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Research article

A comparative analysis of indoor radon activity concentrations in Romanian houses and educational institutions

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A R T I C L E I N F O

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A B S T R A C T

Radon accumulation in indoor environments poses a significant public health concern, especially in educational institutions, where children are particularly vulnerable. This study investigates indoor radon activity concentrations (IRAC) in 198 educational institutions and 266 houses from Cluj-Napoca, Romania, analyzing a total of 1440 rooms. Radon levels were assessed using CR-39 track detectors, with measurements conducted over three and twelve-month periods for educational and residential buildings, respectively. Preliminary results reveal notable differences in IRAC between the two building types, with 24 % of educational institutions and 13 % of houses exceeding the reference level of 300 Bq/m^3. Factors such as the presence of basements, construction materials, and ventilation systems were found to significantly influence IRAC. A room-level analysis highlighted that those laboratories and classrooms that were located on lower floors had the highest IRAC, while flooring type and structural barriers played a critical role in mitigation. The study contributes by reinforcing the importance of accounting for building-specific characteristics in radon exposure assessments and highlights the need for tailored mitigation strategies in different building types. Moreover, the findings raise important questions about the representativeness of residential radon maps for public buildings, emphasizing that spatial correlations between the two building types remain low.

1. Introduction

Radon (Rn-222) is a radioactive noble gas that is part of the natural decay series of Uranium (U-238), which is found in various concentrations in all types of soils and rocks. It can infiltrate buildings through cracks and openings in the foundation, besides drainpipes, as a consequence of diffusion and pressure differential between buildings and soil [1]. When radon gas is released into the air, its short-lived decay products can be inhaled and lodged in the respiratory tract. Radon progenies release alpha particles upon decay, which can cause direct damage to the bronchial epithelium cells in the lungs [2]. This damage can lead to oxidative stress,

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chromosomal aberrations, DNA strands or gene mutations [3–5]. This risk is especially heightened in indoor environments where radon can accumulate to elevated levels, a process that is influenced by geology, soil permeability, building characteristics (age of the building, the existence of basement, the number of floors, heating type, air conditioning, thermal retrofit etc.), meteorological conditions (atmospheric pressure, temperature, humidity, wind direction and speed etc.) and anthropogenic factors (living habits, ventilation pattern) [6–10]. Since individuals tend to spend a significant amount of their time indoors, the likelihood of radon exposure increases. Due to its prevalence and health implications, monitoring and controlling the indoor radon activity concentrations (IRAC) in houses and workplaces is a very important issue worldwide. A special priority is given to educational institutions (nurseries, kindergartens, schools, etc.), as children are notably sensitive to harmful environmental pollutants. Given that children spend more time in school than anywhere else except for home, schools could represent a significant source of radon exposure for many pupils. In addition, the higher respiration rate, as well as morphological differences between children's and adult lungs lead to a three-fold higher risk of lung cancer in children [11]. They also breathe more frequently through the mouth due to higher nasal resistance, which facilitates the deposition of particles in the lungs [12–14].

International recommendations call for the implementation of national radon programs [15–17]. These programs necessitate evaluating radon levels within each country to implement appropriate safety measures. The European Commission (EC) included radon in the legal framework within the Basic Safety Standards (BSS) Directive—Directive 2013/59/Euratom. According to this directive, EU member states are obliged to develop a Radon Action Plan to address long-term risks from radon in dwellings, buildings with public access, workplaces, schools, kindergartens, etc. [15]. Consequently, many countries have established safety standards and guidelines to regulate radon levels in enclosed spaces to reduce potential health risks. Romania updated its laws to comply with European standards by adopting HG No. 526/July 25, 2018, revised in July 2023 by the Order of the President of the National Commission for Nuclear Activities Control No. 153/July 27, 2023, which sets a reference level (RL) of 300 Bq/m^3 for all building types and detailed methodology for measuring IRAC in buildings [18]. Radon measurements are now required in all Romanian buildings with public access, such as public administration buildings, educational institutions, health facilities etc.

A series of studies can be found in the scientific literature on radon measurements in schools, kindergartens or nurseries using specific protocols for this type of assessment [11,19–32]. Worldwide, a broad range of values can be observed for the IRAC means computed for educational buildings. For instance, an arithmetic mean (AM) below 13 Bq/m^3 was reported in a survey covering 32 kindergartens in Iceland [29], 17 Bq/m^3 in a monitoring study of 42 schools in Riyadh, Saudi Arabia [30], a similar value (18 Bq/m^3) being calculated by Maged [31] in an analysis of 25 classrooms in the capital city of Kuwait. At the other end of the range are studies conducted in northern Portugal, where an AM of 197 Bq/m^3 was computed for 13 Porto schools [32], while in Galicia (Spain), the largest radon-prone area of the Iberian Peninsula, a geometric mean (GM) of 174 Bq/m^3 was calculated for 58 public schools [33]. An AM of 318 Bq/m^3 and GM of 171 Bq/m^3 were computed by Vaupotič et al. [28] for educational institutions in Postojna region (Slovenia). According to the Slovenian study, factors such as the absence of a concrete slab beneath the building, the age of the structures, and the presence of cracks in the foundation can facilitate the ingress of radon into indoor spaces. Radon concentrations were found to be higher in buildings with visibly cracked foundations and those older than 50 years [28].

To investigate the influence of different factors on IRAC, the radon variability between buildings, within the same building, between floors or between rooms within the same floor was studied [26,27,32]. In addition, some authors considered other factors such as type of use, building age, building materials, reconstruction and energy-efficiency improvements, ventilation and different geographic contexts (rural vs. urban) [20,26,32].

Such studies have also been initiated regarding radon exposure in homes. The purpose of these studies was both to identify areas with high radon exposure and to detect factors influencing the IRAC, aiming to optimize conditions in new buildings and to implement effective remediation measures in existing ones [1]. Despite the diversity of factors used as predictors, such as meteorological data, geological characteristics, anthropogenic factors, and building features, the percentage of variability for explained IRAC was 7.4 % in a study by Dicu et al. [34], which covered 3132 Romanian houses; 9.7 % in a study by Barros-Dios et al. [35], which included 983 houses in Galicia (Spain); or 40 % in a study involving 3116 Danish houses, to name just a few of the studies carried out in this area [36]. The main identified predictors include the age of the building, presence of a basement, floor type, geology, soil type, number of floors, or building type (detached house vs. apartment) [22,35–37].

If certain common elements can be identified between residential and educational buildings regarding predictors impacting IRAC, factors such as anthropogenic impact and building characteristics undoubtedly play a significant role in IRAC variability between these types of buildings. It should be noted that schools have three types of occupants: students, teachers, and administrative staff, whose occupational behaviors differ from those in residential settings. Additionally, educational institutions, both old and new, maintain a consistent architectural and organizational layout for rooms usage. Most schools have basements extending beneath the entire building, where laboratories and workshops are located; consequently, these areas are used less frequently, increasing the likelihood of radon accumulation compared to the classrooms on the ground floor. Construction materials are generally similar across these institutions, unlike residential buildings, which feature a variety of materials. Thus, the question arises: to what extent residential radon measurements might be representative of nearby educational buildings?

In an analysis assessing the dependence between IRAC in educational buildings and houses, integrating data from Japan, Norway, Poland, Ireland, Slovenia, Switzerland, Italy, and the USA, Zhukovsky et al. [21] obtained a slope of 1.5. The elevated radon concentrations in educational buildings are attributed to poor ventilation, particularly during nighttime, as well as to specific building characteristics [21].

Applying a comparative analysis based on building —residential or educational—this research aims to assess the influence of building characteristics on radon levels. By identifying the key predictors of radon variability, the study seeks to assist targeted mitigation strategies and ensure compliance with safety standards. Furthermore, it examines the extent to which residential radon measurements, used in national radon maps, can accurately represent radon levels in educational facilities, highlighting potential discrepancies and their implications for public health policies.

The article is organized as follows. In Section 2, the study design and statistical analysis are described. Section 3 (Results and Discussion) is structured into six key parts to facilitate the understanding of indoor radon variability. The first two parts focus on educational buildings. Section 3.1 presents the statistical analysis of IRAC distribution at the building level, while Section 3.2 evaluates the IRAC distribution at the room level within the same type of buildings. A similar approach was applied to assess the distribution of IRAC in houses. The house-level analysis is presented in Section 3.3, while Section 3.4 focuses on the room-level distribution. Section 3.5 evaluates the differences in IRAC distribution between the two building types, considering both structural characteristics and spatial variability, while Section 3.6 describes the main limitations of the study. The objective is to assess whether residential radon measurements can be used as a proxy for estimating radon levels in educational buildings and to explore the implications of these differences for public health policies.

2. Materials and methods

2.1. Design of the study and IRAC measurements

The present study analyzes IRAC data of 948 rooms from 198 educational institutions and 492 rooms from 266 houses located in Cluj-Napoca city (Fig. 1). Cluj-Napoca, with a population of about 325,000, is a city in the north-western part of the Transylvanian Depression (Romania). It has an average yearly temperature of 8 °C, 560 mm of precipitation and a temperate-continental climate. The geological setting of the studied area has been previously described by Florică et al. [8].

While IRAC measurements in educational institutions were carried out with funding from local authorities, measurements in houses were part of a larger research project with European funding. A variety of techniques were employed for house selection, the most successful ones included using databases with prior measurements and referrals from friends and neighbors. The houses were chosen based on the following criteria: single-detached dwellings, at least one monitored room in direct contact with the ground, thermally insulated windows and/or thermally insulated construction. In the case of educational institutions, all the buildings made available by the local authorities were studied.

Radon measurements were conducted using CR-39 track detectors, RSKS type (Radosys Ltd., Hungary). Members of the "Constantin Cosma" Radon Laboratory (LiRaCC) team were responsible for managing the installation of radon detectors and completing questionnaires regarding building characteristics.

In educational buildings, rooms selection was performed in accordance with the technical measurement requirements of the current legislation, with most of the detectors being mounted in rooms located on the ground floor (68 %). The median number of

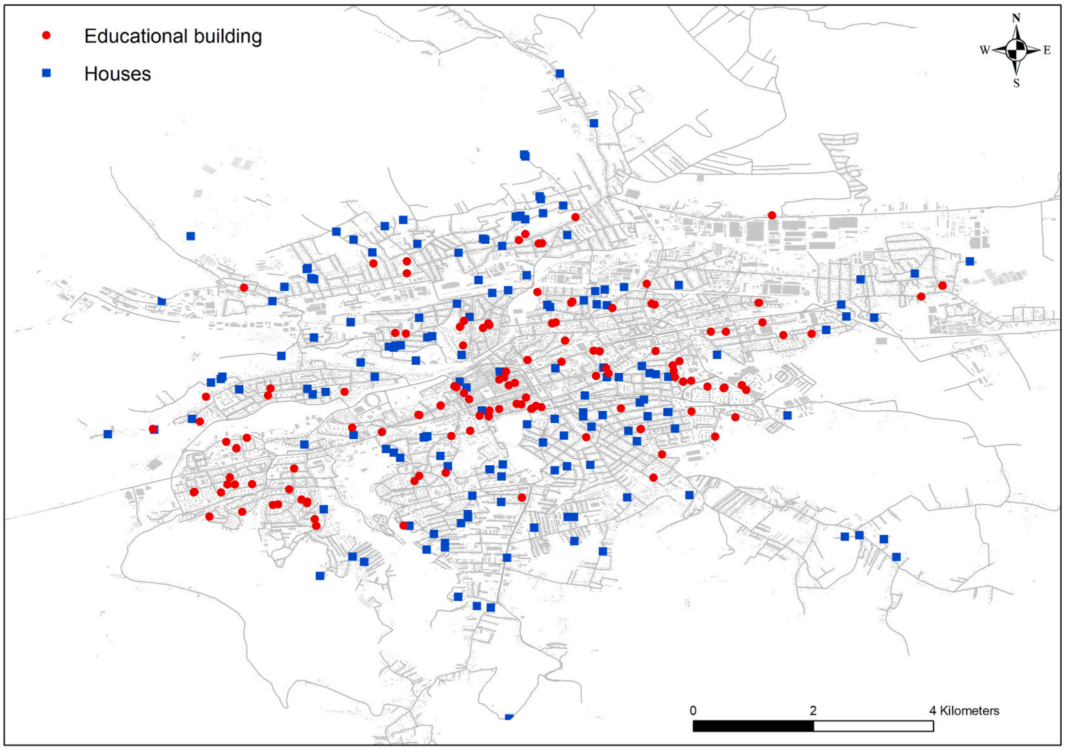

Fig. 1. Distribution of IRAC measurement points in Cluj-Napoca for educational (red) and residential buildings (blue).

detectors installed per building was five, while the number of investigated rooms varied between 3 and 14. The exposure period for radon measurements in educational buildings was three months (September to December). Temporal correction factors were applied to estimate the annual IRAC.

For residential buildings, detectors were placed in bedrooms or living rooms, located also mostly on the ground floor (62 %). Unlike educational institutions, measurements in residential buildings were conducted over two consecutive campaigns, each lasting six months. This approach allowed for the direct calculation of annual IRAC in these houses. At the end of the exposure period, the detectors were transported to LiRaCC where they were processed and analyzed as detailed by Cucoș et al. [38]. The results of the calibration exercise held by the BfS (Germany) and the international intercomparison exercises confirm the accuracy of the integrated radon measurements obtained within LiRaCC [39,40].

2.2. Statistical analysis

Statistical analysis of the data was performed by using SPSS software, version 24 (SPSS Inc., USA) and OriginPro 2024 (OriginLab Corporation, Northampton, MA, USA). The non-parametric Mann-Whitney (M − W) test was used to compare two samples, while the Kruskall-Wallis (K-W) with Dunn's post-hoc analysis for more than two samples. The data distribution evaluated using the Shapiro-Wilk test led to the decision to use nonparametric tests. For this reason, the median (Mdn.) is used to describe the data. For a comparative analysis of the obtained results with those available in the literature, the arithmetic (AM) and geometric means (GM) are also presented. The relative standard error (RSE) and the coefficient of variation (CV) were both used to evaluate the degree of dispersion of the data. The Chi-square test was used to evaluate the degree of association between qualitative variables. The comparative analysis of annual IRAC was conducted according to the building type. For residential buildings, the values were directly measured, whereas for educational buildings, they were estimated using temporal correction factors. The significance level α was chosen at .05.

To evaluate the spatial correlation between educational institutions and houses within varying distance thresholds, the spatial point pattern analysis was used. Data processing started with preprocessing in QGIS, while the final analysis was carried out in R. Advanced spatial point pattern analysis was done using the ′spatstat' package, enabling the computation of pairwise distance matrices between educational buildings and filtered houses. To assess correlations, house attribute values within a series of distance thresholds (0–1000 m) were aggregated and compared to corresponding school values. The coefficient of determination (R^2) was calculated for each threshold.

3. Results and Discussion

3.1. Educational institutions: statistical analysis at building level

Among the 198 educational institutions monitored in this study, 114 (58 %) are schools, 65 (33 %) kindergartens, and the remaining 19 (10 %) are nurseries. The descriptive statistics in Table 1 were based on the AM calculated for each individual building.

Table 1
Descriptive statistics on the impact of the investigated parameters on IRAC (Bq/m^3) at building level for the educational institutions (n = 198).

Characteristic	Description	n[a]	Q1[‡]	Mdn.	Q3	AM (SD)	GM	p
Type of educational institution	Nursery school	19	74	114	155	137 (93)	113	.08
	Kindergarten	65	113	173	304	221 (151)	175	
	School	114	83	154	320	218 (162)	159	
Construction period	Before 1941	33	88	131	225	187 (140)	146	
	1941–1962	24	80	172	356	236 (204)	164	**<.01**
	1963–1977	56	133	272	392	277 (177)	218	
	1978–1991	17	101	139	212	198 (167)	154	
	After 2000	25	81	121	151	129 (98)	108	
Basement	No	54	114	185	333	258 (188)	197	**.02**
	Yes	121	85	150	251	192 (148)	147	
Mechanical ventilation	No	154	91	157	304	220 (170)	165	.20
	Yes	27	82	151	186	160 (108)	130	
No. building floors	Ground floor (GF)	22	167	248	334	291 (170)	247	**<.001**
	GF + 1	52	120	177	323	232 (155)	188	
	GF + 2	45	75	121	280	195 (167)	140	
	GF + ≥ 3	36	59	111	166	127 (90)	105	
Thermal retrofit	No	82	85	153	280	216 (177)	158	.65
	Yes	100	96	160	312	214 (158)	164	
Main construction material	Concrete	25	83	118	280	197 (150)	150	.19
	Bricks	151	92	162	277	210 (157)	160	
	ACC	5	57	114	132	100 (52)	87	

[a] The missing values are given by the difference between the total number of buildings (n = 198) and the sum of the frequencies related to each parameter; Q1 – 25 % quantile; Mdn. – Median (50 % quantile); Q3 – 75 % quantile; AM – Arithmetic mean; SD – Standard deviation; GM – Geometric mean; *p*-value of the Kruskal-Wallis or Mann- Whitney test lower than the significance level of .05 are shown in bold.

For all educational institutions included in the study, the overall AM of the IRAC was 211 Bq/m^3, with values varying from 28 to 729 Bq/m^3. The obtained median (157 Bq/m^3) is approximately 1.7 times higher compared to that reported by Dicu et al. [41] for 12 educational institutions from the same study area. The main reason for the discrepancy is that the measurements in the aforementioned study [41] were primarily conducted in the upper-floor offices, where the IRAC is typically lower. Instead, the findings of this study are consistent with those (AM = 197 Bq/m^3, Mdn. = 154 Bq/m^3) of an investigation conducted by Madureira et al. [32] that focused on 45 classrooms from 13 public schools in Porto, a critical area due to geological factors. Similar values (AM = 209 Bq/m^3, Mdn = 146 Bq/m^3) were reported by Trevisi et al. [42] in a study investigating 438 schools in the province of Lecce, Italy. According to the findings of the present study, this survey ranks among those with the highest IRAC found in educational buildings [32,33,42].

The Shapiro-Wilk test did not confirm a normal distribution of the log-transformed IRAC values ($p = .03$), deviations on both the lower and upper tails of the distribution being observed. Similar deviations from the log-normal distribution were mentioned by Synnott et al. [23] in a survey conducted in 3826 Irish schools, where an average value of 93 Bq/m^3 was computed for radon concentration.

In a study conducted in Bulgaria across schools and kindergartens, Vuchkov et al. [24] found higher IRAC in kindergartens compared to schools. The main reasons cited were the age of the building and lack of basements, along with lower ventilation rates in kindergartens. Similar, our survey revealed higher IRAC values in kindergartens, both in terms of AM (221 Bq/m^3) and median (173 Bq/m^3), followed by schools (AM = 218 Bq/m^3, Mdn. = 154 Bq/m^3) and nurseries (AM = 137 Bq/m^3, Mdn. = 114 Bq/m^3). However, the Kruskal-Wallis (K-W) test did not reveal a statistically significant difference in IRAC medians based on the type of institution ($p > .05$). Furthermore, a detailed analysis regarding the construction year and the percentage of buildings with basements did not reveal any significant differences between kindergartens and schools. Therefore, it is most likely that the observed disparity could be attributed to a different pattern of ventilation and room usage according to the type of institution.

In 48 (24 %) of the investigated institutions, the average of IRAC at the building level exceeds the reference level of 300 Bq/m^3. Among these, 30 are schools, 17 kindergartens, and one is a nursery. A similar percentage (25 %) is reported for the educational sector by Martin-Gisbert et al. [43], pointing out that this rate is higher than that of underground mining and spas, industries where radiation exposure is subject to legal regulations.

According to the data in Table 1, no clear trend could be observed in the evolution of IRAC values relative to the period in which the buildings were constructed, despite variations across different time periods. A statistically significant difference in median IRAC values was identified between buildings constructed between 1963 and 1977 and those built after 2000 ($p < .01$), with the latter showing an IRAC approximately 55 % lower than those from the communist period. Most likely this difference could be related to the quality of the construction materials used, as well as the construction regulations. Interestingly, no buildings in the study were constructed during the decade immediately following the collapse of communism in Romania (1991–2000), an aspect reflecting the economic challenges of the country, demographic decline, and a focus on renovating and thermally rehabilitating existing buildings rather than constructing new ones. A rate of only 5 % was reported for kindergartens built after 1990 in a study conducted in the Czech Republic on the influence of energy-saving measures on the radon concentration [20].

Regarding construction materials, over 75 % of the buildings were primarily constructed with bricks, 13 % with reinforced concrete, and only 5 buildings with autoclaved aerated concrete (AAC). Statistical analysis based on construction material did not show a significant difference in median IRAC values, as evidenced by the K-W test ($p > .05$). Similarly, the M − W test applied on data for buildings made of brick versus those made of reinforced concrete yielded no statistically significant difference ($p = .67$), with AAC buildings excluded due to the small number of samples.

Approximately 60 % of the buildings had basements. A statistically significant difference in median IRAC values was observed, with buildings without basements showing IRAC levels nearly 25 % higher than those with basement ($p = .02$). To assess the impact of the basement on IRAC at the building level, excluding the influence of upper-floor measurements, the analysis included only ground-floor measurements. A statistically significant difference was observed between the IRAC medians ($p < .001$), with values for buildings without basement being approximately 1.75 times higher than those with basements.

Only 14 % of the monitored structures were single-storey (ground floor - GF). The K-W test revealed a statistically significant difference in IRAC values between ground-floor buildings and those with two ($p < .01$) or more than two storeys ($p < .001$). These discrepancies are mostly explained by the fact that, in single-storey buildings (GF), 60 % there were no basements, whereas in multi-storey buildings, the percentage range was 0 % (GF + 3) to 41 % (GF + 2). Second, the overall IRAC average of a tall building would be lowered because additional detectors would need to be installed on the upper floors, where IRAC levels are typically lower than on the ground floor.

Regarding mechanical ventilation, only 15 % of the monitored buildings were equipped with such systems, while the rest relied on natural ventilation. Despite the AM of IRAC being nearly 40 % higher in buildings without mechanical ventilation, neither the non-parametric M − W test on raw data nor the *t*-test on log-transformed data showed a statistically significant difference ($p > .05$). There was no statistically significant difference in median IRAC values based on the presence of thermal insulation in the buildings under observation ($p > .05$).

From the perspective of the variability of radon measurements conducted within the same building, the coefficient of variation (CV) ranged from 1 % to 168 %, with a mean value of 53 % and a median of 49 %. The maximum value was recorded in a school where nine measurements were taken. In this case, the IRAC was monitored in both classrooms and administrative offices, distributed across the ground floor as well as the first and second floors, with IRAC values ranging from 14 to 432 Bq/m^3. A variability of 65 % was reported by Bochicchio et al. [27] in a study conducted in 334 schools in Serbia, while Ivanova et al. [26] obtained a median of 67 %, with values ranging between 17 % and 117 % across 16 schools in Bulgaria.

The variability analysis based on the type of institution revealed greater variability among schools, with a median for CV of 55 %, followed by nurseries (43 %) and kindergartens (42 %). Given the different number of measurements depending on the type of institution, the relative standard error (RSE) of the mean was also assessed. Schools showed a median RSE of 27 %, indicating heterogeneity in the measurements across the same building, followed by kindergartens at 18 %, and nurseries at 17 %. The difference of median RSE values between schools and kindergartens was statistically significant (p = .02), as confirmed by the K-W with Dunn's test.

In summary, higher IRAC levels in kindergartens compared to schools or nurseries can likely be attributed to ventilation patterns and room usage rather than structural differences. The lack of a basement and the construction period of the building were the most significant predictors of IRAC variability in educational institutions.

3.2. Educational institutions: statistical analysis at room level

IRAC was measured in 948 rooms across 198 educational institutions. The results showed a range of values from 11 to 1495 Bq/m^3, with an AM of 208 Bq/m^3, a Mdn. of 123 Bq/m^3, and a GM of 134 Bq/m^3. The overall statistics are slightly different from those examined in Table 1, where the IRAC is displayed as average at the building level. The Shapiro-Wilk test failed to show a normal distribution of the log-transformed IRAC results, even when IRAC was presented at room level ($p < .001$).

Classrooms comprised 60 % of the 948 rooms monitored, while 14 % were administrative spaces such as offices, secretariats, and staff rooms (Table 2). The remaining rooms represented a considerably smaller proportion, serving various functions, including laboratories (3 %), medical offices (5 %), dormitories (1 %), and kitchens (7 %). Spaces categorized as 'Other' (8 %) included technical areas, locker rooms, annexes, and storage rooms.

Although the maximum IRAC values (1308, 1418, and 1495 Bq/m^3) were recorded in classrooms from various schools, the highest statistical indicators were computed for laboratories (informatics, chemistry, physics, engineering, and biology) (AM = 357 Bq/m^3, Mdn = 273 Bq/m^3), libraries (AM = 294 Bq/m^3, Mdn = 194 Bq/m^3) and medical offices (AM = 218 Bq/m^3, Mdn = 145 Bq/m^3). In this study, 88 % of laboratories are located in the basement, semi-basement, or ground floor, compared to 73 % of classrooms. Laboratories are generally much less occupied during the week compared to classrooms, which may lead to poor ventilation and IRAC accumulation.

Higher radon concentrations in laboratories compared to classrooms were also found by Venoso et al. [44] in 30 schools investigated in the Neapolitan area. This discrepancy was attributed to the higher ventilation rates of classrooms compared to other room types. Instead, in a study conducted in 41 Romanian educational buildings, Dobrei et al. [22] identified a significantly higher median for IRAC in classrooms compared to other types of rooms. Instead, Ivanova et al. [26] reported the highest GM of IRAC for dining rooms, because of their location on the basement floor, respectively the way of use. In our case, a statistically significant difference ($p < .001$) was identified between the median IRAC values for laboratories and kitchens, with the latter presenting a median approximately three times lower than that of the laboratories. This difference is most likely attributable to the flooring, particularly the ceramic tiles commonly found in kitchens, as well as the ventilation systems installed in this type of room.

The percentage of rooms with IRAC levels exceeding RL was 21 %, with variations depending on room type, ranging from 5 % in kitchens to 47 % in laboratories, in classrooms the percentage being 22 % (Table 2). The percentage of rooms in which the IRAC was higher than the RL was 15.6 % in the study by Madureira et al. [32] in 43 classrooms from Porto schools and 11 % in the study by

Table 2
Descriptive statistics on the impact of the investigated parameters on IRAC (Bq/m^3) at room level for the educational institutions (n = 948).

Characteristic	Description	n[a]	Q1[‡]	Mdn.	Q3	AM (SD)	No. (%) > RL	p
Room type	Classroom	570	67	119	260	209 (233)	123 (22 %)	**<.001**
	Bedroom	12	79	121	169	163 (163)	1 (8 %)	
	Labs	32	134	273	565	357 (271)	15 (47 %)	
	Administration	136	69	125	269	218 (236)	28 (21 %)	
	Library	14	133	194	250	294 (298)	3 (21 %)	
	Kitchen	66	54	99	153	121 (87)	3 (5 %)	
	Medical office	45	80	145	327	218 (175)	14 (31 %)	
	Other	73	70	117	200	175 (162)	13 (18 %)	
Concrete slab beneath the floor	No	28	88	244	378	292 (240)	10 (36 %)	**.02**
	Yes	876	69	121	259	207 (223)	183 (21 %)	
Floor level	Basement	30	105	194	440	345 (356)	10 (33 %)	**<.001**
	Semi-basement	68	77	118	268	192 (176)	14 (21 %)	
	Ground floor	640	78	141	311	235 (238)	167 (26 %)	
	First floor	168	52	84	133	118 (117)	9 (5 %)	
	Second floor	31	45	69	114	82 (50)	0 (0 %)	
	Third floor or higher	8	44	59	93	71 (39)	0 (0 %)	
Floor type	Ceramic tiles	101	77	105	182	146 (109)	10 (10 %)	**<.001**
	Parquet	634	71	134	293	228 (241)	157 (25 %)	
	Tarkett	155	59	92	159	144 (159)	17 (11 %)	
	Other	43	87	170	440	292 (224)	14 (33 %)	

[a] The missing values are given by the difference between the total number of buildings (n = 948) and the sum of the frequencies related to each parameter; Q1 – 25 % quantile; Mdn. – Median (50 % quantile); Q3 – 75 % quantile; AM – Arithmetic mean; SD – Standard deviation; GM – Geometric mean; No. (%) > RL - the number and percentage of measurements above the RL; *p*-value of the Kruskal-Wallis or Mann- Whitney test lower than the significance level of .05 are shown in bold.

Ivanova et al. [26].

From the perspective of the floor level at which the monitored room is located, 68 % are on the ground floor, 18 % on the first floor, 7 % in the semi-basement, 3 % in the basement, a similar percentage on the second floor, and 1 % on the third floor or higher. A decrease in IRAC can be observed from the basement level to the ground floor and upper floors, with a statistically significant difference in the median IRAC values between the basement, semi-basement, and ground floor compared to the upper floors ($p < .001$).

IRAC levels are around 1.8 times greater in the monitored rooms without a concrete slab beneath the floor than those with this layer ($p < .05$). To emphasize the significance of this layer at the soil-basement border, this research only included rooms that were ground level.

Parquet is the most common flooring type (68 %), followed by ceramic tiles (11 %), and tarkett (17 %). Terrazzo, linoleum, and wooden board floors belong to the 'other' category. The lowest median IRAC (92 Bq/m^3) was found in rooms with tarkett flooring, followed by ceramic tiles (105 Bq/m^3) and parquet (134 Bq/m^3). In fact, a statistically significant difference was found between the median IRAC in rooms with tarkett flooring ($p < .01$) and those with parquet or other types of flooring ($p < .001$). The analysis for the rooms situated at ground floor also yielded a statistically significant result ($p < .01$), with tarkett showing a significantly lower median (99 Bq/m^3) than parquet (159 Bq/m^3) or other flooring types (176 Bq/m^3), a characteristic that suggests a higher level of airtightness for tarkett-type flooring.

Room-level analysis reveals significant variability in IRAC based on room type, floor level, and construction characteristics. Laboratories and libraries, often located on lower floors and with limited ventilation, showed the highest radon levels. The presence of a concrete slab beneath the floor and the tarkett flooring significantly reduces IRAC, emphasizing the importance of structural barriers in radon mitigation.

3.3. Houses: statistical analysis at building level

To perform the IRAC measurement in houses, CR-39 track detectors were installed in two rooms during two consecutive campaigns, each lasting six months. Over the years, several radon measurement campaigns have been conducted in residential buildings from Cluj County. Cosma et al. [45] reported an AM of 121 Bq/m^3 and a GM of 76 Bq/m^3 in a study involving 372 houses. Cucoş et al. [38] subsequently updated the data (AM = 140 Bq/m^3, GM = 89 Bq/m^3) in 2017 due to an increase in the number of measurements to 544 houses. In the current study, IRAC showed a GM of 108 Bq/m^3, a Mdn of 95 Bq/m^3, and an AM of 152 Bq/m^3 for the 266 houses under investigation (Table 3). The fact that some of the chosen houses were drawn from databases that already contain buildings with high radon concentrations, which have been confirmed in earlier measurement campaigns, is perhaps one reason for the increased trend in IRAC over time.

The obtained percentage (13 %) of houses that exceeds the reference level is approximately 2.6 times greater than the one reported by Cosma et al. [45] in a study that aimed to monitor the radon concentration in 1747 residential buildings, 372 of which being from the same county as the buildings from the present study.

According to the construction period, 65 % of the investigated houses were built in the post-communist era (1991–2017); this was impacted by selection criteria, such as thermal insulation. A statistically significant difference was observed between the median IRAC values for houses built in the post-communist era and those constructed between 1941 and 1977 ($p < .05$). Most likely, construction materials, along with substantial changes in building codes, are responsible for these differences. In fact, 94 % of homes built with AAC are from the post-communist era, in contrast to solid brick houses, which make up 60 % of all residences for the same period. A statistically significant difference was observed between the median IRAC values in houses built with brick compared to those constructed with AAC, the latter showing values approximately 30 % lower ($p < .05$). The 'Other' category is quite heterogeneous, encompassing materials such as wood, adobe, and concrete, which led to the absence of any statistically significant difference in comparison to the other two categories.

Table 3
Descriptive statistics on the impact of the investigated parameters on the IRAC (Bq/m^3) at building level for houses (n = 266).

Characteristic	Description	n[a]	Q1[‡]	Q2	Q3	AM (SD)	GM	p
Construction period	Before 1941	30	111	212	340	278 (241)	202	
	1941–1962	29	88	163	283	244 (228)	162	**<.001**
	1963–1977	14	99	208	313	211 (122)	173	
	1978–1991	19	66	132	305	171 (124)	125	
	1992–2006	59	49	77	152	102 (66)	84	
	After 2006	115	53	79	135	111 (92)	88	
Thermal retrofit	No	30	61	113	262	210 (213)	137	.18
	Yes	236	56	94	180	144 (139)	105	
Mechanical ventilation	No	240	61	99	197	159 (155)	112	**<.05**
	Yes	26	54	72	101	91 (56)	78	
Main construction material	Bricks	206	62	102	205	167 (163)	118	
	ACC	36	48	72	126	95 (67)	77	**<.05**
	Other	24	51	80	153	105 (75)	85	

[a] The missing values are given by the difference between the total number of buildings (n = 266) and the sum of the frequencies related to each parameter; Q1 – 25 % quantile; Mdn. – Median (50 % quantile); Q3 – 75 % quantile; AM – Arithmetic mean; SD – Standard deviation; GM – Geometric mean; *p*-value of the Kruskal-Wallis or Mann- Whitney test lower than the significance level of .05 are shown in bold.

Of the 236 houses reporting the presence of thermal insulation, 89 % used polystyrene, 6 % used mineral wool, and 4 % used a combination of the two materials. In contrast to prior research conclusions, the findings of the current study show a minor decrease in IRAC (about 17 %) when compared to homes without thermal insulation. However, since 89 % of the homes under examination had thermally insulated walls as well as windows and the remaining houses (30) had only thermally insulated windows, this difference is not statistically significant ($p > .05$), and the analysis should be regarded with caution.

Just 10 % of the homes under observation had mechanical ventilation, compared to approximately 15 % in educational institutions. The presence of air conditioners, however, resulted in a reduction of almost 25 %, indicating a significant difference in median IRAC levels in homes ($p < .05$). Air conditioners are more common in houses constructed after 1991.

Residential buildings showed a wide variability in IRAC levels, with higher concentrations associated with older construction periods and the absence of mechanical ventilation. This highlights the importance of modern building codes and ventilation systems in mitigating radon exposure.

3.4. Houses: statistical analysis at room level

The study investigated 492 rooms, with the vast majority (62 %) located on the ground floor and the remaining rooms (32 %) on the first floor, as well as the attic/second story (6 %). IRAC showed a range from 10 to 1100 Bq/m^3, with an AM of 177 Bq/m^3, a median of 110 Bq/m^3, and a geometric mean of 120 Bq/m^3 at ground level (Table 4). On the first floor, the range of IRAC variation was narrower (10–403 Bq/m^3), with an AM of 87 Bq/m^3, a Mdn of 64 Bq/m^3, and a GM of 67 Bq/m^3. Although IRAC value did not exceed the reference level, for the attics or the second floors the Mdn (69 Bq/m^3), AM (90 Bq/m^3), and GM (72 Bq/m^3) were slightly higher compared to the first floor. A statistically significant difference was obtained between the medians of IRAC values depending on the floor where the room was located, more precisely between the ground floor and the other floors ($p < .001$).

There was no statistically significant difference in IRAC based on the destination of the room ($p > .05$), with most measurements (58 %) conducted in bedrooms, and the remaining measurements in the living room.

From the standpoint of floor type, laminated flooring is most common (45 %), followed by wood parquet (35 %), while ceramic tiles and wooden flooring were equally represented (10 %). No statistically significant difference was recorded between the median IRAC values with respect to the type of flooring in the monitored room.

The effect of the ceiling material was evaluated only for the ground floor rooms. Fifty-nine percent of the rooms under investigation had concrete ceilings, 35 % had wooden ceilings, and 6 % had other materials (drywall, polystyrene, etc.). The IRAC median (197 Bq/m^3) for rooms with wooden ceilings was about 2.3 higher than the one (87 Bq/m^3) for rooms with concrete ceilings. In fact, the observed difference between the median IRAC values was statistically significant ($p < .001$). The fact that just 26 % of homes with wooden floors had concrete ceilings, compared to 69 % of those with wooden ceilings, may also be a relevant aspect.

At the room level, ground-floor locations and wooden ceilings were associated with higher IRAC values, reinforcing the role of structural characteristics in radon accumulation.

3.5. IRAC in educational institutions vs. houses

In assessing IRAC based on the building type (educational institution or houses), only measurements made on the ground floor were considered to minimize the impact of measurements taken on upper floors on the IRAC mean reported at building level. Thus, 240 houses and 184 educational institutions were included in the analysis. The median number of ground-floor measurements in educational institutions is 3, with a range between 1 and 9. For houses, a single measurement was conducted at ground level in 147 cases, while in 93 cases (39 %), both measurements were taken on the ground floor. As indicated in Table 5, a statistically significant

Table 4
Descriptive statistics on the impact of the investigated parameters on the IRAC (Bq/m^3) at room level for houses (n = 492).

Characteristic	Description	n[a]	Q1[‡]	Mdn.	Q3	AM (SD)	No. (%) > RL	p
Room type	Bedroom	286	49	84	184	143 (149)	33 (12 %)	.66
	Living room	206	51	91	174	145 (147)	26 (13 %)	
Floor level	Ground floor	302	63	110	239	177 (170)	51 (17 %)	**<.001**
	First floor	156	42	64	109	87 (74)	6 (4 %)	
	Attic or second floor	30	41	69	134	90 (60)	0 (0 %)	
Floor type	Ceramic tiles	51	52	77	112	96 (79)	2 (4 %)	>.05
	Laminate flooring	221	51	78	150	117 (103)	16 (7 %)	
	Wood parquet	169	48	112	233	173 (185)	27 (16 %)	
	Wood floor	47	53	102	304	201 (193)	12 (26 %)	
Ceiling type[b]	Concrete	178	57	87	169	147 (152)	22 (12 %)	
	Wood	106	85	197	313	233 (195)	27 (25 %)	**<.001**
	Other	18	80	108	189	141 (92)	2 (11 %)	

[a] The missing values are given by the difference between the total number of buildings (n = 492) and the sum of the frequencies related to each parameter.

[b] Only the ground floor measurements were taken into account; Q1 – 25 % quantile; Mdn. – Median (50 % quantile); Q3 – 75 % quantile; AM – Arithmetic mean; SD – Standard deviation; GM – Geometric mean; No. (%) > RL - the number and percentage of measurements above the RL; *p*-value of the Kruskal-Wallis or Mann- Whitney test lower than the significance level of .05 are shown in bold.

difference is observed in the distribution of buildings by construction period ($p < .001$), with approximately 65 % of residential buildings being constructed after 1991, compared to only 17 % of educational buildings. For educational institutions, roughly one-third were built between 1963 and 1977, whereas only 5 % of houses in the current study were constructed during the same period. When data were analyzed according to each construction period, a significant difference in median IRAC values between the two types of building was found ($p = .04$) only for the pre-1941 period (Fig. 2).

The distinct distribution of construction periods between residential and educational buildings likely accounts for other observed differences, such as the significantly lower percentage of houses with cellars (approximately 30 %) compared to educational buildings, where about 70 % are equipped with a basement, thereby affecting radon exposure levels. A statistically significant difference was also observed regarding thermal insulation, with the percentage of thermally retrofitted houses being approximately 1.65 times higher than that of educational buildings ($p < .001$).

In educational buildings, the IRAC is approximately 1.4 times higher compared to residential buildings in terms of arithmetic mean, median, and geometric mean, the difference being statistically significant ($p < .001$) (Fig. 3). The IRAC ratio between houses and educational buildings in the present study is .71. As a comparison, in the study conducted by Kapdan and Altinsoy [25] in Adapazari (Turkey) the IRAC ratio was found to be 1.04. A similar value (1.09) can be computed for dwellings and public schools in Patras (Greece) [46]. A value of .96 was reported for Ireland as a result of radon measurements including 12,649 homes [47], and 38,531 radon measurements in ground-floor classrooms and offices across 3286 schools [23]. In a study targeting 31 schools and 204 houses in Eastern Sicily, Catalano et al. [48] concluded that radon exposure in houses can be assessed through school-based surveys, given the comparable values observed between these type of buildings. Similarly, Lupiano et al. [49] found a comparable percentage of measurements exceeding the reference level (RL) in both residential buildings and schools, in a study involving 1434 indoor radon measurements across dwellings, schools, and workplaces in Calabria, Italy. Instead, Kullab et al. [50] reported an average value for radon monitored in 74 kindergartens that was approximately twice as high as the average value recorded for Amman dwellings. These studies reveal that only in certain situations, the average level of radon exposure obtained in houses is comparable to those in schools or kindergartens. In general, the data analyzed are regionally aggregated.

A spatial analysis was carried out in the present study to evaluate the representativeness of residential radon measurements for estimating IRAC in educational institutions. Thus, starting from each educational building, a radius ranging from 300 to 1000 m was delineated, and all radon measurements conducted in houses within this area were averaged. The requirement of having at least three houses within a radius of less than 300 m was not fulfilled for the analyzed areas. Subsequently, the residential IRAC average was compared to the mean value obtained from measurements conducted in each educational building.

The findings indicate that spatial correlation, as measured by R^2, increases with the expansion of the radius, whether the analysis includes a minimum of three or five houses per area. The highest correlation ($R^2 = 15.6$ %) is observed at a radius of 1000 m when at least five houses are included in the analysis (Fig. 4).

A significant variability in the determination coefficient between radon levels measured in homes and schools or workplaces is reported in the literature. For instance, a study evaluating the predictability of annual radon concentrations in 81 workplaces (including schools) based on radon measurements in 83 nearby homes found that only 5 % of the variability in workplace radon levels could be explained by residential radon levels [51]. In contrast, Bucci et al. [52] reported a much higher R^2 of 77 % when analyzing the geometric means of radon concentrations in homes and workplaces across 28 municipalities in the Tuscany region, Italy.

The consistently low correlations observed in the present study indicate a weak relationship between residential and educational IRAC levels, likely driven by factors such as ventilation patterns or building-specific characteristics. These findings highlight the importance of conducting independent radon monitoring in educational buildings.

Table 5
Analysis of the distribution of investigated characteristics by building type.

Characteristic	Description	Houses	Educational institutions	p[a]
Construction period	Before 1941	28	31	
	1941–1962	25	24	**<.001**
	1963–1977	13	49	
	1978–1991	17	15	
	1992–2006	50	6	
	After 2006	107	18	
Thermal retrofit	No	27	78	**<.001**
	Yes	213	90	
Mechanical ventilation	No	217	143	.14
	Yes	23	24	
Main construction material	Bricks	187	140	
	ACC	31	4	**<.001**
	Other	22	24	
Cellar/basement	No	170	50	**<.001**
	Yes	70	111	
IRAC (Bq/m^3)	n	240	184	
	AM (SD)	162 (143)	228 (188)	
	Mdn.	107	154	**<.001**
	GM	118	163	

[a] *p*-value of the χ^2 test lower than the significance level of .05 are shown in bold.

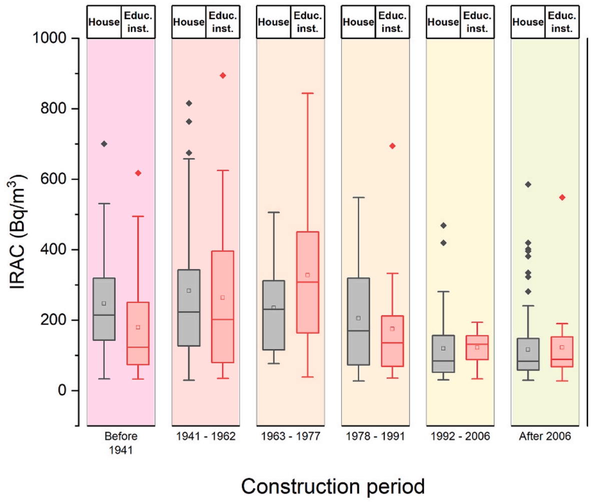

Fig. 2. The impact of construction period on IRAC according to the building type (houses and educational institutions).

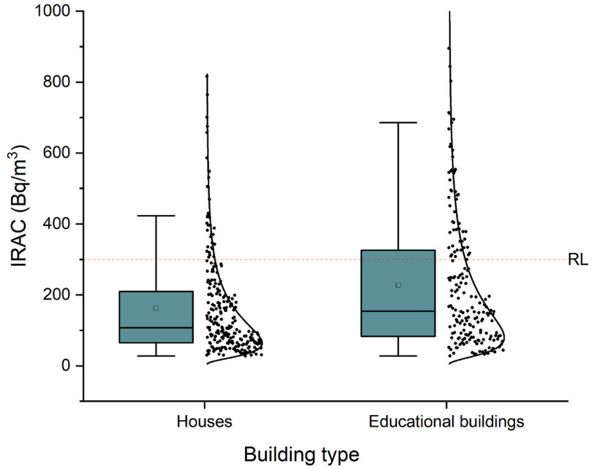

Fig. 3. Distribution of IRAC by building type for ground-floor rooms. The data are represented using a boxplot, where the median value is indicated by the horizontal line inside each box, and the arithmetic mean is marked by a square. The distribution of the data for each building type is further visualized through a fitted log-normal curve. The dashed red horizontal line represents the reference level (RL) of 300 Bq/m^3.

3.6. Study limitations

While this study provides valuable insights into the differences in IRAC between residential and educational buildings, several limitations should be acknowledged to ensure a comprehensive understanding of the results. Firstly, specific characteristics such as room size, the ratio of the area to volume of the room, wall thickness, and the use regime of the rooms (how often is it ventilated, door closed/open, etc.) were all unavailable for analysis. Secondly, unlike residential buildings, where measurements were carried out over the course of a whole year, measurements in educational buildings were limited to a three-month period, during the winter season. Although seasonal correction factors were applied to estimate the annual IRAC in educational institutions, it is important to note that these correction factors, while showing reduced variability in winter months, may introduce additional errors when compared to year-long measurements.

The spatial clustering of educational institutions in the city center poses significant limitations, restricting the number of houses within close proximity and often leading to the same houses being analyzed for multiple educational buildings. Meanwhile, schools in less dense or peripheral areas were excluded due to insufficient nearby houses, and the uneven distribution of houses around educational institutions results in large variations in measurements, affecting correlation reliability. Future research should address these limitations by expanding the study area and the number of measurements, incorporating more detailed building characteristics, conducting year-long measurements in educational buildings, and exploring additional environmental and structural variables that could impact IRAC.

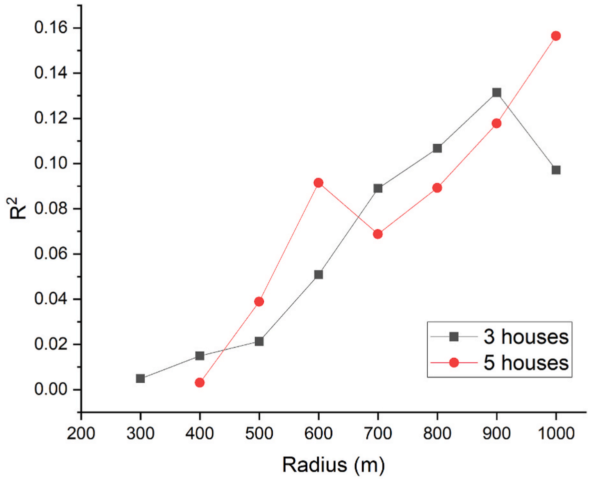

Fig. 4. Spatial analysis comparing averaged IRAC in houses (300–1000 m radius) with IRAC in educational buildings. Thresholds of at least three (gray) and five (red) houses were applied.

4. Conclusions

This study analyzed IRAC in 948 rooms from 198 educational institutions and 492 rooms in 266 houses located in Cluj-Napoca, Romania. Results showed that 24 % of educational buildings exceeded the reference level (RL), compared to 13 % of houses, indicating distinct risk profiles due to architectural and usage differences. Older educational buildings and those without basements had significantly higher IRAC levels, with laboratories and rooms without concrete slabs showing the highest values. In residential buildings, air conditioning systems reduced IRAC by approximately 25 %, while the combination of wooden ceilings and wooden floors contributed to a 2.3-fold increase in IRAC.

Educational institutions recorded IRAC levels 1.4 times higher than residential buildings, emphasizing the need for tailored radon risk assessments. Spatial analysis highlighted that residential radon maps are insufficient for predicting radon levels in other building types.

Although according to Romanian legislation, radon measurement in public buildings, including educational ones, is mandatory, the lack of adequate mechanisms and specific funding represents a serious barrier to the implementation of extensive monitoring programs. The results obtained within the framework of this investigation emphasize that, from a public health policy point of view, systematic radon monitoring in schools and kindergartens should be pursued; financial support for carrying out such measurements is essential and should be provided. It follows that increasing awareness of this issue among those responsible for legislation will ensure greater safety in schools and educational institutions.

CRediT authorship contribution statement

Alexandra Cucoş: Supervision, Resources, Project administration, Methodology, Investigation. **Tiberius Dicu:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Mircea Moldovan:** Writing – original draft, Methodology, Investigation. **Gabriel Dobrei:** Writing – original draft, Methodology, Investigation. **Ancuţa Ţenter:** Writing – original draft, Methodology, Investigation. **Ştefan Florică:** Methodology, Investigation. **Alexandru Lupulescu:** Methodology, Investigation. **Cristian Maloş:** Visualization, Formal analysis, Data curation. **Botond Papp:** Methodology, Investigation. **Kinga Hening:** Methodology, Investigation. **Istvan Pap:** Methodology, Investigation. **Alina Moldovan:** Writing – original draft, Formal analysis. **Bety Burghele:** Methodology, Investigation. **Carlos Sainz:** Supervision, Resources, Project administration, Methodology, Investigation.

Data availability

Data will be made available on request.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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