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Original Research

The Evaluation of Indoor Radon Exposure in Houses

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Abstract

In 2000-07 653 measurements of radon were acquired from houses in Podlasie Province, Poland. In dwelling parts of buildings, arithmetic weighted mean regarding location of the building equal to 72 Bq/m^3, which corresponded to 1.8 mSv of the effective dose. Statistically significant differences between radon concentrations in country and city houses were observed. Arithmetic mean of radon concentrations in dwelling parts of houses in rural areas was 111 Bq/m^3, while in the city it was 45 Bq/m^3. Correlation between radon concentrations in a house and its age was observed. The correlation coefficient was 0.3 at $p<0.05$.

Keywords: indoor radon, seasonal corrective coefficients, buildings, Podlasie Province, Poland

Introduction

Recently, outdoor and indoor toxic substances have been the subjects of numerous studies [1, 2]. Radon, discovered by F. E. Dorn in 1900, is a noble gas formed in the course of radium disintegration. It is the only gaseous radioactive element, the heaviest noble gas with density of 9.73 kg/m^3 at 273 K (approximately 7 times heavier than dry air), colorless and tasteless. Radon is soluble in water (510 cm^3/dm^3 at 273 K (0°C)). The solubility coefficient decreases with temperature growth. It dissolves well in fats and alcohol.

^{226}Ra, found in the earth's crust, construction materials, and water, is a source of radon, and formed in radium disintegration is relatively mobile and can migrate in the earth's crust and air.

^{218}Po, ^{214}Po, ^{214}Bi, and ^{214}Pb are short-life daughters of radon. They are the most significant factors of human exposure from natural sources. Inhalation is the main method of radon exposure. ^{218}Po and ^{214}Po isotopes, as solid bodies, are fixed on the epithelium of the respiratory tract and while disintegrating they emit α radiation. A short range of α radiation results in the absorption of its whole energy in cells covering the respiratory tract.

High exposure to radon in mines and its harmful effect have been known for years. High radon concentrations, thus high values of exposure accumulated during years of work, can be observed in uranium mines.

Thorough examination of miners groups showed significant increase in lung cancer morbidity in relation to subjects without radon exposure [3-5]. Main epidemiological evidence confirming carcinogenic radon activity comes from the analysis of lung cancer morbidity among miners in uranium mines [6-9].

The results were the basis for the assessment of the risk of lung cancer caused by radon and its daughters' exposure, and enabled the determination of exposure-dose ratio [10]. Lung cancer morbidity increases were combined with the amount of accumulated inhaled doses. The relationship between exposure and the risk of the disease is linear.

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In the 1970s it was stated that radon exposure inside the buildings could be relatively high and in some cases it could be comparable to that in the mines. Radon was determined as a first class carcinogen by the International Agency for the Fight with Cancer in 1988 [11].

Radon is a natural element of the environment. However, unconscious activities such as constructing a building at the site of high radon potential or untight building construction, can lead to accumulation of large amounts of radon inside the building. A slight increase in radiation above the mean level of radiation background can cause a slight increase in the probability of neoplasm development. Moreover, neoplasms induced by radiation can be revealed ten years after exposure do not differ from spontaneous neoplasms or those occurring due to other carcinogenic factors.

A collective analysis of results from 13 European studies regarding relations between radon concentration inhaled at home and lung cancer [12] showed that radon is responsible for 2% of deaths due to all neoplasms in Europe and approximately 9% of deaths due to lung cancer. The risk of lung cancer was observed to increase by 8.4% at the increase in concentration by 100 Bq/m^3 [12]. There are also studies that undermine the causative relation between radon exposure and lung cancer [13-15].

Soil substratum is the main source of radon in the air of houses (almost 80%) [16]. The other sources are construction materials, water, ground gas, and outside air.

Indoor radon concentrations undergo seasonal changes. Higher concentrations are most freqently observed in cooler seasons of the year than in warmer ones [17-19]. Seasonal changes of indoor radon concentration are observed in various regions of the world. They depend on many factors, including the type of soil substratum and climate. In order to determine the risk of radon exposure in a house, data concerning mean annual radon concentrations should be acquired. Measuring methods enable merely to establish mean radon concentration during detector exposure. Severalmonths' exposures are most frequently performed. Thus, many corrective coefficients for assessing mean annual radon concentration based on shorter exposure were determined in many countries [20-24]. During examinations carried out in Podlasie Province, seasonal changeability of radon concentrations was also observed in all examined buildings. Most buildings revealed negative correlation of radon concentration in the building and the outside temperature. Coefficients for determining mean radon concentrations on the basis of 3-months' or 6-months' observation were appointed [25, 26].

The area of Podlasie Province constitutes 6.5% of total country area. Thus, it is the 6th as far as mean provinces' area are concerned. The main characteristics of the province are its rural character and undamaged environment preserved in its natural form. The population of the Province is 3.1% of total population, and thus it is on the 13th place as for population density. Nearly 60% of the population lives in an urbanized area. A low percentage of industry results in depopulation of the region, which is confirmed by migration coefficients [27]. As far as radioecology is concerned, the northeastern region of Poland, including Podlasie Province, has already been fragmentarily characterized in our studies [28-32]. The aim of the study is to present our results of long-term measurements of radon as mean annual values and on their basis – to determine effective doses obtained by inhabitants of Podlasie.

Table 1. The values of seasonal corrective coefficients f_3 and f_6.

	f_3	f_6
January	1.08	1.10
February	1.15	1.04
March	1.24	0.99
April	1.11	0.91
May	0.93	0.88
Juny	0.74	0.87
Jule	0.70	0.90
August	0.82	0.96
September	1.00	1.01
October	1.10	1.09
November	1.10	1.12
December	1.01	1.08

Experimental Procedures

The measurements of indoor radon concentrations in houses were carried out in 2000-07 using an integrated method with track detectors. The results constitute the basis of given radon concentrations in the region. There are 653 measurements of radon concentration in the database, a part of them was previously published. Our papers described detailed issues connected with the geological location [33, 34] of typical concrete slab buildings [35]. There are about 230 unpublished measurements of radon concentration in the database. They were performed successively, to increase the area of sampling and widen the database of measurements.

Detector distribution was carried out mainly by students and acquaintances who supervised exposure while at home in various periods of the year. All 653 measurements were included in the study.

Track detectors were exposed in several series and exposure time was from 3 months to 1 year. Annual exposure was carried out in 279 cases, 374 measurements were performed based on several months of exposure. Due to established seasonal changeability of radon concentrations, the values of its concentration, obtained during shorter exposure, were divided by corrective coefficients to assess mean annual concentration. The values of corrective coefficients f_3 and f_6 assigned for northeastern Poland

Table 2. Values of parameters concerning statistical distribution of radon concentrations in air in whole group of examined buildings. AM – arithmetic mean, GM – geometric mean, M – median, GSD – geometric standard deviation.

	Number of measurements	AM [Bq/m^3]	M [Bq/m^3]	Min [Bq/m^3]	Max [Bq/m^3]	GM [Bq/m^3]	GSD
whole building	653	81	37	9	2,200	46	2.36
part of flat	604	78	36	9	2,200	44	2.34
basements	49	116	61	21	1,010	71	2.36

Table 3. Distribution of number of radon concentration measurements in particular (right-hand closed) compartments in air of inhabited parts of building.

Radon concentration [Bq/m^3]	Number of measurements	Measurement percentage [%]
0-40	352	58
40-100	172	28
100-200	34	6
200-400	27	4
above 400	19	3

were presented in Table 1. All values of radon concentration, analyzed in our study, are mean annual values as they were obtained during 1 year- or several months-exposure, corrected to the annual ones.

CR-39 detectors were used in NRPB chambers and diffusive chambers of Karlsruhe type. Foil calibration was performed in radon chamber in the H. Niewodniczański Institute of Nuclear Physics in Kraków and Radon Standard Post in CLOR. After exposure, detectors were etched in 10 N solution of NaOH at 70ºC for 8 hours. Density of tracks was calculated on the basis of counted tracks using automatic computerized reader in 100 vision field, total area of 39 mm^2.

The accuracy of measurement of radon in the air of examined flats is estimated to be about 10% [36]. As the distribution of radon concentration in the whole set of measurements was close to the lognormal one, statistical analysis was performed with non-parametrical Mann-Whitney and Kruskal-Walis tests. It was assumed that differences between compared groups are statistically significant at $p<0.05$. Correlation between analyzed parameters or groups was assessed using non-parametric coefficient of Spearman correlation.

Distribution of indoor radon concentrations in the group of 604 flats was examined. The measurements were partially performed in basements in order to determine the amount of radon that penetrates to the building on the lowest level.

Distribution of radon concentration was close to the lognormal one in the examined area.

Results and Discussion

According to the National Cenzus of 2002, there were 18,070 buildings with approximately 35,700 flats permanently inhabited in Podlasie Province. Measurements were performed in one per 591 inhabited flats of the province, that is about 0.2% of all inhabited flats [37]. The results are presented in Table 2.

The number of measurements in particular ranges of radon concentration values noted in the living quarters (i.e. without basement) is presented in Table 3.

Most measured radon concentrations in the examined flats was included in the range of 0-40 Bq/m^3. Values above 400 Bq/m^3 were observed in 19 cases, i.e. 3% of the examined group of flats.

The results depended on building type, construction materials, building age and location.

Building Type

Soil is most frequently the main source of radon in building air. The building itself can favor or limit penetration of radon inside due to its construction features.

There are two mechanisms that cause radon transportation inside. One of them is convection, the other diffusion. Convection usually plays a crucial role when velocity of radon inflow is high [38]. Convective flow is caused by pressure difference and occurs mainly through cracks and leaks of the building. The difference in pressure occurs between the inside air and the atmospheric air and depends on the square of wind velocity and temperature difference between the inside and the outside of the building. If the difference is 5 Pa, the building behaves like a sucking pump. The efficacy of pressure difference in radon pushed from the soil through the foundation strongly depends on permeability of both the foundation and the adjacent soil. Thus, types of buildings and construction materials were carefully checked in Podlasie Povince. Most buildings (about 96.3%) are rather small, free-standing houses. The structure of buildings in Podlasie Province is presented in Table 4.

Radon concentrations were analyzed in reference to building type. There were two types of buildings differentiated in the course of study: free-standing, mostly one-family houses and blocks of flats with several dozen flats.

Table 4. The structure of buildings in Podlasie Province.

Number of flats in buildings	Percentage of buildings of this type in Podlasie
1 flat	90.6
2 flats	4.9
3 flats	0.8
4-5 flats	0.7
6-9 flats	0.5
10-19 flats	0.5
20-49 flats	1.3
> 49 flats	0.6

Large differences in radon concentrations in various types of houses in the area were observed. The results were shown in Fig. 1. The differences were statistically significant.

Radon concentrations were lower in blocks of flats due to construction features and technology, and limited inflow of radon from soil to upper floors.

The basement is an important construction element of a building. Radon concentrations in buildings with and without basements were compared. Most of the examined buildings (439) had basements, and a small number of one-family houses (28) did not. Radon concentrations on the 1st floors of the buildings with and without basements were compared in order to eliminate the influence of the floor on radon levels. Statistically significant differences between those groups of buildings were observed and the results are presented in Fig. 2 and in Table 5.

Higher radon concentrations were revealed in buildings without basements bacause without an additional barrier between the soil, which is the main source of radon, and the dwelling part of the building, radon penetrates the flat directly from the soil.

Construction Materials

The type of building determines the type of construction material. Thus, buildings were divided into 4 groups according to the construction material: wood, bricks, foamed concrete, concrete slabs. The relation of indoor radon concentrations to the type of construction material was analyzed. The results are shown in Fig. 3.

Differences between radon concentrations measured in buildings constructed from wood and foamed concrete, wood and concrete slabs, foamed concrete and brick, and foamed concrete and concrete slabs were statistically significant. The differences are derivatives of various types of buildings.

Free-standing buildings were built from bricks, foamed concrete and wood. Blocks of flats were constructed mainly from concrete slabs. Differences of radon concentrations between buildings from foamed concrete, bricks, concrete slabs, and wood probably did not result from exhalation of radon from construction materials. Earlier measurements of radium concentrations in construction materials and raw materials used in northeastern Poland did not show significant differences between radium concentrations in prefabricated elements and bricks [39].

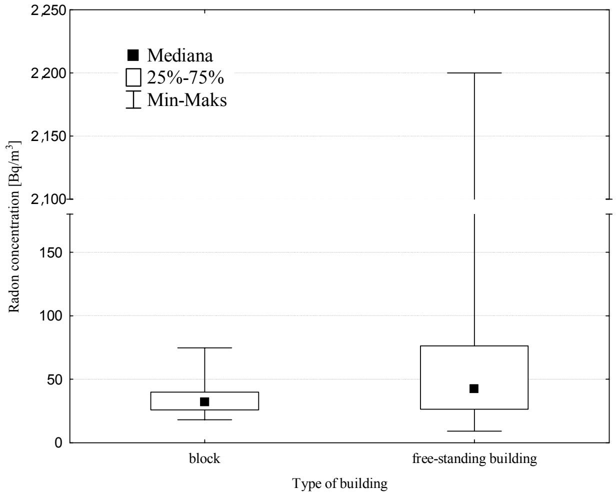

Fig. 1. Distribution of radon concentration in living quarters of part of various types of buildings.

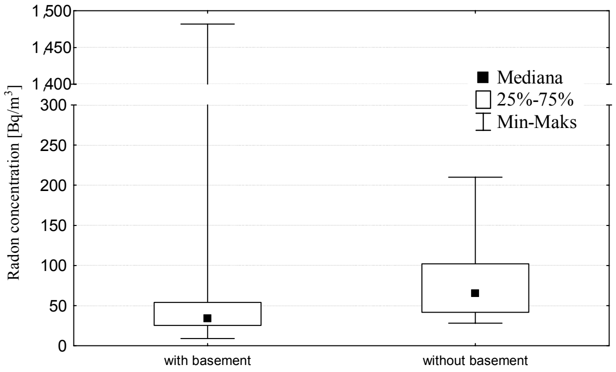

Fig. 2. Radon concentration distribution in air on the first floor of buildings with and without basements.

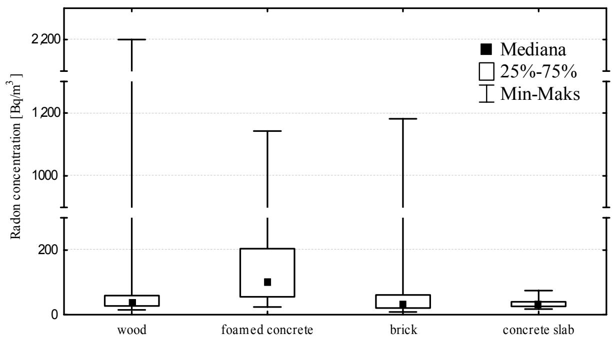

Fig. 3. Distribution of radon concentrations in inhabited parts of buildings in relation to construction materials.

Table 5. Parameters of radon distribution in houses with and without basements (e.g. values measured on the first floor).

	Number of measurements	AM [Bq/m^3]	M [Bq/m^3]	Min [Bq/m^3]	Max [Bq/m^3]	GM [Bq/m^3]	GSD
Houses with basement	143	65	34	9	1481	39	2.87
Houses without basement	28	78	65	28	210	58	2.58

Age

The age of a house determines construction features of the house, technologies and materials. Cracks and lack of continuity appear together with age in construction material and increase radon inflow. As far as age is concerned, building structures are fairly differentiated in Poland. The percentage of old buildings, i.e. constructed before 1945, is higher in western and northern Poland than in the eastern and central provinces. The highest percentage of houses built before 1945 is found in Lubuskie and Dolnośląskie provinces (above 60%, out of which more than 25% were built before 1918) [40].

Fig. 4. presents a comparison of ages of buildings and flats in Poland and Podlasie Province.

It is obvious that age structure of buildings in Podlasie Province changes naturally and old buildings are lost with time. The national census of 1988 and 2002 showed that 3,700 buildings and 5,200 flats were lost in the group of oldest houses. The number of youngest flats increased between census counts, 23,500 of buildings with 68,100 of flats were built after 1988 [37].

The changes of mean radon concentrations in examined buildings of Podlasie Province in relation to the age were analyzed and five age categories were specified.

The number of measurements in particular age categories was presented in Table 6. However, it was not possible to determine exactly the age of a building and thus the number of analyzed houses is in this aspect smaller than the total number of houses.

A weak correlation was observed between radon concentration and building age, correlation coefficient was 0.28 for the whole building and 0.3 for the dwelling part ($p<0.05$). Statistical analysis showed that building age had a statistically significant influence on radon concentrations in the buildings.

The differences of radon concentrations are statistically significant between categories 4 and 2, 4 and 3, and between categories 5 and 2, and 5 and 3. The highest mean arithmetic and geometric values of radon concentrations were determined for houses built between 1945 and 1970. Concentration values in the particular age categories are shown in Fig. 5.

Building Location

The distribution of radon concentrations in relation to building location was analyzed: houses built in rural areas and those built in towns. According to the 2002 census, there were 60,100 houses in towns and 120,600 houses in rural Podlasie. There were 235,200 flats in towns and 133,400 in rural areas.

Examination of radon concentrations was performed in one per 434 rural houses (0.2%) and one in 791 town flats (0.1%). Statistically significant differences between radon concentrations in buildings in towns and rural areas were stated for all buildings and their dwelling parts ($p<0.05$).

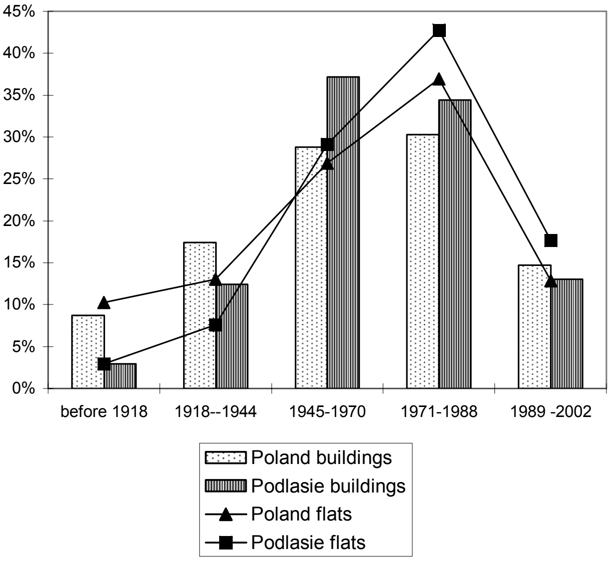

Fig. 4. The percent structure of the age of houses and flats in Poland and Podlasie Province [37, 40].

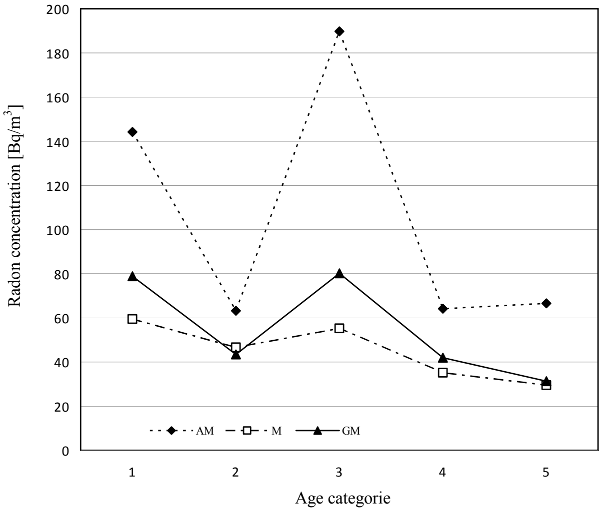

Fig. 5. Mean arithmetic, mean geometric and medians of radon concentrations in inhabited parts of houses in particular age categories of Podlasie Province buildings.

Table 6. The number of measurements in particular age categories.

Category	Construction period	Number of measurements
1	before 1918	8
2	1918-1944	46
3	1945-1970	78
4	1971-1988	316
5	1989-2002	78

The structure of buildings in the country is fairly consistent with rather small one-flat houses. On the other hand, the building structures in towns are more differentiated. Besides free-standing houses there are also blocks of flats with low radon concentrations.

However, the different construction methods in town in comparison to consistent rural buildings cannot explain observed differences of mean indoor radon concentrations.

On the other hand, differences in radon concentrations in free-standing houses in towns and in the country were observed. Statistical parameters of radon concentration distribution in rural and town buildings and radon concentration distributions in free-standing buildings in towns and country are presented in Table 7.

The age structures of the buildings are different in towns than in rural areas and that can be one of the reasons for higher mean values of radon concentrations in rural houses.

The number of flats in particular rural and town categories is shown in Fig. 6.

Thus, we decided to examine relations of radon concentration to typical construction materials and techniques. It turned out that country buildings in Podlasie Province have elevated values of radon concentration. Therefore, they should undergo detailed measurments in order to locate flats with high radon concentrations and possibly undertake preventive actions.

Our measurements took into account seasonal coefficients and thus enabled us to determine more detailed mean annual radon concentrations at a place of exposure on the basis of shorter exposure times.

When corrective coefficients are not taken into consideration, a 3-month exposure can lead to underassessment by 30% or over-assessment by 24% as far as the mean annual concentration values are concerned. In case of 6-month exposure, the error would be smaller and the range of deviations would be equal to 25% of mean value.

On the basis of the 2002 census, we can state that 41.3% of the province population lived in the country and the value of mean arithmetic radon concentration in rural house air was 111 Bq/m^3. The majority of the population lived in towns (58.7%) with mean radon concentrations of 45 Bq/m^3. Thus, a statistical inhabitant of a town receives an effective dose of inhaled radon of about 1.1 mSv, while a statistical inhabitant of a rural area 2.8 mSv. Mean weighted value of radon concentration in relation to location was 72 Bq/m^3, higher than the mean appointed for Poland (AM=49.1 Bq/m^3 [41] and mean weighted for 29 European countries (59 Bq/m^3) [38]. Taking into account lifetime exposure to such radon concentrations, the estimated risk of deaths due to lung cancer in Podlasie Province population is approximately 1.28%.

The value of the effective dose per statistical province inhabitant can be determined on the basis of appointed mean weighted value of radon concentrations – 1.8 mSv.

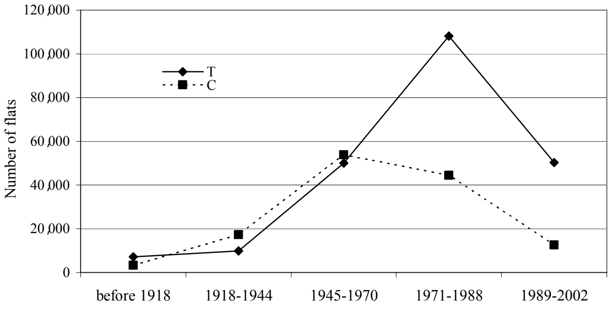

Fig. 6. The number of flats in particular categories of flats: rural – C and town – T.

Table 7. Distribution of radon concentrations in air of buildings in town and rural areas with regard to free-standing houses in town and country.

		Number of measurements	AM [Bq/m^3]	M [Bq/m^3]	Min [Bq/m^3]	Max [Bq/m^3]	GM [Bq/m^3]	GSM
Country (only free-standing houses)	whole building	331	116	48	10	2,200	60	2.65
	dwelling parts	307	111	48	10	2,200	58	2.66
	basement	24	176	73	21	1,010	96	2.86
Town	whole building	322	46	32	9	1,182	35	1.83
	dwelling parts	297	45	32	9	1,182	33	1.82
	basement	25	59	52	23	136	53	1.61
	dwelling parts of free-standing building	111	65	30	9	1,182	36	2.50

The inhabitants of 3% of buildings with radon concentrations above 400 Bq/m^3 obtain the effective dose of inhaled radon of more than 10 mSv.

Conclusions

Radon concentrations in one-family houses were higher than in the blocks of flats. Houses without basements revealed higher radon concentrations than houses with basements, probably due to lack of a barrier of radon inflow. A slightly positive correlation between radon concentration and building age was connected with the processes of construction material aging and change in their properties. The relations of radon concentrations to location, type, age, and construction materials cannot be observed separately. While measuring radon concentrations we obtained results of connected factors. In a given period of time in given social and economic conditions, typical buildings were constructed with typical materials using typical standards of construction techniques. The mean value of radon concentrations in Podlasie is higher than the mean appointed for Poland. Higher radon concentrations in Podlasie are probably due to lack of space between the building and the soil in rural areas as a result of construction features and construction material age.

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