Indoor radon exposure and living conditions in patients with advanced lung cancer in Lublin region, Poland

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Abstract. – OBJECTIVE: **Radon (Rn-222) is a noble gas formed in the uranium path (U-238) as a decay product of radium (Ra-226). It is estimated to cause between 3% to 14% of all lung cancers, depending on the national average radon level and smoking prevalence. Radon molecules emit alpha radiation, which is characterized by low permeability through tissues, but due to its remarkably high energy, it has a high potential for DNA damage. The aim of our research was to assess the radon concentration inside the houses of patients with advanced lung cancer and to analyze their socio-economics status.**

PATIENTS AND METHODS: The measurements of radon concentration were performed in 102 patients with stage 3B or higher lung cancer in the region of Lublin, Poland. One month of radon exposure measurement was performed with alpha-track detectors. In addition, patients filled in a detailed survey about factors that might influence the concentration of radon inside their houses.

RESULTS: The average concentration of radon during the exposure of the detector in the residential premises of the respondents was at the level of 69.0 Bq/m³ [37.0-117.0]. A few significant correlations were discovered, e.g., higher levels of radon in countryside houses or in houses equipped with air conditioning.

CONCLUSIONS: As radon exposure is a modifiable risk factor for lung cancer, it is extremely important to find factors that may reduce its concentration in dwelling places. Since our research was performed in houses of people with lung cancer, taking corrective actions based on our findings could prevent new lung cancer incidence in patients' flatmates.

Key Words:
Residential radon, Lung cancer, Exposure.

Abbreviations

α – alpha (radiation); ADC – adenocarcinoma; ALK – anaplastic lymphoma kinase; Bq – becquerel (the SI derived unit of radioactivity); EGFR – epidermal growth factor receptor; IPF – idiopathic pulmonary fibrosis; KRAS – (Kirsten rat sarcoma virus) gene for K-Ras protein; LCC – large cell carcinoma; NO_2 – nitrogen dioxide; NOS – not otherwise specified (lung cancer); NSCLC – non-small cell lung cancer; PD-L1 – programmed death-ligand 1; $PM_{2.5}$ – particulate matter with a diameter of 2.5 μm or less; Po – polonium; Ra– radium; Ra-226 isotope; Rn – radon, Rn-222 isotope; ROS-1 – proto-oncogene tyrosine-protein kinase; SCLC – small cell lung cancer; SSNTD – solid state nuclear track detectors; SQC – squamous cell carcinoma; U – uranium.

Introduction

Lung cancer accounted for 11.4% (2.2 million) of all cancer cases and 18% (1.79 million) of cancer-related deaths in 2020[1]. Due to the global scope of the disease, the fight against lung cancer should be a priority[2]. While tobacco smoking is undeniably the primary risk factor for lung cancer[3-8], multiple studies have shown that exposure to radon is the second most significant contributor[9-14].

Radon (Rn-222) is a noble gas formed in the uranium series (U-238) as a byproduct of radium (Ra-226). Although radon can enter residential houses through building materials, water or natural gas, the most significant source of its presence indoors is soil. The concentration of radon in residential houses, apart from the geological properties of the soil on which the building is located, is influenced by many other factors, such as the tightness of the foundations and installations or even the habits of residents[15]. In addition to sub-

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slab, sump and sub-membrane depressurization, block wall suction and physical sealing[16], room ventilation is also an effective intervention to reduce the concentration of radon in the indoor air[17].

Radon molecules emit alpha radiation, which is characterized by low permeability through tissues; however, due to its remarkably high energy, it has a high potential to cause DNA damage. DNA damage due to alpha radiation can occur in two ways: first, by the direct breaking of the DNA double helix, and second, by the action of the oxygen reactive species[18,19].

The harmful activity of radon is most frequently manifested in the respiratory system due to inhalation exposure. It has been proven that exposure to radon at home and in the workplace is the primary risk factor for lung cancer in non-smokers, and the second in tobacco smokers[18,20]. The far-reaching synergistic effect of radon and tobacco smoke in inducing lung cancer has also been well proven[21-25]. It is suspected that radon may induce genetic mutations and chromosomal aberrations typical for lung cancer[17]. A large study conducted in France by Mezquita et al[26], showed a statistically significant correlation between radon concentration and the occurrence of oncogenic alterations, such as EGFR, ALK, BRAF, KRAS and HER2, while other studies indicate TP53 or HPRT[18] mutations. Casal-Mouriño et al[25] indicated that never-smokers with adenocarcinoma with genetic mutations had significantly longer survival, however, higher indoor-radon exposure resulted in reduced survival probability. Therefore, it should be concluded that not only the smoking cessation, but also reduction of exposure to radon is an important modifiable factor that can potentially reduce the incidence of this disease.

The purpose of the study was to investigate the concentration of radon in the places of residence of patients diagnosed with advanced, inoperable lung cancer and to determine how living conditions and lifestyle factors influence these levels.

Moreover, if the study detects a high concentration of radon in the patient's residence, it aims to notify the other residents and suggest methods to reduce their exposure to radon. This is done to ensure the safety of all residents.

Patients and Methods

Study Group

The examined group consisted of 102 patients treated at the Department of Pneumonology, Oncology and Allergology of the Medical University of Lublin, Poland because of inoperable lung cancer stage 3B or higher. All patients were residents of the Lublin region, southeast of Poland. The study group consisted of 39 women (38.2%) and 63 men (61.8%). The majority of the analyzed group were patients over 65 years of age (n = 63; 61.8%), while younger patients accounted for 38.2% of the study group.

Patients with the diagnosis of non-small cell carcinoma accounted for 78.4% (n = 80), 41.2% (n = 42) had adenocarcinoma subtype, squamous subtype occurred in 26.5% (n = 27), and not otherwise specified (NOS) due to an uncertain histological subtype was found in 6.9% (n = 7). Four patients were diagnosed with rare types of lung cancer. In this subgroup of patients, there were neuroendocrine, mixed histology of adenosquamous and two patients with large cell tumors. Small cell carcinoma was treated in 21.6% (n = 22) of patients. Characteristics of the study group are presented in Table I.

Most of the patients were smokers or ex-smokers. The smoking status of examined patients is presented in Table II.

Radon Exposure Measurements

The measurements of indoor radon concentration were made with the use of a passive method with solid-state nuclear track detectors (SSNTD) of CR-39 type. The detectors of RSKS type (Radosys Ltd., Hungary) have been used. A detailed description of the detectors and their application can be found in a previous paper by Grzy-

Table I. Characteristics of the study group.

Variable	Study group n = 102 (%)
Gender	
Male	63 (61.8%)
Female	39 (38.2%)
Age	
≥ 65 years	63 (61.8%)
< 65 years	39 (38.2%)
Lung cancer type	
Adenocarcinoma	42 (41.2%)
Squamous-cell carcinoma	27 (26.5%)
NOS	7 (6.9%)
Small-cell lung cancer	22 (21.6%)
Other	4 (3.9%)
Voivodeship of residence	
Lublin Voivodeship	99 (97.1%)
Other (Silesian Voivodeship or Holy Cross Voivodeship)	

Table II. Smoking status of patients of the examined group.

Factor		Study group, n = 102 (%)
Smoking status	Current smoker	35 (34.3%)
	Ex-smoker	49 (48.0%)
	Non-smoker	18 (17.6%)
Second-hand smoking exposure	Yes	36 (35.3%)
	No	66 (64.7%)

wa-Celińska et al[27]. Detectors were sent to patients' houses with detailed instructions on their installation requirements to capture exposure data properly. The time of detectors' exposure in a chosen room (mostly bedrooms and living rooms) was a minimum of 30 days. After that time, the detectors were sent back to the Laboratory of Radiometric Expertise, Institute of Nuclear Physics of the Polish Academy of Sciences in Cracow, Poland, where they were etched and read. Based on the track densities read on each detector, the average radon concentration during the detector's exposure in a patient's house has been determined. The patients also sent back a short questionnaire containing information about the conditions of detector's exposure as well as basic information about their house (type of building, year of construction, heating, ventilation etc.). The process of etching, reading of detectors, and the determination of average radon concentration has been described in detail in our previous article[27]. This method of indoor radon measurement is accredited by the Polish Centre for Accreditation (certificate AB 788) according to the PN-EN ISO/IEC 17025:2018-02 standard.

Statistical Analysis

The statistical analysis of the data collected in the spreadsheet was performed using the MedCalc (v.15.8) and Statistica (v.13) software. Categorized data is presented in absolute numbers and as percentages. The p-value < 0.05 was considered statistically significant. Due to the different-than-normal distribution of a given continuous, the average radon concentration during the detector exposure in the examined person's apartment was presented using the medians and the interquartile range. The distribution of the variable – mean radon concentration during the exposure of the detector in the apartment of the examined person – was assessed using the D'Agostino-Pearson test. Due to the lack of normality in the distribution of the studied variable, the comparisons depending on demographic, clinical and living factors were made based on the non-parametric Mann-Whitney U test (comparisons of 2 independent groups) and the Kruskal-Wallis ANOVA test (comparisons of more than 2 independent groups). For the same reason, the non-parametric Spearman's rank correlation test was used to assess the correlation between the average radon concentration during the detector's exposure in the apartment of the examined person and other continuous variables.

Results

We analyzed radon concentration levels in the homes of patients with advanced lung cancer considering the following variables:

- Features of the place of residence: size of the place of residence, type of building, main building material, presence of basement, basement floor finish, protection of building foundations with moisture insulation, presence of water installation, presence of sewer, presence of gas installation, presence of central heating, presence of air-conditioning, window frames material (Table III).
- Information on the place where radon concentrations were measured: kind of room in which radon was measured, the floor on which radon measurement was made, finishing of the walls of the room where radon was measured, finishing of the floors of the room in which radon was measured (Table IV).

Significantly higher values of the average radon concentration during the exposure of the detector in residential premises were observed in patients with lung cancer if the measurement was performed in the countryside compared to a large city (82.0 *vs.* 39.5 Bq/m^3; p = 0.0232; Figure 1).

It was found that there were significantly lower values of the average radon concentration during

Table III. Comparison of the average radon concentration during detector exposure in residential premises in patients with lung cancer depending on selected variables related to the housing conditions of the subjects – features of the place of residence.

Variable	Examined group (%)	Mean radon concentration during detector exposure (Bq/m^3)	*p*-value
Size of place of residence			**0.0232** (1 *vs.* 3)
1. Large town (> 100,000 inhabitants) (1)	34 (33.3)	39.5 [34.0-79.0]	
2. Small town (< 100,000 inhabitants) (2)	25 (24.5)	74.0 [41.5-120.0]	
3. Village (3)	43 (42.2)	82.0 [63.0-119.0]	
Type of building			0.3647
Block of flats	36 (35.6)	47.5 [33.0-121.0]	
Detached house	53 (52.5)	78.0 [56.2-117.2]	
Apartment building	12 (11.9)	57.0 [34.0-102.5]	
Main building material			0.6839
Concrete	9 (8.8)	65.0 [37.2-119.0]	
Bricks	21 (20.6)	64.0 [36.7-86.2]	
Wood	13 (12.7)	79.0 [66.7-134.2]	
Hollow blocks	36 (35.3)	76.5 [36.5-112.0]	
Large concrete slabs	23 (22.5)	52.0 [32.7-125.2]	
Presence of basement			0.2956
Partial basement	6 (5.9)	82 [69.0-119.0]	
No	20 (19.6)	72.5 [34.0-132.0]	
Yes	76 (74.5)	66.0 [37.0-104.0]	
Floor finish in the basement			**0.0234**
1. Wood	6 (7.3)	30.5 [21.0-36.0]	(1 *vs.* 2,3,4)
2. Ceramic floor tiles	5 (6.1)	119.0 [99.7-171.2]	
3. Concrete screed	67 (81.7)	69.0 [38.2-99.7]	
4. Soil	4 (4.9)	76.5 [71.5-98.5]	
Protection of foundations with moisture insulation			
No	23 (22.5)	68.0 [35.0-113.2]	0.6624
Yes	79 (77.5)	69.0 [37.2-116.7]	
Presence of sewer			
No	18 (17.6)	80.0 [36.0-120.0]	0.5741
Yes	84 (82.4)	69.0 [37.0-116.5]	
Presence of gas installation			
No	36 (35.3)	74.5 [35.0-127.0]	0.5147
Yes	66 (64.7)	68.5 [37.0-100.0]	
Presence of water installation			
No	1 (1.0)	36.0 [36.0-36.0]	0.3590
Yes	101 (99.0)	69.0 [37.0-117.2]	
Presence of central heating			
No	22 (21.6)	68.5 [42.0-144.0]	0.2845
Yes	80 (78.4)	70.0 [36.5-98.0]	
Presence of air-conditioning			**0.0456**
No	95 (93.1)	67.0 [36.0-114.0)	
Yes	7 (6.9)	95.0 [78.2-134.2]	
Using a gas cooker			0.4980
No	13 (12.7)	65.0 [34.2-82.2]	
Yes	89 (87.3)	74.0 [37.0-118.0]	
Other sources of heating			0.1782
Electrical devices	5 (16.1)	75.0 [61.2-121.7]	
Coal	21 (67.7)	87.0 [56.2-132.7]	
Other	5 (16.1)	45.0 [34.2-55.5]	
No data (n = 71)			
Window frames material			**0.0350**
Wood	16 (15.7)	40.0 [35.0-67.50]	
Plastic	86 (84.3)	75.0 [39.0-118.0]	

detector exposure in residential premises in patients with lung cancer in the cases where the basement floors were wooden compared to other possible materials (wood *vs.* ceramic tiles or concrete or soil, respectively: 30.5 *vs.* 119.0 or 69.0 or 76.5 Bq/m^3; p = 0.0024; Figure 2).

Table IV. Comparison of the average radon concentration during detector exposure in residential premises in patients with lung cancer depending on selected variables related to the housing conditions of the subjects – information on the place where radon concentrations were measured.

Variable	Examined group n = 102 (%)	Mean radon concentration during detector exposure (Bq/m^3) [min-max value]	*p*-value
Kind of room where radon concentration was measured:			0.9670
Kitchen	13 (12.7)	69.0 [35.7-123.7]	
Living room	51 (50.0)	75.0 [38.2-92.5]	
Bedroom	38 (37.3)	70.0 [32.0-120.0]	
The storey on which radon measurement was performed			0.3789
Ground floor	60 (58.8)	74.5 [46.0-117.5]	
1st floor	19 (18.6)	65.0 [32.0-96.5]	
2nd floor	1 (1.0)	33.0 [33.0-33.0]	
Upper floor	22 (21.6)	58.0 [35.0-123.0]	
Finishing material of the walls in the room where the radon measurement was performed			0.2734
Panelling	9 (8.8)	63.0 [43.7-93.0]	
Paint	79 (77.5)	69.0 [36.0-114.0]	
Wallpaper	11 (10.8)	91.0 [67.5-137.0]	
Other	3 (2.9)	35.0 [31.2-67.2]	
Finishing material of the floor in the room where the radon measurement was performed			0.9348
Concrete	7 (6.9)	75.0 [37.7-86.5]	
Wood	39 (38.2)	67.0 [35.0-119.5]	
Parquet	37 (36.3)	69.0 [37.0-102.0]	
Polyvinyl chloride floor lining (PVC)	7 (6.9)	69.0 [41.0-138.0]	
Ceramic tiles	11 (10.8)	71.0 [54.0-112.0]	
Other	1 (1.0)	119.0 [119.0-119.0]	

Significantly higher values of the average radon concentration during detector exposure were observed in patients with air conditioning (95.0 *vs.* 67.0 Bq/m^3; $p = 0.0456$; Figure 3). Moreover, in patients whose window frames were made of plastic instead of wood, the mean values of radon concentration during detector exposure were significantly higher (75.0 *vs.* 40.0 Bq/m^3; $p = 0.0350$; Figure 4).

Detailed data on the comparison of the average radon concentration during detector exposure in residential premises in patients with lung cancer depending on selected variables

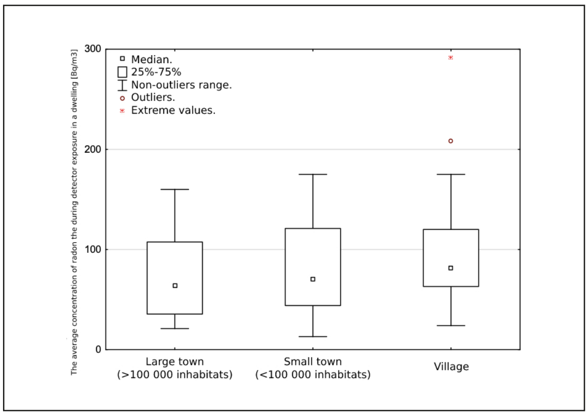

Figure 1. Comparison of the average radon concentration during detector exposure in a dwelling depending on the size of population at the place of residence.

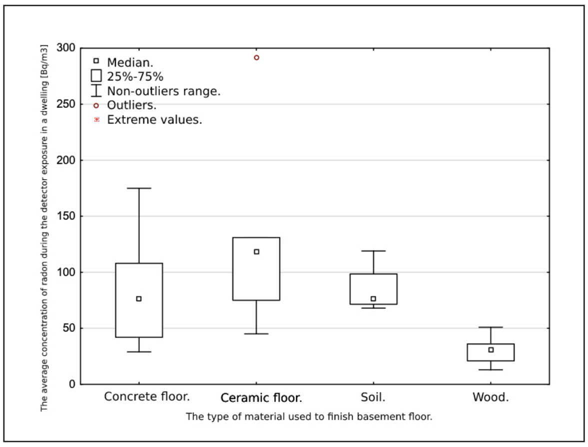

Figure 2. Comparison of the average radon concentration during detector exposure in a dwelling depending on the type of material used to finish the basement floor.

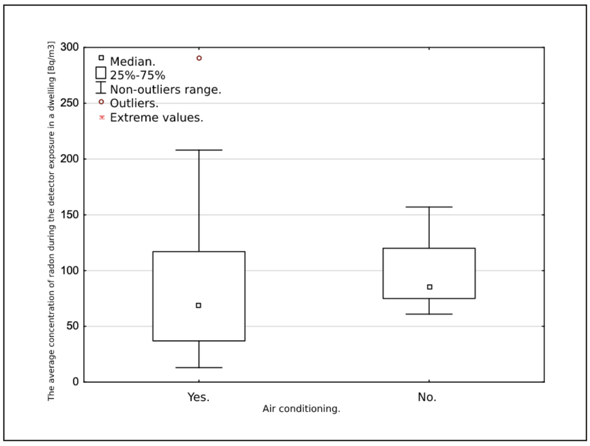

Figure 3. Comparison of the average concentration of radon during the detector exposure in a dwelling depending on air conditioning.

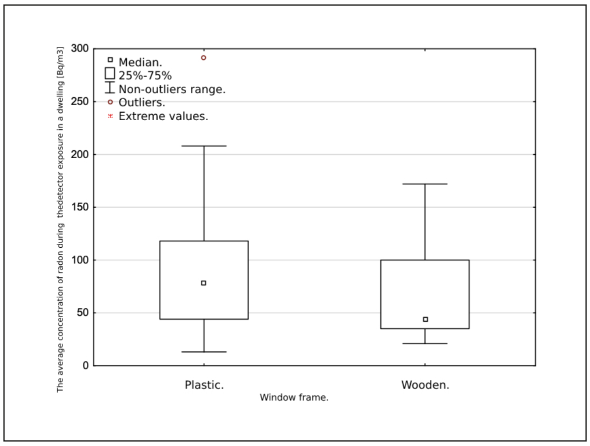

Figure 4. Comparison of the average concentration of radon during the detector exposure in a dwelling depending on the type of window frame material.

related to housing conditions are presented in Table V.

Discussion

Poland is not currently covered by a comprehensive radon concentration assessment. Older data[28] conducted in Poland, estimate the average household radon concentration at 49 Bq/m^3. The current map of natural radioactivity available on the website of the European Commission[29] indicates that in Lublin, the average concentration of radon in dwellings was 100-200 Bq/m^3. Our measurements show that radon concentrations were lower.

Literature data indicate a number of factors influencing the concentration of indoor radon. The presence of a cellar in the building promotes the penetration of radon into its interior, as the cellar “pierces” the soil layer. Radon is penetrating from the ground into a building because of the temperature gradient – the warmer the building, the greater the radon concentration. Leaks in the building structure cause heat loss, but at the same time, they are a gateway for radon flowing in from outside[30]. Thus, higher radon concentrations may occur in older buildings, which is confirmed by the observations of Kropat et al[31]. Their research has also discovered that a higher concentration of radon occurs in detached houses, which is due to the advection process, driven by the difference in temperature inside and outside the building. The presence of ventilation and sewage systems, which increases the radon concentration gradient between the inside of the building and the soil, also contributes to the increase in radon concentration, causing it to pass into the building[30].

A principal factor reducing the level of radon inside the building is frequent ventilating of the apartment, which can reduce the radon concentration by up to 70%[32]. The issue of building materials seems more complicated as they contain radioactive elements, including radium Ra-226, which decay into radon. The importance of building materials as a radon source increases with the height of the building, as soil remains the main source of radon on the lower floors. Indoor radon levels can be reduced by the presence of a concrete floor screed[30,33].

The observations made in our research are partially consistent with the literature data, but they also brought some surprising findings. Our study shows that higher concentrations of radon occur in buildings located in the countryside. This may be due to the common presence of basements and the low height of buildings (usually no more than two floors). On the lower floors, the level of radon is determined by its content in the substrate. It is likely that the buildings in the countryside are often in worse technical conditions; they have more leakages in foundations, which cause an inflow of radon from the soil.

It has also been confirmed that the level of radon is increased by the presence of air conditioning, which intensifies the transport of radon from the soil to the interior of the building. The

Table V. Comparison of the average radon concentration during detector exposure in residential premises in patients with lung cancer depending on selected variables related to the housing conditions of the subjects – living habits of residents.

Variable	Examined group n = 102 (%)	Mean radon concentration during detector exposure (Bq/m³)	*p*-value
Heating the water with a gas stove			0.3279
No	65 (63.7)	67.0 [35.0-110.0]	
Yes	37 (36.3)	75.0 [44.7-119.0]	
Using a gas cooker			0.4980
No	13 (12.7)	65.0 [34.2-82.2]	
Yes	89 (87.3)	74.0 [37.0-118.0]	
Using a gas cylinder			0.3615
No	39 (49.4)	52.0 [34.2-85.7]	
Yes	40 (50.5)	66.0 [36.5-105.0]	
No data (n = 23)			
Using other sources of heating			0.1782
Electrical devices	5 (16.1)	75.0 [61.2-121.7]	
Coal	21 (67.7)	87.0 [56.2-137.7]	
Other	5 (16.1)	45.0 [34.2-55.5]	
No data (n = 71)			
Gas installation technical inspection ever performed			0.5612
No	2 (2.9)	93.0 [68.0-118.0]	
Yes	66 (97.1)	71.5 [38.0-108.0]	
No data (n = 34)			
Gas installation ever replacement			0.5396
No	55 (82.1)	74.0 [39.0-106.0]	
Yes	12 (17.9)	47.5 [37.0-100.5]	
The main source of drinking water			0.8790
Mineral	7 (6.9)	75.0 [54.7-112.0]	
Water supply	95 (93.1)	69.0 [36.2-116.0]	
Frequency of ventilation of the room in which radon was measured			0.2402
Several times a week	14 (13.7)	70.5 [44.0-100.0]	
Once a day	20 (19.6)	86.5 [55.5-120.5]	
Most of the day or several times a day	68 (66.7)	65.0 [34.5-117.5]	

opposite results were presented by other studies confirming the decrease in the average value of radon in the room during the operation of air conditioning[34,35]. In our research, we examined radon concentrations in residential homes, where air conditioning is still not commonly used in Poland. Our results may be altered since among the examined flats, only less than 7% were equipped with air conditioning.

The higher radon levels were also associated with the presence of plastic window frames compared to wooden frames. It can be assumed that such frames are more airtight and thus reduce natural ventilation and allow the interior to be kept at a higher temperature, favoring the accumulation of radon.

Another interesting result is lower radon concentration in houses with wood-finished basements compared to other materials (including concrete). However, it cannot be treated as a rule due to the small number of houses with this kind of basement studied in our research. This result requires more investigation, mainly of radon in soil and soil permeability.

In our research, we have determined that there are some practical solutions to reduce indoor radon, using wooden window frames rather than plastic frames and limiting the use of air conditioning. It should be noted that the Lublin region, the area where the measurements were carried out, has a relatively low concentration of radon in soil[27], which results from its location on loess rocks. Therefore, it is possible that other parts of the relationship would be revealed only in a study carried out in radon-prone areas. Therefore, further research is recommended, which would allow us to identify modifiable factors influencing the concentration of radon and formulate recommendations to reduce contact with this pathogenic element.

Limitations

Apart from interesting findings, our research also has some limitations. First, a weak point is the small size of the study group as well as the choice of houses to be studied. The choice of houses was determined by the occurrence of lung cancer among residents because one of our aims was to check radon concentrations in these houses to protect flatmates from this disease in case of detecting high levels of indoor radon.

In addition, we have adopted a fairly short period of exposure of the detectors, which, however, is accepted in the studies as an adequate time to determine exposure to radon, but we know that a longer exposure could show more reliable results.

Conclusions

Our study shows that higher concentrations of radon occur in buildings located in the countryside. The level of radon was higher in the presence of air conditioning, which intensifies the transport of radon from the soil to the interior of the building. The higher radon concentrations were also associated with the presence of plastic window frames compared to wooden frames. The results of our study can support efforts to reduce radon concentrations to the lowest possible level.

As radon exposure is a modifiable risk factor of lung cancer, finding radon protection methods is extremely important. Since our research was performed in houses of people with lung cancer, our findings could show the way to prevent new lung cancer incidence in patient's flatmates.

Conflict of Interest

The Authors declare that they have no conflict of interests.

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Authors' Contribution

Conception and design of the study: Grzywa-Celińska A. Krusiński A, Kozak K, Mazur J. Acquisition of data: Grzywa-Celińska A. Krusiński A, Chmielewska I, Kozak K, Mazur J, Grządziel D. Analysis and interpretation of data: Grzywa-Celińska A. Krusiński A, Kozak K, Mazur J, Grządziel D., Dos Santos Szewczyk K. Drafting the article: Grzywa-Celińska A. Krusiński A. Chmielewska I. Making critical revisions related to relevant intellectual content of the manuscript: Dos Santos Szewczyk K, Kozak K, Mazur J. Validation and final approval of the version of the article to be published: Milanowski J Supervision, validation, and final approval of the version of the article to be published: Grzywa-Celińska, Milanowski J.

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Data Availability

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

Informed Consent

The informed consent was obtained from the patients participating in the study.

Ethics Approval

The Ethics Approval was obtained from the Medical University of Lublin, Poland (KE 0254/39/2017, 2017.02.23).

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