to other regions, whereas the lowest mean values were found in Jazan and Najran regions. On the other hand, Asir region showed the highest mean values for outdoor dose rates of H*(10) and H′(0.07). These results were also confirmed by box plot graphics in Figs. 2 and 3 that visualizing the distribution of the data by displaying the mean, median and dispersion of the gamma dose rates for the five studied regions. The variability of the data on gamma dose rates may be explain by variations in geological features, topographical latitudes, and the radioactivity levels of soil, building materials, and the atmospheric conditions (Al-Saleh, 2007; Al-Ghorabie, 2005; Miah, 2004).

From Tables 1 and 2 it can be seen that the indoor H*(10) and H′(0.07) doses exceed the outdoor, particularly in Makkah and AlBaha regions. Higher indoor gamma dose rates relative to outdoor is expected if the natural radionuclides in building materials are the main source of indoor gamma radiation dose. This could be the cause for the observed values in the present study. In addition, poor ventilation conditions inside the buildings enhances the radon and radon daughters' concentrations; this can also contribute to the elevation of indoor gamma dose relative to the outdoor dose. However, in Jazan and Najran regions the indoor gamma radiation levels were found to be comparable with the outdoor measured dose rates. Thereby showing that the indoor gamma radiation level is mostly from the radioactivity content of the soil with a small amount of contribution from the radioactivity content of the building materials.

Fig. 4a and b shows the correlation between the H*(10) and H′(0.07) dose rates for the indoor and outdoor locations in all regions. As can be seen in these figures, H′(0.07) showed statistically strong positive correlation (p < 0.0001) to H*(10) for the indoor and outdoor cases with correlation coefficients of 0.96 and 0.98 and with mean ratio values of 0.88 and 1.15, respectively. On the other hand, Fig. 5a and b shows the linear regression analysis for the indoor-to-outdoor H*(10) and H′(0.07) dose rates. Positive correlation (P < 0.0001) is evident in the figure with correlation coefficients of 0.46 and 0.54. The mean ratio values of 0.94 and 0.86, respectively, were in correspondence with the range of 0.6−2.3 reported by UNSCEAR (2000).
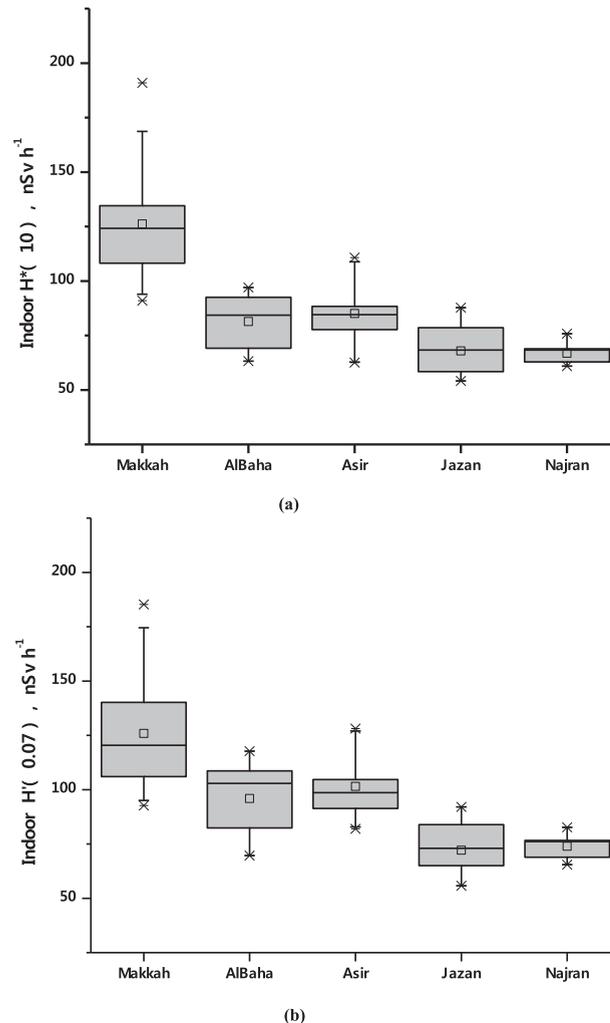
Fig. 2. Box-plot for the indoor dose rates of (a) local ambient H*(10) and (b) directional H′(0.07) (in nSv h⁻¹) for the five investigated regions. The box shows the median (long horizontal line) and values between the 25 and 75% percentiles. The short horizontal lines label the 10 and 90% percentiles, and stars mark the lowest and highest values.

Another noteworthy comparison was made between the present results and those obtained previously by Aleissa and Enany (2012) in Riyadh region using the same kind of dosimeters. The indoor H*(10) and H′(0.07) in Riyadh region were ranged from 61 to 135 and from 67 to 142 nSv h⁻¹ for the indoor, and from 57 to 105 and from 59 to 110 nSv h⁻¹ for the outdoor, respectively. Thus, the results of gamma radiation doses in Riyadh region were in general agreement with the corresponding ranges of the present study as given in Table 2.

4.2. Indoor radon concentrations

Table 3 summarizes the results of the measured indoor radon levels in the 1119 dwellings investigated in the study. The mean, range and geometric mean (GM)
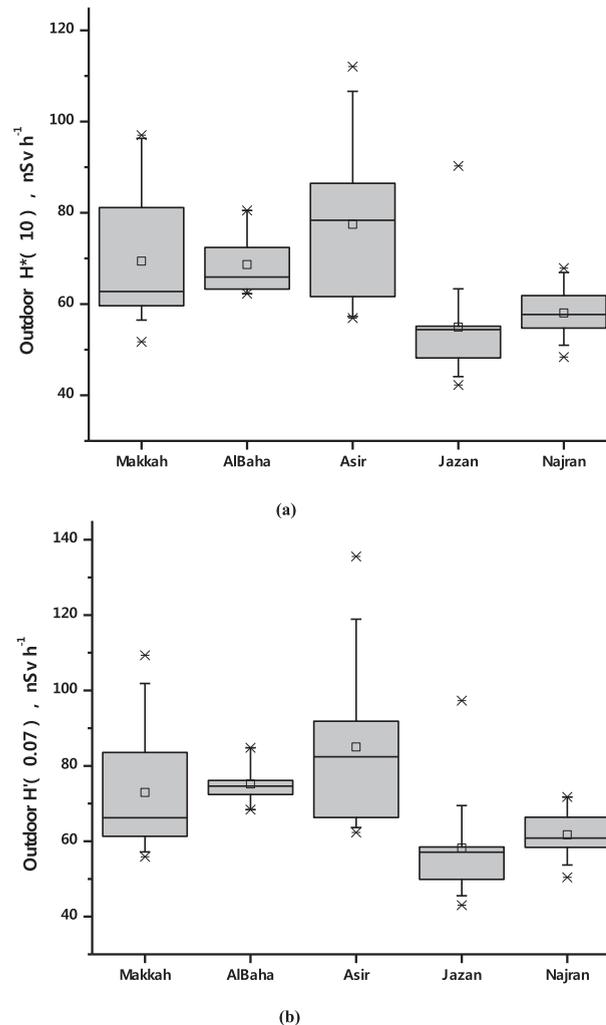
Fig. 3. Box-plot for the outdoor dose rates of (a) local ambient H*(10) and (b) directional H′(0.07) (in nSv h^{-1}) for the five investigated regions. The box shows the median (long horizontal line) and values between the 25 and 75% percentiles. The short horizontal lines label the 10 and 90% percentiles, and stars mark the lowest and highest values.

values of indoor radon concentrations obtained from each region are tabulated in Table 3. The indoor radon concentrations in the surveyed houses of all regions were ranged from 11 to 137 Bq m^{-3} with an overall mean ($\pm$SD) value of 32 ± 15 Bq m^{-3}, which is below the worldwide arithmetic mean value of 40 Bq m^{-3} (UNSCEAR, 2000). It is worth to mention that all observed indoor radon concentrations were well below the action level of 200 Bq m^{-3} reported by the ICRP (1993) for new homes. Even the reference level of 100 Bq m^{-3}, proposed by the World Health Organization (WHO, 2009) to minimize health hazards from indoor radon exposure, was only locally exceeded in Makkah and Asir regions. As can be seen in Table 3, the highest mean indoor radon concentration of 37 ± 28 Bq m^{-3} was recorded in Najran, whereas the lowest mean value of 23 ± 16 Bq m^{-3} was found
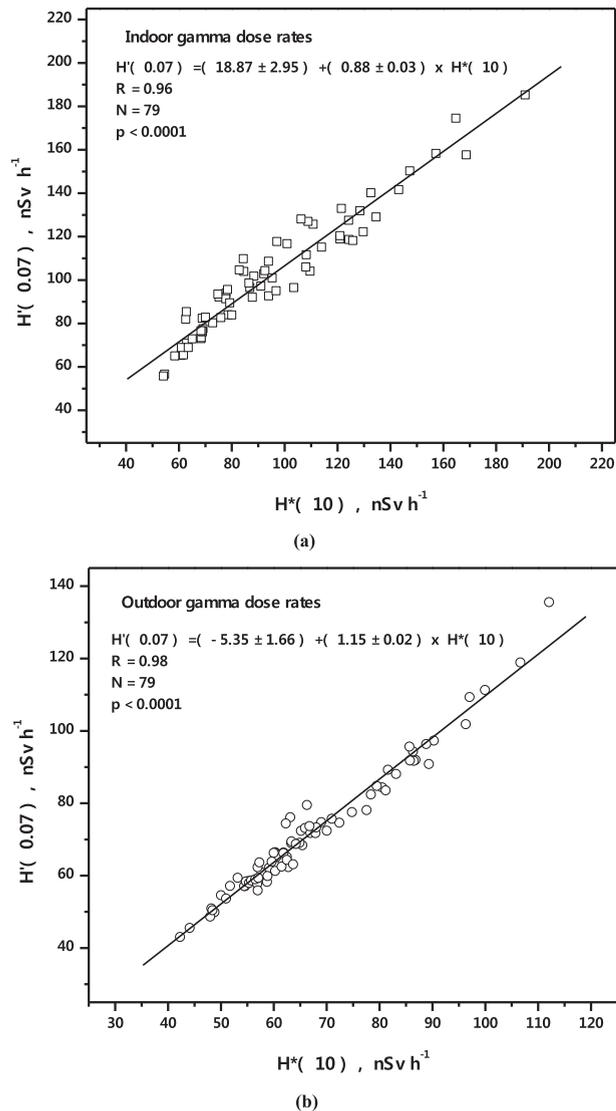
Fig. 4. Linear regression of the relationship between the (a) indoor, and (b) outdoor H*(10) and H′(0.07) dose rates for all investigated TLDs.

in Jazan. The variability of indoor radon concentrations was larger in the most populated region of Makkah than other regions, probably because of the greater number of radon detectors distributed. However, variations of indoor radon concentrations among various locations were also observed in each region and can be attributed to many other factors like variations in geological, topographical and meteorological natures, types of building materials used for construction, cooling and ventilation rates, aging effects on the buildings, and social habits of the dwellers. For the specific case of Jeddah and Makkah cities in Makkah region, indoor radon concentrations were observed to be relatively higher than those of rural areas in the same region. This could be attributed to an intervening factor that influences the survey results and rise up radon concentrations in big cities compared to small towns and villages.
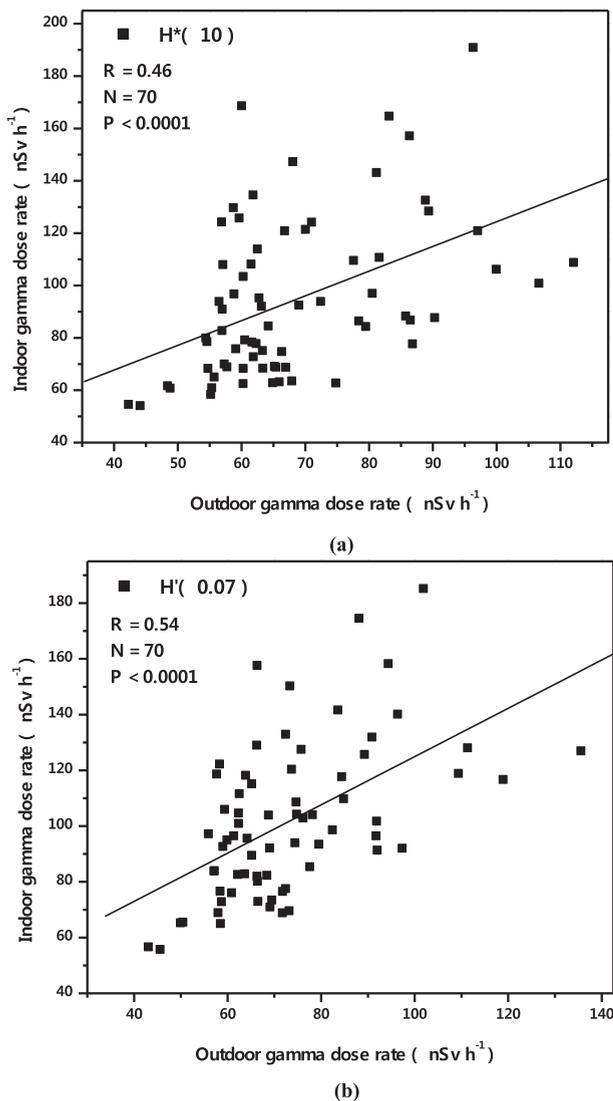
Fig. 5. Linear regression of the indoor-to-outdoor H*(10) and H′(0.07) gamma dose rates for all investigated regions.

This factor is the fact that the majority of residents of the big cities are either students, employees or workers and their dwellings are kept closed during the work time, which may cause in raising the radon levels due to the lack of ventilation.

Shown also in Table 3 the slight variations in indoor radon concentrations among the three types of houses investigated in the five regions. The general trend for the mean indoor radon concentrations in the three types was in the following order: apartments > villas > traditional houses. This trend of indoor radon concentrations may be supported by the fact that villas and modern style apartments has a feature that usually their dwellers keep the windows closed to avoid dust and save energy, which in turn may results in raising the radon levels in these houses. Depending on the use of the room, the mean indoor radon concentrations in bedrooms were always higher than

Table 3. Mean indoor radon concentrations in the different types of houses.

Region	Type of house						Type of room				Statistics			
	Traditional house		Villa		Apartment		Bedroom		Living room					
	No[a]	Rn[b]	No	Rn	No	Rn	No	Rn	No	Rn	Min	Max	Mean (SD)	GM (GSD)
Makkah	84	31	148	33	349	37	219	37	362	35	12	137	35 (27)	29 (2)
AlBaha	19	27	37	28	61	31	41	31	76	28	15	79	29 (21)	24 (2)
Assir	73	23	16	25	89	27	107	27	71	22	13	128	25 (18)	21 (2)
Jazan	86	22	13	24	47	25	84	25	62	19	13	57	23 (16)	19 (2)
Najran	55	34	5	38	37	40	53	38	44	35	11	93	37 (28)	31 (3)

[a] Number of detectors.

[b] Average radon concentration (Bq m^{-3}).

those in living rooms for all surveyed regions as depicted in Table 3. This is usually happened due to the reduction in ventilation rates in bedrooms.

There have been some few studies which assess radon levels in dwellings in other regions of Saudi Arabia. For example, Alghamdi and Aleissa (2014) have conducted a survey to assess the variability of exposure levels in 786 dwellings in Riyadh city using E PERM detectors and found a mean indoor radon concentration of 25 Bq m^{-3}. Another study was conducted by Al-Ghamdi (2014) to determine the seasonal indoor and soil radon concentrations in two villages in Najran region using CR-39 detectors. The mean indoor radon concentrations in both villages were 42 and 74 Bq m^{-3}.

Based on the obtained mean indoor radon results, a rough estimate of the annual mean effective dose rate E (nSv y^{-1}) can be determined in each of the five studied regions based on the UNSCEAR (2000) model as:

$$E = C \times F \times H \times T \times D \tag{3}$$

where C is the mean radon concentration in C (Bq m^{-3}), $F = 0.4$ (ICRP, 1994) is the equilibrium factor, $H = 0.8$ is the home occupancy factor, $T = 8760$ h y^{-1} is the number of hours in a year, and $D = 9$ nSv per Bq m^{-3} (ICRP, 1994) is the dose conversion factor.

The annual mean effective dose rates from radon and its decay products were estimated to be in the range from 0.57 to 0.93 mSv y^{-1}, with an overall mean of 0.76 mSv y^{-1} for all houses (Table 4). It should be noted that these dose estimates are based on short term measurements that may not accurately reflect radon levels throughout the year. Therefore, the obtained dose rates should be considered as rough estimates of exposure from radon and its decay progenies. However, the obtained effective dose equivalent values are well below the recommended action level of 3−10 mSv y^{-1} as adopted by ICRP (1993) indicating relatively low levels of indoor radon in the dwellings of western and southwestern regions of Saudi Arabia. Finally, the accumulation of indoor radon and decay products that emanate from

Table 4. Annual mean effective dose equivalent E and mean lifetime risk for indoor radon exposure in the different types of houses.

Region	E (mSV)	Risk $\times 10^{-3}$
Makkah	0.89	3.1
AlBaha	0.73	2.6
Assir	0.64	2.2
Jazan	0.57	2.0
Najran	0.93	3.2

walls and floors may have carcinogenic effects. The excess lifetime risk can be calculated as an estimate of the probability of developing lung cancer due to radon exposure over the man lifetime using the expression:

$$Risk = E \text{ (Sv y}^{-1}) \times DL \text{ (y)} \times RF \text{ (Sv}^{-1}) \tag{4}$$

where DL was taken to 70 years as the average lifetime duration, and RF is 0.05 Sv^{-1} as the fatal risk factor as per ICRP-106 (ICRP, 2008). The mean risk values for indoor radon exposure are tabulated in Table 4 for each of the investigated regions, with an overall mean of 2.7×10^{-3}, which is still below the maximum risk of 3.5×10^{-3} that yields from maximum acceptable annual effective dose of 1 mSv y^{-1}.

5. Conclusions

In this survey, the indoor and outdoor natural dose rates of H*(10) and H′(0.07) as well as the indoor radon concentrations in the western and southwestern regions of Saudi Arabia were investigated. A total number of 885 TLD-100H dosimeters for environmental gamma radiation and 2238 E-PERM detector for indoor radon measurements were distributed in selected locations and dwellings in Makkah, AlBaha, Assir, Najran, and Jazan regions. The indoor and outdoor rates of H*(10) varied from 54 to 191 nSv h^{-1} and from 42 to 112 nSv h^{-1}, respectively. The indoor H′(0.07) rate was in the range of 56−185 nSv h^{-1}, while it was in the range of 43−135 nSv h^{-1} for outdoor H′(0.07). Makkah region showed the highest mean indoor H*(10) and H′(0.07) rates, whereas Assir region showed the highest mean outdoor rates. For both indoor and outdoor cases, the two measured gamma dose rates were significantly correlated. The indoor H′(0.07) to H*(10) has a mean ratio of 0.88, while it has a mean ratio of 1.15 for the outdoor.

On the other hand, the indoor radon concentration levels were ranged in 11−137 Bq m^{-3} with an overall mean of 32 ± 15 Bq m^{-3} for all surveyed houses. This corresponds to an overall annual mean effective dose rate from radon and its products of 0.76 mSv y^{-1} for all houses. Finally, the lifetime estimates from indoor radon exposure showed mean values within the permissible limits.

Declarations

Author contribution statement

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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