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**HEALTH RISK ASSESSMENT ASSOCIATED WITH RADON
EXPOSURE**

331.02 – Hygiene

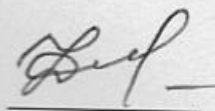
Abstract of the Doctoral Thesis in Medical Sciences

Chisinau, 2026

The thesis was prepared within the Scientific Laboratory of Radiation Hygiene and Radiobiology of the National Agency for Public Health.

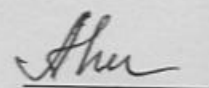
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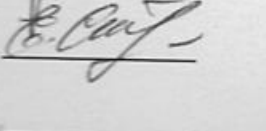
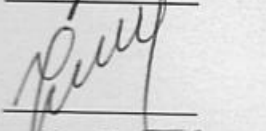
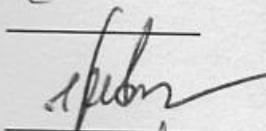
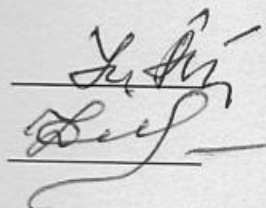
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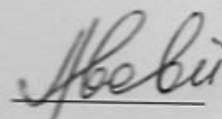
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INTRODUCTION

Relevance and significance of the addressed problem. The relevance of the topic is determined by the continuous increase in lung cancer incidence, correlated with elevated radon levels and the prevalence of tobacco smoking in the population. Studying radon exposure and the synergistic “radon $\times$ smoking” effect is essential for understanding the etiological mechanisms of the disease and for substantiating prevention policies [1–3].

An essential role in affecting human health is attributed to radon (^{222}Rn) and its progeny (^{218}Po , ^{214}Po , ^{214}Pb , and ^{214}Bi), which are responsible for approximately 50% of the total exposure of the population to natural sources of ionizing radiation (IR) [3–7]. Radon is a naturally occurring radioactive, colourless, and odourless gas originating from the Earth's crust that diffuses into indoor environments. Inhalation of its progeny, attached to aerosols, generates alpha (α) particles that interact directly with the bronchial epithelium. Indoor radon exposure is the second leading cause of lung cancer after tobacco smoking and is responsible for 3–14% of all lung cancer cases worldwide [3, 7–12]. The risk is amplified by the synergistic effect of radon $\times$ tobacco smoke.

In the Republic of Moldova, research on population exposure to radon was initiated within the National Agency for Public Health, focusing on radon measurements in dwellings, public buildings, and certain environmental factors (water and soil) [1, 3]. Screening investigations (short-term radon measurements) were not intended to determine population exposure to ionizing radiation sources emitted by radon [3, 7, 12–25]. Subsequent studies carried out with the support of the International Atomic Energy Agency (2018–2020) demonstrated that in 51% of the investigated dwellings radon exceeded the national reference level of 300 Bq/m^3 , while in some cases values above 1000 Bq/m^3 were recorded [4, 13, 14]. These data highlight the need for both dynamic monitoring of residential radon concentrations and epidemiological research on the interaction between radon exposure and other risk factors, particularly smoking as a trigger factor in lung cancer [3, 10]. Council Directive 2013/59/Euratom establishes requirements regarding national reference levels for radon and the development of national action plans [20]. Most countries have developed and are implementing national programmes/action plans for controlling population exposure to radon. In the Republic of Moldova, this objective remains at an early stage. The lack of a national radon risk communication strategy and an updated regulatory framework for radiological protection against natural sources of ionizing radiation, including radon, represents important gaps [15–25]. Thus, the proposed research responds to a pressing public health need, contributing to the development of a scientific basis for reducing oncological risk, improving the national regulatory framework, and integrating the Republic of Moldova into European practices for radon exposure control [10, 28–33]. The lack of representative national metrological and epidemiological data, correlated with the requirements of Council Directive 2013/59/Euratom, required an in-depth analysis of the determinants of exposure and their impact on public health [3, 7, 10, 20].

In this context, the aim and objectives of the present study were formulated.

Aim of the study. Assessment of the health risk associated with radon exposure and development of measures for the control, reduction, and prevention of the influence of the radiological stressor on health, in the context of Council Directive 2013/59/Euratom.

Research objectives:

1. To determine indoor radon concentrations in dwellings located in rural and urban localities of the main geographical regions of the Republic of Moldova using long-term passive and active measurement methods.
2. To investigate the influence of abiotic environmental factors (temperature and humidity) and geological factors (soil type) on indoor radon concentrations.
3. To determine the interaction between residential radon concentration and lung cancer development based on cluster analysis.
4. To investigate the synergism between radon exposure and tobacco smoking in the development of respiratory diseases, including lung cancer, based on correlation and regression analyses using Statistica 10 software.

5. To develop measures for the control, prevention, mitigation, and remediation of the risk associated with population exposure to ionizing radiation caused by radon.

General research methodology. The research used a multidisciplinary approach based on the collection, analysis, and interpretation of data on population exposure to indoor radon and the role of behavioural and abiotic factors in the etiology of lung cancer. The study used a retrospective, cross-sectional, descriptive-analytical design, which allowed assessment of the distribution of radon concentrations across the Republic of Moldova, analysis of the relationship between exposure and health indicators, and investigation of the interaction between radon exposure and tobacco use.

Scientific novelty and originality of the obtained results. For the first time, the study provides original data on the distribution of indoor radon concentrations in dwellings located in the North, Centre, and South development regions of the Republic of Moldova. The research quantifies the effective dose of population exposure exclusively to radon, taking into account the characteristics of the living environment and residential buildings. Furthermore, the analysis of the correlations between radon levels and public health indicators, including the incidence of lung cancer, makes it possible to identify synergistic relationships between radon and other risk factors, such as tobacco consumption.

Scientific problem addressed in the thesis. The research contributed to the assessment of population exposure to radon in the Republic of Moldova and its health effects, providing the scientific basis for revising the national radiological protection regulations and updating the National Radon Action Plan. The results make it possible to identify regions with an increased risk of radon exposure and to guide prevention measures and risk communication strategies, thereby supporting public authorities in reducing the burden of oncological diseases associated with radon exposure.

Theoretical significance of the study. The study results provide original data on population exposure to radon and its interaction with tobacco smoking in the development of lung cancer. These findings contribute to a better understanding of risk mechanisms and the synergistic effects of environmental factors, providing a theoretical basis for population risk assessment and the optimization of public health surveillance.

Practical significance of the study. The study results provide practical support for the development of public health strategies and lung cancer prevention by identifying areas with an increased risk of radon exposure and vulnerable population groups. The collected data support the planning of monitoring, information, and intervention measures at both national and regional levels, contributing to the development of integrated policies for reducing exposure to natural ionizing radiation and to evidence-based decision-making by public health authorities in accordance with European radiological protection standards.

Implementation of the scientific results. The scientific results were implemented through their validation at national and international scientific conferences and invention and innovation exhibitions, forming the basis for the development of a Guideline on Radon Risk Communication and two monographs dedicated to population exposure to radon in the Republic of Moldova and the methodology for measuring radon in dwellings.

Validation of the results. The scientific results obtained were presented and discussed at the following scientific forums: the International Scientific Conference “The One Health Approach in a Changing World”, Chişinău, 4–5 November 2021; the 16th International Specialized Exhibition of Intellectual Property, Creativity and Innovation INFOINVENT 2021, 20–23 November 2021; the 13th European Exhibition of Creativity and Innovation – EUROINVENT 2021, Iaşi, Romania; the 14th European Exhibition of Creativity and Innovation – EUROINVENT 2022, Iaşi, Romania, 26–28 May 2022; the Annual Scientific Conference Research in Biomedicine and Health: Quality, Excellence and Performance, 19–21 October 2022; the 37th International Scientific Conference “Perspectives of Balkan Medicine in the Post-COVID-19 Era”, Chişinău, 7–9 June 2023; the 15th European Exhibition of Creativity and Innovation – EUROINVENT 2023, Iaşi, Romania, 11–13 May 2023; the 11th Conference of the Doctoral Schools of Dunărea de Jos University of Galaţi, Perspectives and Challenges in Doctoral Research, Galaţi, Romania, 8–9 June 2023; INVENTICA 2023 – the 27th International Exhibition of Inventions, Iaşi, Romania; the Scientific Conference Cultural Heritage of Yesterday – Implications for the Development of

Tomorrow's Sustainable Society, 8th edition, Chişinău, 8–9 February 2024; Iasi–Chisinau–Lviv, 9th edition, 2024; the National Conference of the Romanian Society for Radiological Protection (SRRp) entitled “The Use of Radiation for the Benefit of the Sustainable Development of Romanian Society”, Bucharest, Romania, 17 October 2024; the 12th Conference of the Doctoral Schools of Dunărea de Jos University of Galaţi, Perspectives and Challenges in Doctoral Research, Galati, Romania, 8–9 June 2024; the 16th European Exhibition of Creativity and Innovation – EUROINVENT 2024, Hybrid Edition, Iaşi, Romania, 5–8 June 2024; INVENTCOR 2025 – The 6th International Exhibition, Deva, Romania, 3–5 April 2025; the International Conference on Applications of Radiation (RAP 2025), Hellenic Centre for Marine Research (HCMR), Gournes–Heraklion, Crete, Greece, 26–30 May 2025; the 17th European Exhibition of Creativity and Innovation – EUROINVENT 2025, Hybrid Edition, Iaşi, Romania, 8–10 May 2025; and the 6th National Conference with International Participation dedicated to the National Congress of Oncology 2025, Chişinău, Republic of Moldova, 9–10 October 2025.

Publications related to the thesis. Based on the thesis materials, 67 scientific works and research outputs were prepared and published, including 2 monographs, 1 guide, 6 articles published in journals indexed in recognized international databases, including Web of Science, Scopus and EBSCO, of which 3 were single-author articles, 2 articles published in national scientific journals of category B, 6 articles in proceedings of international scientific conferences, and 34 abstracts, summaries, and theses published in the proceedings of national and international scientific conferences and events. The research results were also disseminated through participation in invention and innovation exhibitions and salons, as well as 9 active participations in scientific forums, including 4 oral presentations and 5 poster presentations. The list also includes 6 scientific works protected by copyright and 2 innovator certificates.

“Quantification of the Health Risk Associated with Exposure to Ionizing Radiation in the Context of Council Directive 2013/59/Euratom,” 2020–2023, Project No. 20.80009.8007.20.

“Monitoring Occupational and Public Exposure to Ionizing Radiation and Development of Radiological Protection Measures,” 2024–2027, Project No. 13.01.02.

Furthermore, the research results were discussed and approved at the joint meeting of the Scientific Laboratory of Radiation Hygiene and Radiobiology of the National Agency for Public Health (Minutes No. 15 of 28 April 2026) and at the meeting of the Specialized Scientific Seminar of the Nicolae Testemiţanu State University of Medicine and Pharmacy, Profile 331 – Public Health, specialties: 331.01 Epidemiology and 331.02 Hygiene, and Profile 333 – Occupational Health and Biomedicine, specialty 333.01 Occupational Hygiene (Minutes No. 8 of June 18th 2026).

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The body of work on radon exposure was recognized at the governmental level and was awarded the Excellence Scholarship of the Government of the Republic of Moldova for doctoral students, in accordance with Government Decision No. 70 of 22 February 2023.

Volume and structure of the thesis. The thesis is written in Romanian and comprises 125 pages, including the title page, table of contents, list of tables and figures, introduction, five chapters, discussion, research limitations, general conclusions and practical recommendations, a bibliography comprising 209 references, 6 appendices, the declaration of responsibility, and the author's curriculum vitae. The illustrative material includes 20 tables and 69 figures. The doctoral research received a favourable opinion from the Research Ethics Committee of the Nicolae Testemiţanu State University of Medicine and Pharmacy (Minutes No. 2 of 21 September 2021).

CONTENT OF THE THESIS

1. Health risk assessment associated with radon exposure

A comprehensive analysis of the data regarding population exposure to radon in the Republic of Moldova, in both rural and urban areas, was carried out, taking into account the geoclimatic, geological, and socio-economic characteristics affecting public health. The study analysed the existing legislative framework and the prevention and assessment practices applied in different countries, with particular emphasis on Council Directive 2013/59/Euratom. The assessment revealed major gaps in the system for monitoring, reporting, and controlling residential radon exposure in the Republic of Moldova. The absence of a nationally adopted regulatory framework (National Radon Action Plan) was identified. To address this issue, the research included direct measurements of indoor radon concentrations, calculation of exposure doses, mapping of these doses, and analysis of their correlation with environmental factors and behavioural risk factors (tobacco smoking). An additional sociological study on public knowledge provided evidence supporting the need to implement radon risk communication measures, thereby confirming the relevance and timeliness of implementing the National Radon Action Plan.

2. MATERIALS AND RESEARCH METHODS

The research is multidisciplinary in nature and is based on a comprehensive methodology integrating descriptive, analytical, and epidemiological observational components, using radiometric, clinical, and epidemiological data. The study was designed and conducted in accordance with the recommendations of the World Health Organization (WHO), the International Atomic Energy Agency (IAEA), and the provisions of Council Directive 2013/59/Euratom, with the aim of assessing the impact of residential radon exposure on the health of the population of the Republic of Moldova.

The research algorithm was structured into three consecutive stages. The first stage included the methodological and ethical framework of the study, the development of the research protocol, obtaining the approval of the Ethics Committee, the conclusion of the collaboration agreement between the National Agency for Public Health and the Oncology Institute, as well as the design of the sampling procedure using stratified random sampling based on the Lambert–GISCO grid.

The second stage included: measurement of residential radon concentrations in 1,099 dwellings using passive RADTRAK² detectors (90-day exposure); assessment of public knowledge and perception regarding radon in a sample of 400 respondents using the IAEA questionnaire (Regional Project – STEAM RER9153); a descriptive observational study of lung cancer morbidity using data from the National Agency for Public Health and data on tobacco-use prevalence from the STEPS 2021 study; and an epidemiological case–control study for which the sample size was calculated as 93 participants for each group. The final analysis included 72 complete epidemiological questionnaires in the case group, of which 69 patients had radon concentration measurements, while the control group included 106 persons. During the third stage, the data were analysed using descriptive statistics, normality tests, correlation analyses, and cluster analysis, using Statgraphics Centurion XVIII, SPSS, and Microsoft Excel. The results were integrated into geographic information systems for spatial modelling of residential radon concentration distribution and development of the national digital map according to the JRC methodology. The research substantiated the development of recommendations for radon exposure control, preparation of the national radon risk communication guide, and updating of the Programme, including the National Action Plan on Radon Exposure Control; the results were disseminated through scientific publications and presentations (figure 1).

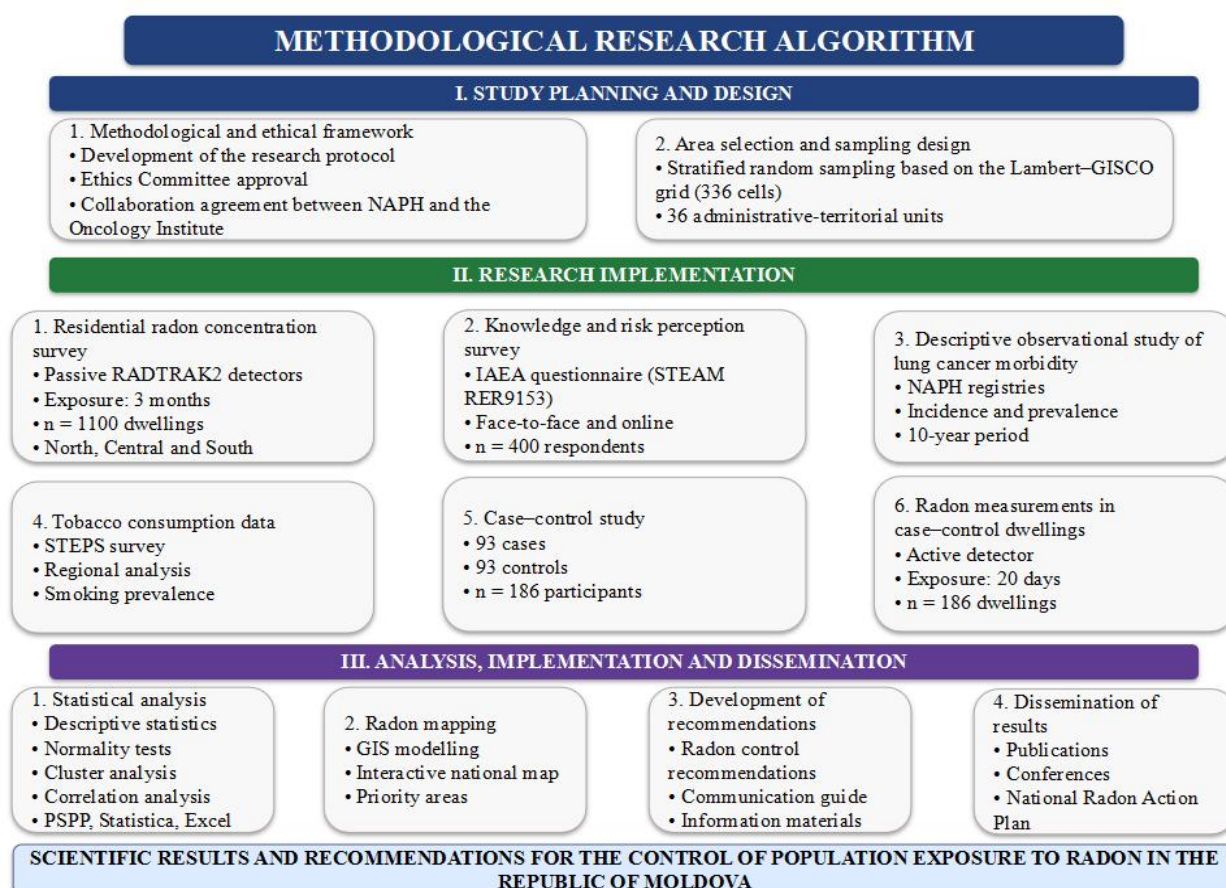


Figure 1. Research design

3. ASSESSMENT OF THE RESULTS OF RADON CONCENTRATION MEASUREMENTS IN DIFFERENT TYPES OF DWELLINGS IN URBAN AND RURAL AREAS OF THE REPUBLIC OF MOLDOVA

3.1. Assessment of the results of radon investigations in different types of dwellings in urban and rural areas

The results of the study revealed significant variability in radon concentrations in dwellings across the Republic of Moldova. The maximum recorded values were 1,160 Bq/m³ in the Central region, 1,260 Bq/m³ in the Northern region, and 950 Bq/m³ in the Southern region, while the mean concentrations were 211.67 Bq/m³, 240.55 Bq/m³, and 285.57 Bq/m³, respectively, remaining below the national reference level of 300 Bq/m³. Nevertheless, a considerable proportion of dwellings exceeded the reference level, accounting for 25.3% in the Central region, 31.06% in the Northern region, and 38.58% in the Southern region.

The assessment of radon concentrations in urban and rural dwellings across the regions of the Republic of Moldova, constructed between 1820 and 2020, demonstrated lower concentrations in urban buildings compared with rural dwellings, with the exception of the Central region, where the opposite trend was observed. The lowest concentrations were recorded in dwellings constructed during the periods 1921–1940 (Central region – 90.5 Bq/m³) and 1981–2000 (204.7–245.9 Bq/m³), whereas the highest values, ranging from 250.0 to 381.8 Bq/m³, were identified in dwellings constructed during other periods, exceeding the national radon reference level.

The distribution of radon concentrations across the three geographical regions of the Republic of Moldova is determined by local geological and climatic characteristics. The Central region, characterized by clay soils and low-permeability sedimentary bedrock, showed a higher proportion of locations (51.56%) with radon concentrations below 150 Bq/m³. In the Northern region, crystalline geological formations and a humid climate contributed to greater variability in radon concentrations, with 31.06% of

the investigated locations exceeding 300 Bq/m³. The Southern region, characterized by permeable sandy soils and a warm, dry climate, favours radon accumulation, with 38.58% of the investigated locations recording concentrations above the reference level. In addition, the stack effect, which is more pronounced during the cold season, enhances radon migration from the soil into dwellings, particularly in buildings with negative pressure at the basement and ground-floor levels (figure 2).

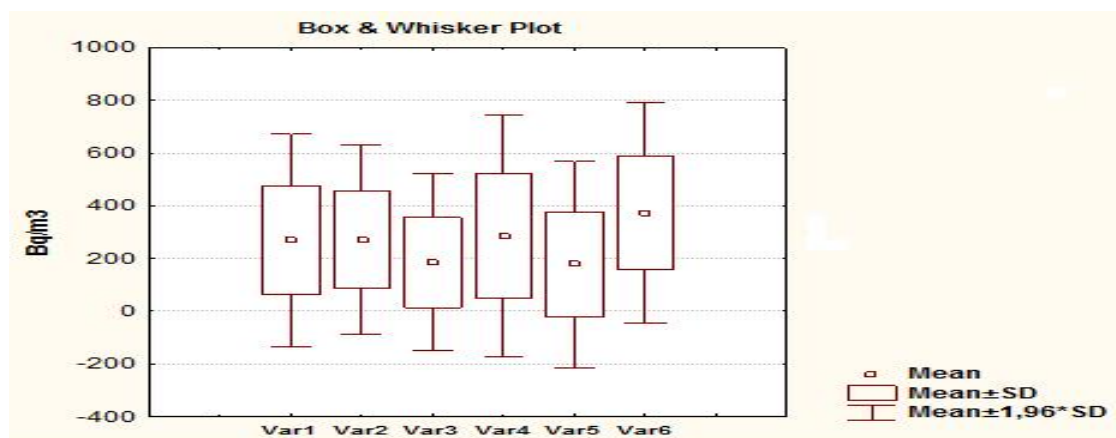


Figure 2. Radon concentration (Bq/m³) in the development regions of the Republic of Moldova

Var1 – North Development Region, urban area; Var2 – North Development Region, rural area; Var3 – Central Development Region, urban area; Var4 – Central Development Region, rural area; Var5 – South Development Region, urban area; Var6 – South Development Region, rural area.

3.2. Quantification of indoor radon exposure in the north, central, and south regions of the Republic of Moldova

The descriptive statistical analysis of radon concentrations measured in the investigated dwellings across the different development regions of the Republic of Moldova revealed relevant territorial variations. The mean radon concentration was 211.67 Bq/m³ in the Central region, 240.55 Bq/m³ in the Northern region, and 285.57 Bq/m³ in the Southern region, indicating the highest levels in the southern part of the country. Likewise, the median values followed the same increasing trend (140.00 Bq/m³, 180.00 Bq/m³, and 250.00 Bq/m³, respectively), suggesting a non-uniform distribution of radon concentrations across the country. The variability of the data was comparable among the regions, with standard deviations ranging from 199.24 to 207.78 Bq/m³.

Table 1. Descriptive statistical indicators of the distribution of radon concentrations across the Central, Northern, and Southern geographical regions of the Republic of Moldova

		DEVELOPMENT REGIONS		
		Central	Northern	Southern
Total,1099	Valide, 1099	450	396	253
Mean (M) Bq/m ³		211,67	240,55	285,57
Standard Error of the Mean(SEM)		9,42	11,05	12,93
95% Confidence Interval, (95% CI)		193,2 - 230,1	220,1 - 261,0	260,5 - 310,6
Median (M _e), Bq/m ³		140,00	180,00	250,00
Standard Deviation (SD)		199,240	207,783	202,773
Maximum Value, Bq/m ³		1160	1260	950
Range		1150	1250	940
Interquartile Range (IQR)		268,66	280,29	273,54

3.3. Analysis of the Results of Indoor Radon Concentration Measurements in Dwellings in Chişinău Municipality

The analysis of indoor radon concentrations measured in 265 investigated dwellings in Chişinău Municipality revealed a mean value of 158.62 Bq/m³ and a median of 71.00 Bq/m³, suggesting a skewed distribution of the data, influenced by the presence of elevated radon concentrations. The variability of the data was high, as reflected by a standard deviation of 173.14 Bq/m³ and a coefficient of variation of 119.9%, with values ranging over a wide interval (range of 930 Bq/m³) and a maximum value of 940 Bq/m³.

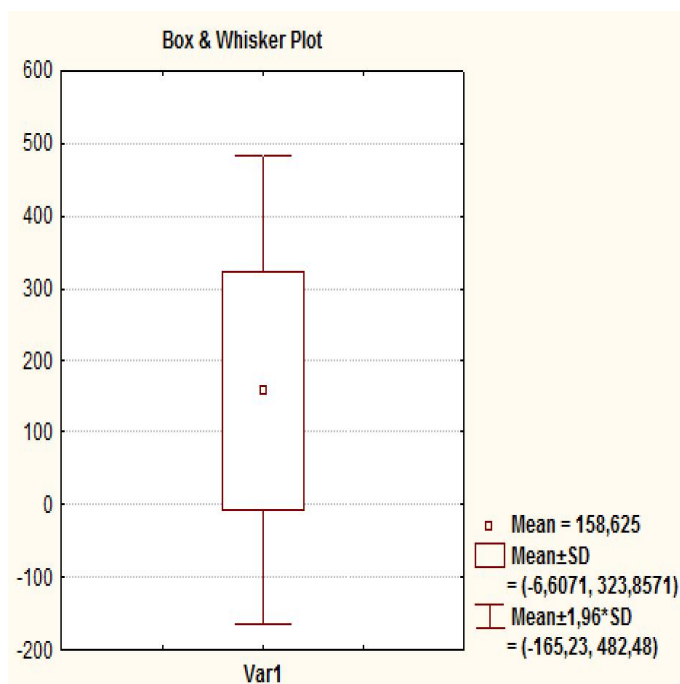


Table 2. Descriptive statistics of residential radon concentrations in Chişinău Municipality

<i>Radon concentration, Bq/m³</i>	
Valid cases (N)	265
Mean, Bq/m ³	158,62
Median	71,00
Standard deviation	173,144
Interquartile range (IQR)	45,0 - 230,0
Maximum value, Bq/m ³	940
Standard error	10,64
95% confidence interval	137,7-179,47
Coefficient of variation, %	119,9
Geometric mean, Bq/m ³	90
Range	930

Figure 3. Radon concentration (Bq/m³) in the indoor air of dwellings in Chişinău Municipality

The geometric mean of 90 Bq/m³ indicates that the majority of dwellings had relatively moderate radon concentrations; however, the presence of extreme values confirms the heterogeneity of residential radon exposure in the urban environment.

3.4. Risk assessment, including the calculation of individual exposure doses at different residential radon concentrations

The results of passive radon measurements performed using RADTRAK2 detectors with a 90-day exposure period showed that, of the 1,099 investigated dwellings, 45.1% were classified as low risk (≤ 150 Bq/m³), 24.5% as moderate risk (150–300 Bq/m³), and 30.4% exhibited radon concentrations corresponding to the high-risk category (> 300 Bq/m³). Regional analysis demonstrated a non-uniform distribution of risk, with the highest proportion of low-risk dwellings observed in the Central region (51.8%) and the highest proportion of high-risk dwellings in the Southern region (38.4%), confirming the existence of significant geographical differences in population exposure to radon in the Republic of Moldova.

Table 3. Results of radon concentration measurements using RADTRAK2 detectors (passive measurement, 90-day exposure period) in dwellings located in rural and urban areas of the Republic of Moldova, classified according to the risk associated with residential radon concentration ranges

Development Region	Low risk (≤ 150 Bq/m³)			Moderate risk (150-300 Bq/m³)			High risk (>300 Bq/m³)			Total number of dwellings	
	Number of dwellings										
	V. abs	%	(95% CI)	V. abs	%	(95% CI)	V. abs	%	(95% CI)	V. abs	%
Central	233	51,8	47,2-56,4	103	22,9	19,0-26,8	114	25,3	21,3-29,3	450	100
North	182	46,0	41,1-50,9	91	23,0	18,9-27,1	123	31,0	26,4-35,6	396	100
South	81	32,0	26,2-37,8	75	29,6	23,9-35,3	97	38,4	32,4-44,4	253	100
Total	496	45,1	42,1-48,1	269	24,5	22,0-27,0	334	30,4	27,7-33,1	1099	100

The analysis of the mean annual effective dose from radon exposure across the regions of the Republic of Moldova revealed significant exceedances of the reference level of 4 mSv/year, established in accordance with Council Directive 2013/59/Euratom. The calculated mean values were 13.47 mSv/year in the Southern Development Region, 11.35 mSv/year in the Northern Development Region, and 9.98 mSv/year in the Central Development Region, corresponding to residential radon concentrations ranging from 211.67 to 285.57 Bq/m³(table 4).

Table 4. Mean annual effective dose ($\pm$ SD) (mSv/year) from residential radon exposure across the development regions of the Republic of Moldova

Development Region	Mean Radon Concentration Bq/m ³ ($\pm$ SD)	Mean Effective Dose, mSv/year($\pm$ SD)
North	240,55 $\pm$ 207,783	11,35 $\pm$ 9,88
Central	211,67 $\pm$ 199,240	9,98 $\pm$ 9,42
South	285,57 $\pm$ 202,773	13,47 $\pm$ 9,58

The results indicate a high level of population exposure, particularly in the Southern Development Region, and justify the need to implement national measures for monitoring, mitigation, and prevention of radon-related health risks. All three analysed development regions recorded annual effective doses from radon exposure that substantially exceeded the 4 mSv/year threshold, which is considered a reference level for initiating remediation measures (figure 4).

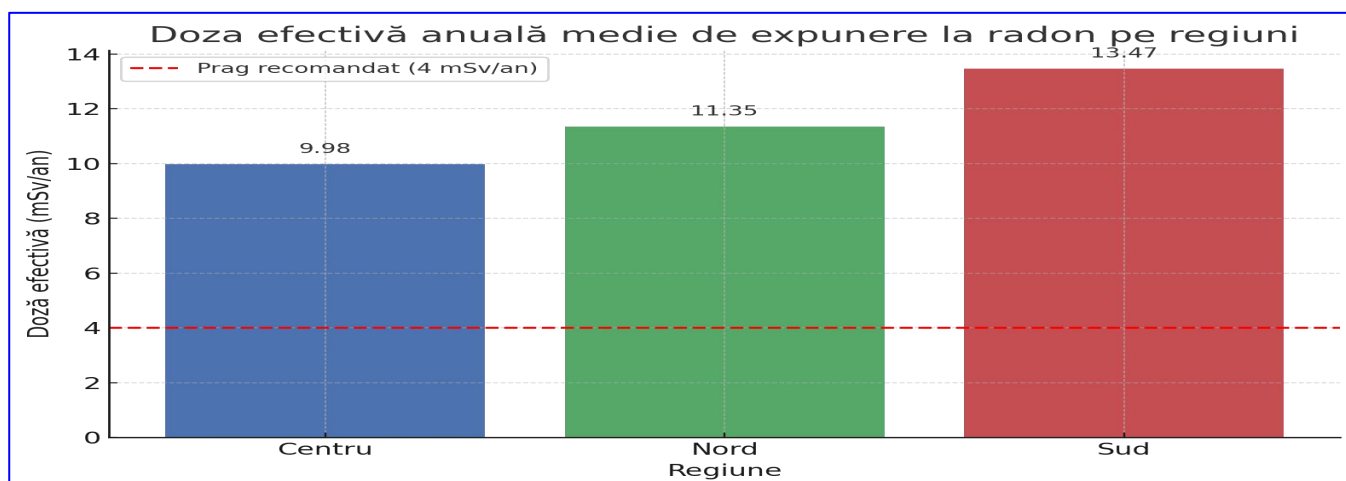


Figure 4. Mean annual effective dose from residential radon exposure according to the development regions of the Republic of Moldova (Central, Northern, and Southern)

The calculation of the excess risk of lung cancer demonstrated a directly proportional relationship between radon concentration and the probability of developing the disease. At exposure levels exceeding 300 Bq/m³, the estimated risk of developing lung cancer is approximately 6%, corresponding to an incidence of approximately one case per 17 individuals exposed over their lifetime. The analysis of the distribution of radon concentrations made it possible to estimate the excess risk of lung cancer by development region and category of residential radon exposure (figure 5).

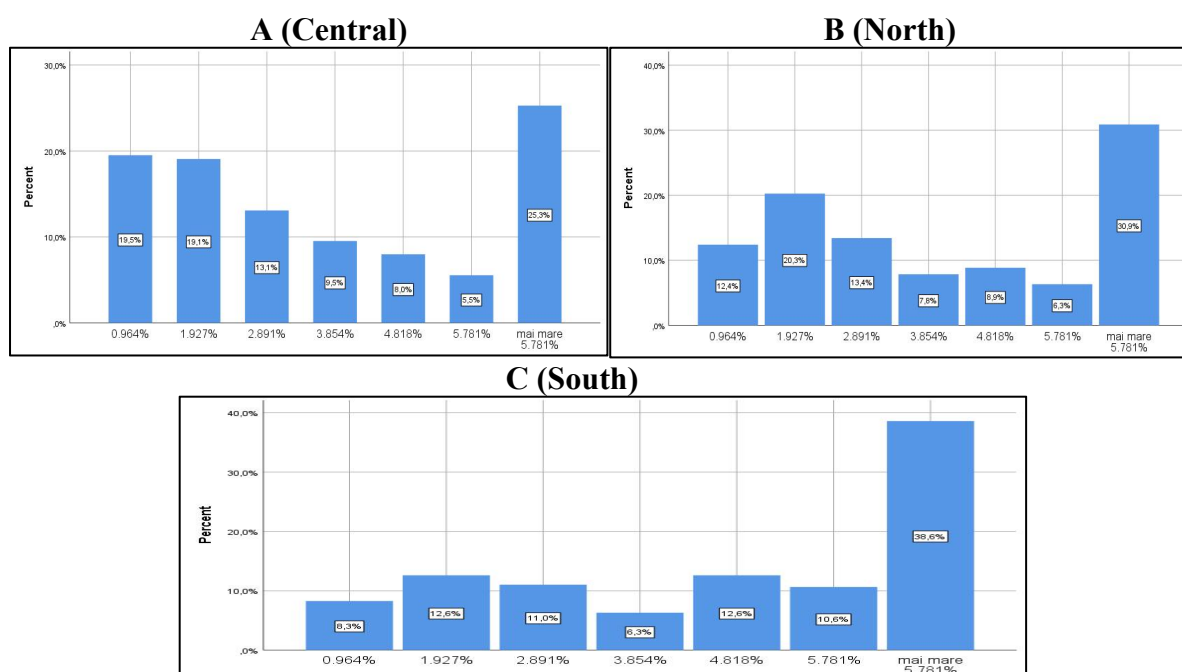


Figure 5. Distribution of residential radon concentrations in the Central, Northern, and Southern Development Regions according to the lifetime excess risk of lung cancer for residential radon concentration ranges of ≤50 Bq/m³, 51–100 Bq/m³, 101–150 Bq/m³, 151–200 Bq/m³, 201–250 Bq/m³, 251–300 Bq/m³, and >300 Bq/m³

3.5. Investigation of the interaction between radon and abiotic environmental factors

Cluster analysis revealed a strong correlation between radon concentration and climatic variables (air temperature, soil surface temperature, and relative humidity), highlighting the influence of the interdependence of these factors on radon dynamics. The study identified a pronounced seasonal variation in residential radon concentrations.

During the cold season, the highest radon concentrations were recorded, resulting from an inverse relationship with temperature and a reduced natural ventilation rate (to preserve indoor heat), which favours the accumulation of radon in enclosed spaces.

During the warm season, radon concentrations decreased significantly due to increased ventilation and a more pronounced temperature gradient between the soil and the atmosphere (figure 6).

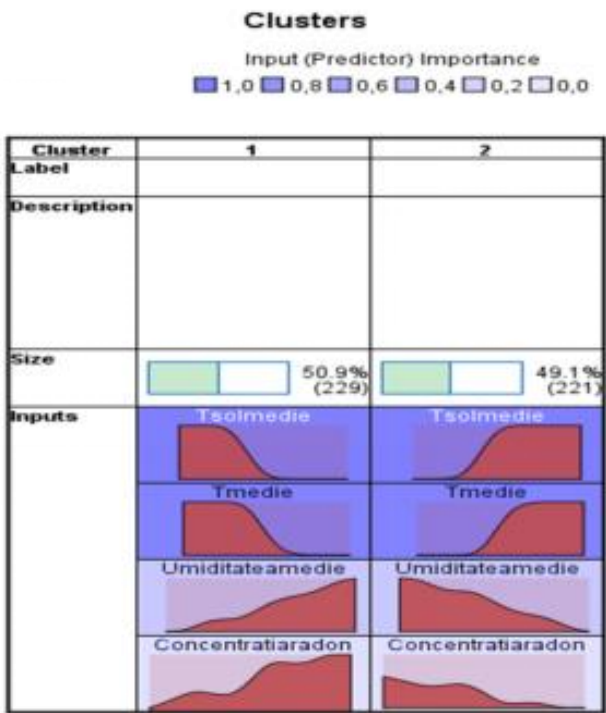


Figure 6. Cluster analysis of the interaction between radon concentration and environmental factors

The statistical models confirmed the major influence of thermal variables on radon concentration, highlighting the role of thermal processes and local atmospheric conditions in radon accumulation. These findings emphasize the multifactorial nature of seasonal variations in radon concentrations and the need to incorporate climatic parameters into predictive models and radon exposure risk management strategies. These results underline the importance of radon risk mapping and population exposure monitoring, providing a solid basis for preventive measures aimed at reducing the incidence of radon-associated lung cancer.

3.6. Mapping of indoor radon concentrations across the republic of moldova and identification of localities at increased risk of radon exposure

The spatial mapping of indoor radon concentrations across the territory of the Republic of Moldova revealed a non-uniform geographical distribution of population exposure. Static and interactive cartographic representations enabled the identification of regional differences, showing an increasing trend in radon concentrations in the southern areas (shown in red), intermediate values in the central region (yellow), and relatively lower levels in the northern region (blue). The spatial analysis confirmed the presence of geographical hotspots of elevated radon exposure, suggesting the need to prioritize monitoring and risk reduction interventions in areas with higher radiological burden (figure 7).

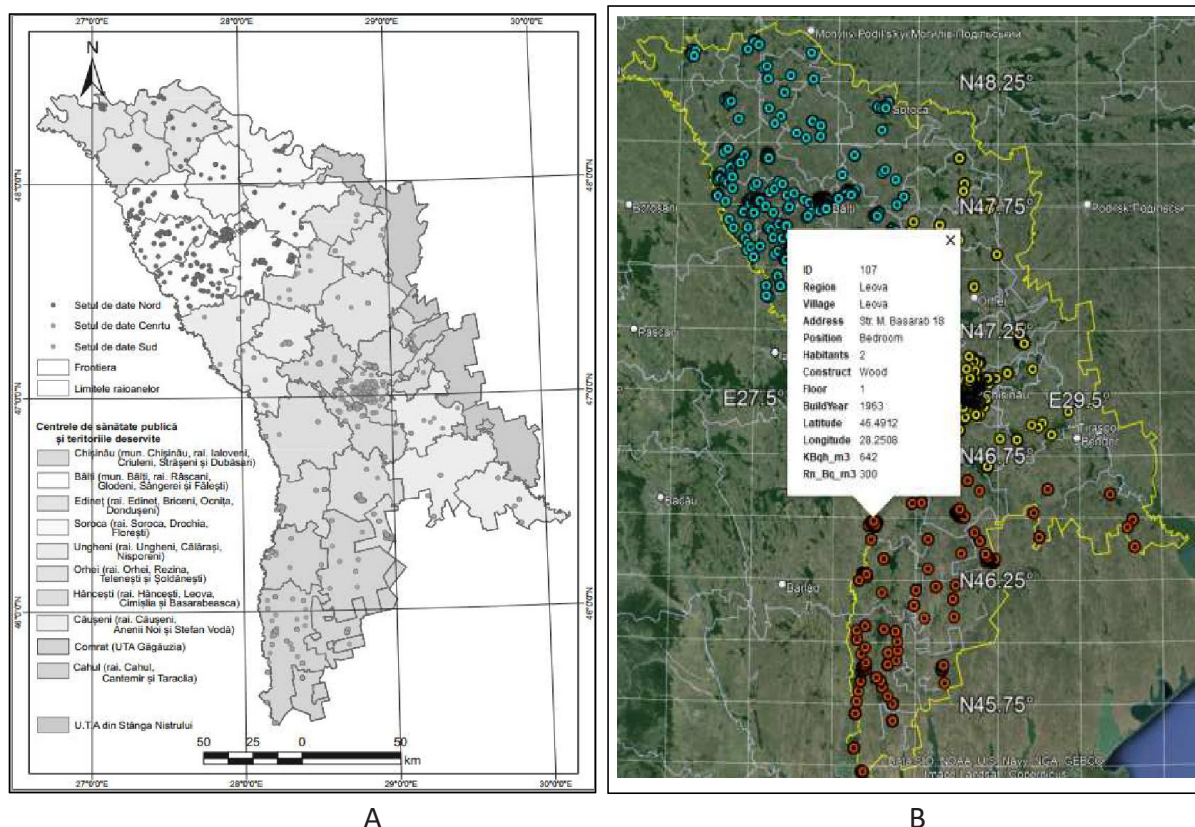
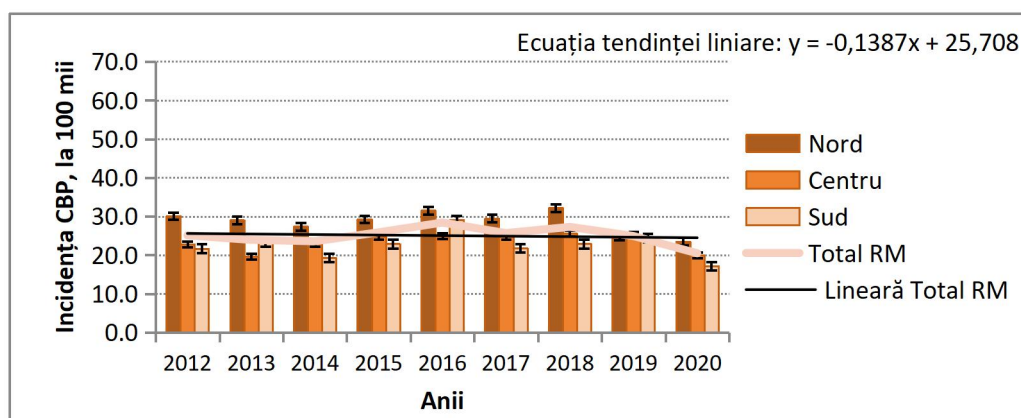


Figure 7. Spatial distribution map (A) and interactive map (B) of indoor radon concentrations in different types of dwellings across the Republic of Moldova (North – blue, Central – yellow, South – red)

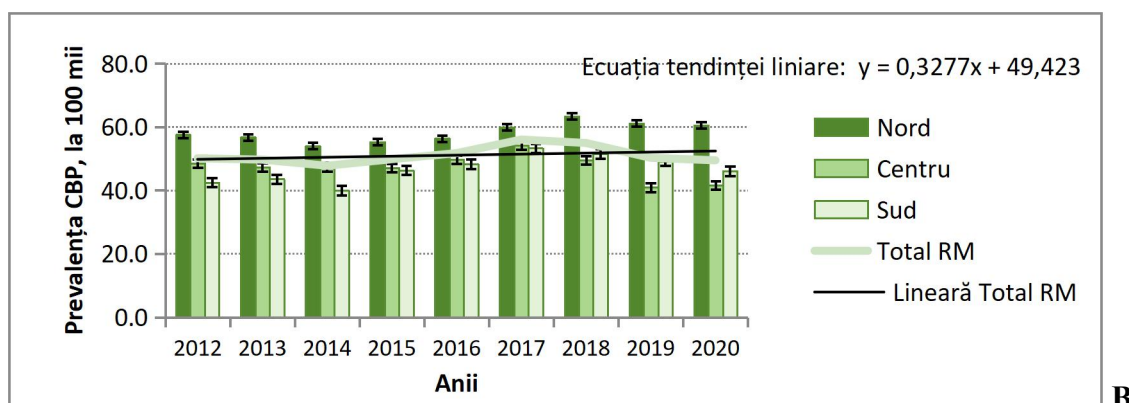
4. DETERMINATION OF THE INTERACTION BETWEEN “INDOOR RADON CONCENTRATION × TOBACCO SMOKING × LUNG CANCER DEVELOPMENT” AT THE POPULATION AND PATIENT LEVEL USING STATISTICAL METHODS

4.1. Determination of the interaction between “indoor radon concentration × tobacco smoking × lung cancer development” at the population level using statistical methods

Based on the statistical evaluation of the interaction between radon exposure, national tobacco consumption, and lung cancer morbidity indicators, cluster analyses demonstrated significant interactions between radon exposure and tobacco smoking, acting synergistically as triggering factors in the development of lung cancer.



A



B

Figure 8. Lung cancer incidence (A) and prevalence (B) per 100,000 population, 2012–2020

A comparative analysis of radon exposure indicators and epidemiological parameters by region revealed significant regional differences across the Republic of Moldova. The mean volumetric activity concentration of radon ranged from 237.9 Bq/m³ in the Northern region and 246.0 Bq/m³ in the Central region to 316.6 Bq/m³ in the Southern region, with a national mean of 261.8 ± 213.97 Bq/m³. The maximum value reached 971.5 Bq/m³ in the Southern region, indicating the presence of areas with elevated radiological exposure, while the minimum concentrations ranged from 11.7 to 20.0 Bq/m³. Assessment of behavioural risk factors showed a heterogeneous regional distribution of smoking prevalence, with a higher rate in the Central region (1,021.1 per 100,000 population) compared with the Northern and Southern regions. Lung cancer incidence ranged from 22.5 to 28.6 per 100,000 population, while prevalence varied from 46.7 to 58.3 per 100,000 population. These findings indicate a heterogeneous regional distribution of the analysed indicators and support a multifactorial interpretation of the relationship between radon exposure, tobacco smoking, and lung cancer (table 5).

Table 5. Descriptive statistical indicators of the variables studied across the regions of the Republic of Moldova

Variabila	Region			
	<i>Northern</i>	<i>Central</i>	<i>Southern</i>	<i>National total</i>
Mean radon concentration, Bq/m ³ , (±DS)	237,9 ±209,4	246,0 ±199,8	316,6 ±203,2	261,8 ±213,97
Maximum radon concentration, Bq/m ³ (2019)	834,2	873,8	971,5	885,7
Minimum radon concentration, Bq/m ³	20,0	11,7	14,7	15.4
Total number of smokers (per 100,000 population), 2013 (aged 18–69 years) (±SD)	572,3 ±159,79	1021,1 ±1030,14	545,2 ±286,2	736,7 ±971,8
Lung cancer incidence (per 100,000 population), 2012–2020 (±SD)	28,6± 3,34	23,4±3.98	22,5±3,6	25,0 ±4,48
Lung cancer prevalence (per 100,000 population), 2012–2020 (±SD)	58,3±23,2	47,4±18,55	46,7±19,3	51,1 ±20,61

The overlay analysis of the lung cancer incidence maps and the residential radon concentration maps demonstrated that the health effects are cumulative, with the outcome of chronic exposure being influenced by tobacco smoking and other exogenous factors.

4.2. Determination of the interaction between “indoor radon concentration × tobacco smoking × lung cancer development” Using the case–control methodology

The results of the epidemiological case–control study showed an association between residential radon exposure and lung cancer. The final analysis included 69 cases for which radon concentration measurements were available and 106 participants in the control group. The mean radon concentration was higher in the case group (183.67 Bq/m³) than in the control group (148.47 Bq/m³), as shown in figure 10.

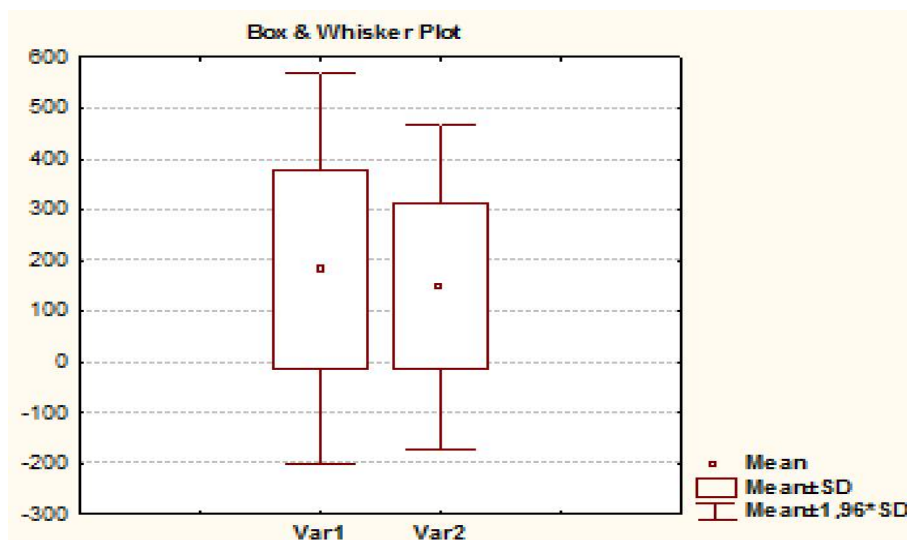


Figure 10. Distribution of radon concentrations in the case–control study groups: patients with lung cancer (Var1) and the control group (Var2)

The analysis of smoking history showed a higher proportion of participants with more than 10 years of smoking experience in the case group (29.21%) than in the control group (9.47%). Exposure to tobacco smoke at the workplace was also more frequent among patients with lung cancer (51.69%) than among controls (37.89%). Analysis of the clinical-anatomical forms of lung cancer showed a predominance of central endobronchial forms (45.6%), followed by peripheral lung cancer presenting as a spherical tumour (42.2%).

Statistical analysis of the data presented in Table 19 showed a statistically significant association between radon exposure and lung cancer in the studied sample. For exposure to radon concentrations ≥ 200 Bq/m³, the odds ratio was 2.60 (95% CI: 1.30–5.20; $p = 0.01$), indicating 2.6-fold higher odds of belonging to the case group compared with participants exposed to concentrations below this threshold. The proportion of participants exposed to radon concentrations ≥ 200 Bq/m³ was higher in the case group, at 37.68%, compared with 18.87% in the control group, supporting an association between residential radon exposure and the disease.

With regard to chronic tobacco use, an OR of 0.81 (95% CI: 0.36–1.84; $p > 0.05$) did not indicate a statistically significant association in the studied sample. This finding should be interpreted with caution, including in the context of the limited sample size and the small number of chronic smokers in the case group. Of the 11 participants with chronic tobacco use in the case group, all were simultaneously exposed to radon concentrations ≥ 200 Bq/m³, with some values ranging from 600 to 800 Bq/m³. This overlap of exposures in this subgroup suggests a possible interaction between radon exposure and tobacco use; however, the results obtained in the present sample do not allow statistical confirmation of a synergistic or multiplicative effect.

Table 6. Comparative analysis of risk factors in the case–control study

		<i>Radon exposure >200 Bq/m³</i>	<i>Radon exposure <200 Bq/m³</i>	<i>Chronic tobacco smoking</i>	<i>No tobacco smoking</i>
Cases (patients with lung cancer)	Number (n)	26	43	11	58
	%	37,68	62,32	15,94	84,06
	95% CI	26,1-49,2	50,8-73,9	7,3- 24,6	75,4-92,7
Controls (without oncological disease)	Number (n)	20	86	20	86
	%	18,87	81,13	18,87	81,13
	95% CI	11,5-26,2	73,8-88,5	11,5-26,2	73,8-88,5

5. ASSESSMENT OF PUBLIC KNOWLEDGE REGARDING RADON EXPOSURE AND DEVELOPMENT OF RECOMMENDATIONS FOR RADON EXPOSURE CONTROL

5.1. Assessment of the results of the population survey on knowledge of radon exposure

The analysis of the data obtained through the questionnaire revealed a low level of public awareness regarding the risks associated with radon exposure, despite the respondents' declared willingness to undertake corrective measures if the reference level of 300 Bq/m³ is exceeded. Although the majority of respondents acknowledged the impact of air quality on health (73.9%) and recognized radon as a risk factor for lung cancer (64.4%), only approximately 10% reported having detailed knowledge of the risks associated with radon (figure 11).

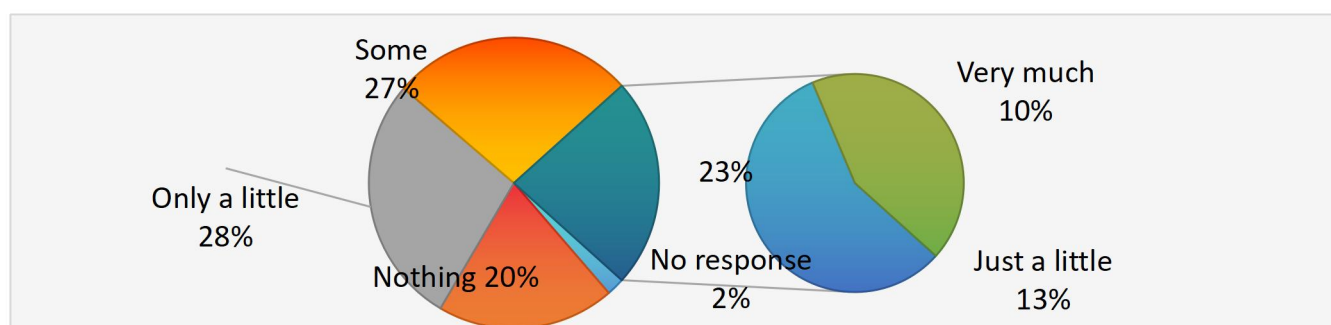


Figure 11. Level of knowledge regarding the health effects of radon

At the same time, 69.93% (95% CI: 65.2–74.3) considered home testing a priority and stated that they would take immediate action if the limit values were exceeded. The results highlighted the importance of risk communication channels, showing that the mode and format of information delivery influence public perception and action. The study revealed a cognitive asymmetry between invisible risks, such as radon, and highly publicized risks, which may lead to an underestimation of the health effects of radon (figure 12).

The analysis of responses regarding the frequency of information sources used indicates that respondents obtain information about radon and health risks from a variety of sources, with differing frequency and levels of trust. The Internet was identified as a frequently used source by approximately 51% (95% CI: 46.1–55.9), followed by television at 28% (95% CI: 23.6–32.4) and the National Agency for Public Health at approximately 30% (95% CI: 23.6–32.4). Traditional sources, such as radio and the printed

press, were perceived as less relevant, with a majority of 60.0% (95% CI: 55.2–64.8) of respondents indicating that they used them “just a little” or “not at all” (figure 12).

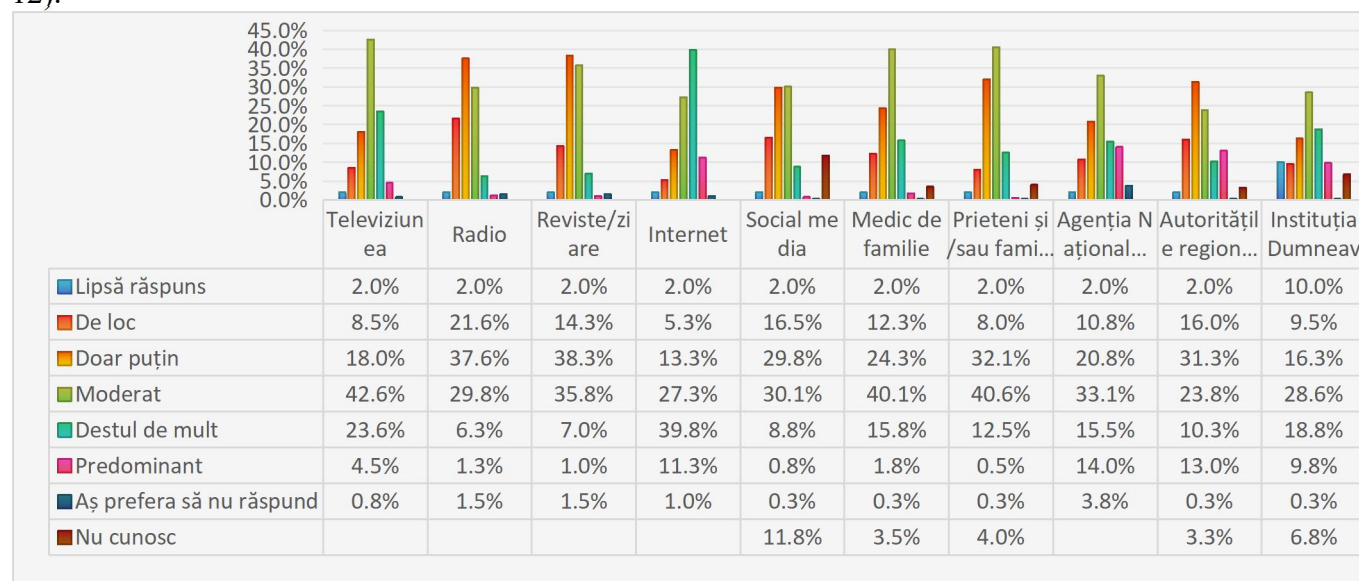


Figure 12. Main sources of information on health risks reported by the respondents

Furthermore, medical sources, such as family physicians, and institutional sources, including local authorities or respondents’ own institutions, were less frequently reported as the main channels of information. Public trust in healthcare professionals and public health authorities represents a key factor in the success of information campaigns and in the implementation of testing and remediation interventions in high-risk areas. The implementation of an effective radon risk communication strategy requires a multisectoral and adaptive approach that integrates active public participation, adherence to testing and remediation campaigns, as well as the involvement of public institutions and decision-makers in achieving the common objective of reducing chronic exposure and the population-level risk associated with radon.

5.2. Development of Recommendations for the Implementation of the Risk Communication Strategy on Exposure to Natural Ionizing Radiation, Including Radon

The analysis of perceptions regarding the risk of radon exposure revealed a low level of awareness among the population, characterized by a discrepancy between the declared willingness to take protective measures and the actual perception of the risk associated with radon exposure. The assessment of the population’s general knowledge showed that most respondents considered radon to be an insignificant risk factor, whereas highly publicized threats were perceived as more important, reflecting a limited culture of prevention. This finding highlights the need for educational and risk communication campaigns promoted by public health authorities and healthcare professionals, who are regarded as credible sources of information. Based on the results obtained, the implementation of integrated and multisectoral public policies is required, including continuous nationwide monitoring and mapping of radon concentrations, the establishment of technical regulations for new buildings, remediation measures for existing dwellings, and communication strategies adapted to the socio-cultural context of the population. These measures may contribute to reducing exposure to radon and the associated risk of lung cancer, while strengthening public health in the Republic of Moldova, in accordance with international practices and the scientific evidence presented in this thesis.

5.3. Development of the draft national programme and action plan for radon exposure control

Based on the research findings, a draft National Programme “On the Control of Radon Exposure for 2026–2030” and the related National Action Plan were developed, aimed at establishing a strategic framework for reducing population exposure to radon in the Republic of Moldova. The Programme proposes harmonizing national legislation with the provisions of Directive 2013/59/Euratom and the recommendations of the World Health Organization, strengthening institutional mechanisms for monitoring and control, developing a national radon map, identifying high-risk areas and workplaces, implementing preventive and remediation measures in buildings, and developing an integrated strategy for information, education, and risk communication.

At the same time, the draft provides for the continuous professional training of specialists, the establishment of a national register of radon measurements, and the promotion of intersectoral cooperation, thereby serving as an operational tool for reducing the risk of lung cancer associated with radon exposure and strengthening national radiation protection policies.

GENERAL CONCLUSIONS

1. The national study of residential radon concentrations revealed an uneven distribution across the territory of the Republic of Moldova. Although the regional mean values remained below the national reference level of 300 Bq/m³, a substantial proportion of dwellings exceeded this threshold, with higher frequencies recorded in the Southern region, followed by the Northern and Central regions, as well as in the districts of Edineț, Ceadâr-Lunga, Căușeni, Vulcănești, Taraclia, and Cimișlia. Elevated concentrations were identified more frequently in rural than in urban areas, highlighting territorial differences relevant to the assessment of population exposure.

2. The distribution of residential radon concentrations is determined by the interaction of geological, climatic, construction-related, and microclimatic factors, which influence spatial and seasonal variations in indoor radon levels and justify the need to adapt monitoring and remediation strategies to regional characteristics.

3. The integration of data on residential radon concentrations, lung cancer morbidity, and the prevalence of tobacco use revealed the existence of epidemiological associations at the regional level. The epidemiological case–control study demonstrated a statistically significant association between residential exposure to radon concentrations above 200 Bq/m³ and lung cancer (OR = 2.60; 95% CI: 1.30–5.20; $p = 0.01$), supporting the importance of including radon among the risk factors assessed in public health surveillance and prevention activities.

4. The analysis of the relationship between radon exposure and tobacco use supports the existence of a cumulative effect of these factors in relation to lung cancer. In the case–control study, the overlap of the two exposures suggests a possible interaction; however, the results do not allow statistical confirmation of a synergistic or multiplicative effect. The findings, interpreted in the context of the scientific literature, highlight the need to integrate measures aimed at reducing radon exposure and controlling tobacco use into lung cancer prevention strategies.

5. The research enabled the identification of areas with elevated residential radon concentrations, the estimation of effective doses and the additional risk of lung cancer associated with exposure, as well as the development of the first national interactive map of radon distribution in the Republic of Moldova. These results provide a basis for the development and implementation of national measures for monitoring, preventing, and controlling population exposure to radon.

PRACTICAL RECOMMENDATIONS

The set of recommendations developed within the framework of the present research for the prevention and control of population exposure to radon is structured according to the following levels of intervention:

Recommendations for decision-makers and central public authorities

1. Approval and implementation of the National Radon Action Plan (NRAP) through strengthening intersectoral collaboration among central public authorities, research and higher education institutions, local public authorities, and other institutions with responsibilities in the fields of public health, radiation protection and construction.
2. Development and implementation of permanent national public information and education programmes on the risks associated with radon exposure, with particular emphasis on residential radon testing, the application of remediation measures and lung cancer prevention. To this end, the coordinated use of mass media, digital platforms and public communication campaigns is recommended, in accordance with the principles of risk communication.
3. Integration of health education activities on radon exposure into educational institutions through the development of educational materials and the training of teaching staff and healthcare professionals involved in health promotion activities.
4. Establishment of a sustainable funding mechanism for radon monitoring, implementation of prevention and remediation measures, development of geographical information systems (GIS), and support for applied research in the fields of radiation protection and public health.
5. Establishment of a national programme for periodic testing of residential radon concentrations, with priority given to areas identified as having high radon potential, public buildings and private dwellings.

Recommendations for implementing authorities (Ministry of Health, National Agency for Public Health and other responsible institutions)

1. Strengthening institutional capacity for the implementation of the National Radon Action Plan (NRAP) through the development of the infrastructure of the National Radon Laboratory of the National Agency for Public Health (NAPH), equipping it with modern radon monitoring equipment, expanding analytical capacities, and providing continuous training of specialized human resources in the field of radiation protection.
2. Periodic organization of national information and awareness campaigns on radon exposure, including within the framework of the European and National Radon Awareness Week, through the involvement of public health institutions, local authorities, educational institutions and the mass media, using information and educational materials developed by the National Agency for Public Health.
3. Implementation and dissemination of guidelines, brochures and other educational materials intended for the general public, healthcare professionals, teaching staff, the administrations of educational institutions and construction professionals, with the aim of increasing awareness of the risks associated with radon exposure and the corresponding preventive measures.
4. Prioritization of monitoring and remediation measures in dwellings located in the high-radon areas identified in the present research (Edineț, Ceadâr-Lunga, Căușeni, Vulcănești, Taraclia and Cimișlia) through the application of recommended technical solutions for reducing indoor radon concentrations, including optimized ventilation, the installation of radon barriers and radon membranes, and the periodic monitoring of the effectiveness of remediation interventions.

Recommendations for the educational system and educational institutions

1. Integration of fundamental knowledge on radon, its health effects, exposure prevention methods and the principles of risk communication into the initial and continuing education programmes for healthcare professionals, teaching staff and public health specialists, in accordance with the recommendations of the World Health Organization (WHO) and the International Atomic Energy Agency (IAEA).
2. Development of partnerships between higher education institutions and the National Agency for Public Health (NAPH) for the implementation of joint research projects on the monitoring of radon concentrations in dwellings and public buildings, the use of research findings in bachelor's, master's and doctoral theses, and the preparation of research proposals within national research programmes.

Recommendations for the National Agency for Regulation of Nuclear and Radiological Activities (ANRANR), the Ministry of Health, the Ministry of Economic Development and Digitalization, and the Ministry of Infrastructure and Regional Development

1. Strengthening the regulatory framework for the prevention of radon exposure in new and existing buildings through the continuous harmonization of national legislation with the provisions of Council Directive 2013/59/Euratom and international recommendations in the field of radiation protection.
2. Standardization of procedures for measuring radon concentrations, ensuring quality control, and developing a unified system for the interpretation and reporting of monitoring results.
3. Implementation of the measures provided for in the National Radon Action Plan (NRAP) by identifying buildings with radon concentrations exceeding the national reference level, informing property owners of the measurement results, and promoting the implementation of remediation measures in accordance with international best practices.

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INFORMATION ON THE DISSEMINATION OF THE RESEARCH RESULTS LIST OF PUBLICATIONS AND PARTICIPATION IN SCIENTIFIC FORUMS

by Ms. Aurelia Ababii

related to the doctoral thesis in Medical Sciences

entitled: *Assessment of Health Risks Associated with Radon Exposure*

Doctoral Programme: 331.02 – Hygiene

Doctoral Supervisor: Liuba Corețchi, Doctor Habilitatus in Biological Sciences, Associate Research Professor

Monographs

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ADNOTARE

Ababii Aurelia

“Evaluarea riscului pentru sănătate asociat expunerii la radon”

Teză de doctor în științe medicale, Chișinău, 2026

Actualitatea cercetării: Expunerea populației la radon reprezintă una dintre principalele surse naturale de radiații ionizante și un factor de risc demonstrat pentru dezvoltarea cancerului bronhopulmonar. În Republica Moldova, lipsa monitorizării sistematice a expunerii rezidențiale la radon, a cartografierii naționale și a unui Plan Național de Acțiuni privind controlul radonului justifică necesitatea evaluării riscurilor asociate și alinierii cadrului normativ național la cerințele Directivei 2013/59/Euratom.

Scopul cercetării: Evaluarea riscului pentru sănătate asociat expunerii la radon și elaborarea măsurilor de control, diminuare și prevenire a influenței factorului radiostresogen asupra sănătății populației.

Obiectivele cercetării: Determinarea concentrațiilor de radon în aerul locuințelor din mediul rural și urban; Evaluarea influenței factorilor abiotici și geologici asupra concentrațiilor de radon; Analiza relației dintre concentrația radonului și cancerul bronhopulmonar; Studierea sinergismului dintre expunerea la radon și consumul de tutun; Elaborarea măsurilor de control și prevenire a expunerii populației la radon.

Metodologia cercetării: Studiul a avut caracter multidisciplinar, retrospectiv, transversal și descriptiv-analitic, bazat pe integrarea datelor radiometrice, epidemiologice și clinice. Au fost utilizate măsurări pasive și active ale radonului în locuințe, studii observaționale și caz-control, analize statistice multivariate și modelare GIS pentru evaluarea distribuției radonului și estimarea riscului populațional.

Noutatea și originalitatea științifică: Pentru prima dată în Republica Moldova au fost obținute date complexe privind distribuția radonului în locuințe, apă și sol, cu estimarea dozelor efective de expunere și analiza relației dintre radon, factorii de mediu și indicatorii de sănătate, inclusiv cancerul pulmonar și interacțiunea cu fumatul.

Problema științifică soluționată: A fost fundamentată științific evaluarea expunerii populației la radon și impactul acesteia asupra sănătății, fiind identificate zonele cu risc crescut și argumentată necesitatea actualizării normelor naționale de protecție radiologică și implementării Planului Național de Acțiuni privind controlul radonului.

Semnificația teoretică: Rezultatele contribuie la aprofundarea cunoștințelor privind rolul radonului și al factorilor comportamentali în etiologia cancerului bronhopulmonar și oferă suport teoretic pentru evaluarea riscului populațional și supravegherea sanitară.

Valoarea aplicativă: Rezultatele oferă suport practic pentru elaborarea strategiilor de sănătate publică, monitorizarea expunerii la radon, comunicarea riscului și implementarea măsurilor integrate de reducere a expunerii la radiații ionizante naturale.

Implementarea rezultatelor științifice: Rezultatele cercetării au stat la baza elaborării recomandărilor pentru Planul național de control al radonului, dezvoltării hărții digitale naționale a radonului, ghidurilor de comunicare a riscului și implementării în practică prin 4 acte de implementare.

Prezentarea rezultatelor cercetării: În baza materialelor tezei au fost publicate 73 lucrări științifice, inclusiv articole în reviste indexate WoS și SCOPUS, reviste naționale și internaționale, monografii, ghid, rezumate și lucrări ale conferințelor științifice. Totodată, au fost obținute 4 certificate de inovator, 6 opere științifice cu drept de autor și 4 acte de implementare.

Volumul și structura tezei: Teza este redactată în limba română pe 152 pagini și include introducere, 5 capitole, discuții, limitările cercetării, concluzii generale și recomandări, 207 referințe bibliografice și 5 anexe. Materialul ilustrativ include 20 tabele și 91 figuri.

Cuvinte-cheie: radon, expunere rezidențială, cancer bronhopulmonar, risc pentru sănătate, radiații ionizante, factori de mediu, tutun, prevenire.

ANNOTATION

Author: Ababii Aurelia

Title: “Health Risk Assessment Associated with Radon Exposure”

PhD Thesis in Medical Sciences, Chisinau, 2026

Relevance of the research: Population exposure to radon is one of the primary natural sources of ionizing radiation and a proven risk factor for the development of lung cancer. In the Republic of Moldova, the absence of systematic monitoring of residential radon, the lack of national radon mapping, and the pending status of a National Radon Action Plan justify the urgent need for assessing associated health risks. This research aligns the national regulatory framework with the requirements of Directive 2013/59/Euratom.

Aim of the research: To assess health risks associated with radon exposure and to develop evidence-based measures for the control, mitigation, and prevention of radiostressogenic factors' influence on public health.

Research objectives: Determination of radon concentrations in the indoor air of rural and urban dwellings across the Republic of Moldova; Assessment of the influence of abiotic (climatic) and geological factors on indoor radon concentrations; Analysis of the correlation between residential radon levels and the incidence of bronchopulmonary cancer; Investigation of the synergistic effect between radon exposure and tobacco consumption; Development of strategies for the control, prevention, and remediation of population exposure to radon.

Research methodology: The study employed a multidisciplinary, retrospective, cross-sectional, and descriptive-analytical design. It integrated radiometric, epidemiological, and clinical data. Methods included passive and active radon measurements in dwellings, a case-control study, multivariate statistical analysis (using Statistica 7 and SPSS), and GIS modeling for national radon mapping.

Scientific novelty and originality: For the first time in the Republic of Moldova, comprehensive data were established regarding radon distribution in dwellings, water, and soil. The research quantifies annual effective exposure doses and provides an original analysis of the relationship between radon, environmental factors, and health indicators, specifically focusing on the synergistic interaction with smoking in lung cancer etiology.

Scientific problem solved: The study provides the scientific foundation for assessing population exposure to radon and its health effects. It identifies high-risk geographical areas and substantiates the mandatory requirement for updating national radiological protection standards and implementing the National Radon Action Plan.

Theoretical significance: The findings contribute to a deeper understanding of the mechanisms of environmental risk and the role of radon as a co-carcinogen alongside behavioral factors. It provides a theoretical framework for population risk assessment and the optimization of radiological health surveillance.

Practical value: The results offer practical support for public health strategies through the identification of vulnerable populations and high-risk zones. The data facilitate the orientation of monitoring, risk communication, and the implementation of integrated measures to reduce exposure to natural ionizing radiation in line with European safety standards.

Implementation of scientific results: The research served as the basis for the National Radon Control Plan, the creation of the national digital radon map, and risk communication guidelines. The results are supported by 4 implementation acts.

Publications and dissemination: The research findings are disseminated through 73 scientific works, including articles in WoS and SCOPUS-indexed journals, monographs, and conference proceedings. The intellectual property is protected by 4 innovator certificates and 6 copyrighted scientific works.

Thesis structure: The thesis is drafted in Romanian on 152 pages and includes 5 chapters, 207 bibliographic references, and 5 appendices. The illustrative material comprises 20 tables and 91 figures.

Keywords: radon, residential exposure, bronchopulmonary cancer, health risk, ionizing radiation, environmental factors, tobacco, prevention.

Ababii Aurelia

**HEALTH RISK ASSESSMENT ASSOCIATED WITH RADON
EXPOSURE**

331.02 – Hygiene

Abstract of the Doctoral Thesis in Medical Sciences

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