ORIGINAL ARTICLE

Radon risk assessment and mitigation deadlines

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Abstract

***Background*:** Radon is a radioactive natural gas that is the leading cause of death from lung cancer in non-smokers. It is responsible for the highest share of the yearly effective doses a person is exposed to, and, in many cases, it is the most important indoor pollutant. National regulations on radon typically use derived reference levels, except for occupationally exposed workers that are monitored using a graded approach (e.g. in Switzerland and EU). However, in some countries, radon concentrations in dwellings or workplaces are high and the effective doses are comparable, and even greater than those measured in occupational workplaces. The times spent in different places and the presence of children or disabled people (that usually spend more time indoor) bring a need for assessing the risks of indoor radon exposure using a graded approach for both dwellings and workplaces. It is essential to highlight that the Covid-19 pandemic made more people work from home, and this new situation may be permanent for some workers.

***Objective and Design*:** On this basis, the objectives of this work are to demonstrate the importance of adequate monitoring of natural radioactivity, simulate effective doses due to radon with the new effective dose coefficients (EDCs) proposed by International Commission on Radiological Protection (ICRP) (publication 137), show case studies that illustrate the need for effective dose calculation and propose a method to set radon mitigation deadlines for buildings with high radon activity concentrations. Moreover, this work will shed light in the question about the possible need for new radon reference levels after the new EDCs were proposed.

***Conclusions*:** One important outcome of this work is the application of the dose approach in a case study conducted in a dwelling, the measurements and calculations show high annual effective doses (up to 350 mSv/year).

Keywords: *graded approach; radon risk; radon mitigation; effective dose coefficients; effective doses; natural radioactivity; reference levels; indoor air quality*

This article will focus on Rn-222 due to the increased availability of data in the literature. However, Rn-220 should not be underestimated. In some parts of the world, the presence of radon in the soil and rocks is so high that it represents a serious problem for people's health (1). According to ICRP 126 (2), for many individuals, including some workers, radon is the main contributor to radiation exposure.

Very often, natural radioactivity is considered non-dangerous, especially when compared to artificial radioactivity, but that is not the case (3). The effective dose received by an individual during his/her life is caused mostly by natural radioactivity and specifically by indoor exposure to radon (3). This is especially true in countries where radon activity concentrations in buildings can be higher than the average world value of 39 Bq/m^3 (4).

In this work we will demonstrate that the effective doses resulting from exposure to radon in dwellings may become much higher than those at the workplace and, in some cases (see the case study), could reach and even exceed 100 mSv annually. This value is the same level indicated by the ICRP as the maximum value for a reference level, incurred either acutely or in a year. Exposures above 100 mSv would be justified only under extreme circumstances such as the saving of lives or the prevention of a serious disaster (5).

The objectives of this work are:

- Demonstrate the importance of adequate monitoring of natural radioactivity.
- Simulate doses due to radon with the EDCs proposed by ICRP (6).
- Show case studies that illustrate the need for effective dose calculations.
- Propose a method to set radon mitigation deadlines for buildings with high radon concentrations.
- Simulate the Derived Reference Levels (DRLs) with the new effective dose coefficients (EDCs) to check if they should be updated.

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Methodology

This work is a review article based on the most recent research available about radon reference levels worldwide and several years of practice in the field of radon measurements and mitigation. The case study is based on real measurements made in Switzerland by ECONS SA.

Instruments

The best practices in radon measurements were followed, the radon monitor used for short-term measurements was RadonMapper, manufactured by TECNAVIA (Lugano, Switzerland) and calibrated by METAS (Swiss Federal Institute of Metrology). Figure 1 illustrates an example of the graphic generated by the instrument, showing the measurement made in the bedroom of the new-born of the dwelling we present as a case study in this work (section 'Iragna dwelling'). Moreover, SSNTDs (solid-state nuclear track detectors) were used for long-term measurements during wintertime. The SSNTDs are manufactured by Mi.am and the model is the RadOut® (dimensions: 25 × 25 × 1.5 mm) that uses CR-39, they are approved by METAS in Switzerland and had good performance in intercomparisons done by different Institutions (such as Paul Scherrer Institute – PSI and BfS).

Effective doses

Effective dose calculation is based on the latest EDC of 3 mSv per mJ h m^{-3} recommended by ICRP 137 (6, 7). The corresponding EDC for Rn-222 activity concentration, in equilibrium with its short life daughters, is 1.67×10^{-5} mSv per Bq m^{-3} h.

The effective doses were calculated using Eq. 1.

$$E = c \times F \times C_{Rn} \times \Delta(t) \quad (1)$$

Where,

E = effective dose calculated over the Δ(t) (mSv);
c = effective dose coefficient (mSv m^3/h Bq);
F = equilibrium factor;
C_{Rn} = average radon activity concentration (Bq/m^3) measured during a period of time (Δ(t) in hours);
Δ(t) = exposure duration (hours).

The calculations used an equilibrium factor of 0.4, unless otherwise stated. Thus, the term c × F is equal to 6.7×10^{-6} mSv per Bq m^{-3} h.

Natural background in perspective

The main objective of this section is to discuss how the natural background is sometimes confused with the radon concentration indoors.

A clear distinction between these two concepts is important because the recommended effective dose (that will be explored further) sometimes exclude the contribution due to the natural background. Quoting the ICRP 103, paragraph 369 (5), 'With radiation there is another source of reference, and that is the natural background radiation to which such animals and plants are continuously and "typically" exposed'.

The keyword in this definition is 'typically', since it is a vague word, it can be interpreted in many ways. However, the usual take on the natural background is the effective dose due to the presence of natural radionuclides in a certain environment, without anthropogenic contributions. It is important to highlight that this means outdoor exposure, not indoor, because we have control over human-made constructions (8).

Radon is one of the radionuclides responsible for the natural background, but, usually, the radon concentrations outdoors contribute only to a small fraction of the annual natural background dose (8) because it tends to dilute rapidly in the air (2). Worldwide, the total effective dose average, due to natural sources, is ~2.4 mSv per year (9). Table 1 shows the natural radioactivity in perspective.

Some studies claim that populations exposed to higher background radiation may evolve to be more resistant to develop some types of cancer and others claim that the cancer rate is higher in areas with high natural radioactivity.

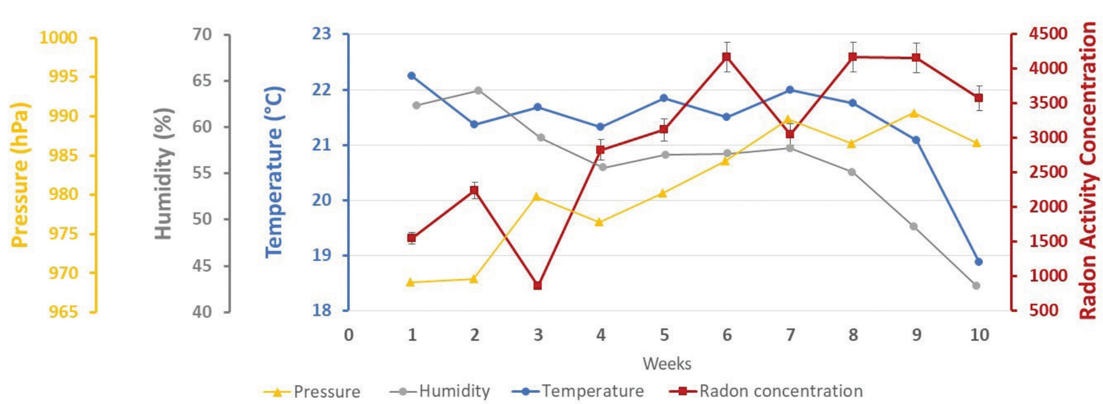

Fig. 1. Radon activity concentration (Bq/m^3), temperature (°C), humidity (%), and pressure (hPa) for the measurement period in the bedroom of the new-born in the Iragna dwelling.

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However, systematic review research concluded that the results are inconclusive, and most of the researches that approached these differences analyse small samples, making it difficult to draw conclusions from them (16). Moreover, we must consider the effects on the people who migrate from other places where the natural background level is low.

Reference levels

According to ICRP 103 (5), the reference level represents the level of effective dose or risk, above which is judged to be inappropriate to plan to allow exposure to occur, and for which therefore protective actions should be planned and optimised. The optimisation should be applied as appropriate even below the reference level, not only above.

The goal is to reduce all effective doses to a level that is as low as reasonably achievable (ALARA), taking economic and societal factors into account.

ICRP recommends a different effective dose range for each exposure situation:

- 20–100 mSv/year in case of emergency exposure situation;
- 1–20 mSv/year in case of existing and planned exposure situations (5).

Indoor radon exposure is considered as an existing exposure situation; therefore, the ICRP 103 suggests assessing the risk using the reference levels that should typically be set in 1–20 mSv band (2). ICRP 126 (p. 6 and 17) (2) recommends a reference level of 10 mSv/year both for the workplaces and for the dwellings (maximum total effective dose: 20 mSv/year).

ICRP 126 states that radon is not likely to give rise to an emergency exposure situation, but they do not exclude the possibility (2).

The reference levels are set based on the probability of causing deterministic or stochastic health effects. ICRP 103 (206) (5) states that at effective doses higher than 100 mSv there is an increasing possibility of deterministic effects and a significant risk of cancer. Exposures above 100 mSv, incurred either acutely or in a year, would be justified only under extreme circumstances either because the exposure is unavoidable or in exceptional situations such as the saving of life or the prevention of a serious disaster.

As a term of reference, under a special allowance from the then-regulator, the Nuclear and Industrial Safety Agency, workers at Fukushima Daiichi were permitted doses of up to 250 mSv. That limit was lowered back down to 100 mSv in December 2011 (17). In Europe, some Member States (11, 12, 18) already started to measure radon in workplaces using the effective dose limit of 20 mSv/year recommended by ICRP (2) as recommended in the European Commission Directive 2013/59 (19).

A summary of the ICRP recommendations is provided at Table 2.

Effective dose coefficients

The EDCs was introduced by ICRP in 1993 to transform effective doses to radon activity concentrations which is a measurable quantity expressed in Bq/m^3.

According to ICRP 137 (6), an EDC of 3 mSv per mJ h m^{-3} is recommended for the inhalation of radon and radon progeny. The corresponding EDC expressed in terms of radon-222 gas indoor exposure depends on the equilibrium factor, F, between radon gas and its progeny. Using the standard assumption of $F = 0.4$ for most indoor situations, this EDC corresponds to 6.7×10^{-6} mSv per Bq h m^{-3}. While ICRP 137 (6) does not specifically address

Table 1. Effective dose levels (mSv) in different situations

Effective dose(mSv)	Description	Exposure duration
<1	Residents of other European countries during Chernobyl accident (10)	In the first year
1.19	Average natural background in Lugano (Ticino, Switzerland) (11)	1 year
2.4	Average natural background radiation in the world (10)	1 year
2.28	Radon in average USA home (12)	1 year
9	Residents of contaminated areas due to the Chernobyl accident (10)	First 20 years
10	Abdomen and pelvis CT scan (13)	Acute
30	115,000 evacuees from the Chernobyl area (10)	Acute
68	Evacuation in Fukushima (14)	3 months
100	BfS (Bundesamt für Strahlenschutz) lower estimate for the threshold for damage to the unborn child (15)	Acute
100	ICRP 103	Acute or 1 year
120	Average dose among 530,000 recovery operation workers in Chernobyl (10)	1986–1990
250–350	Iragna case (case study presented in this work)	1 year
500	BfS typical threshold value for deterministic effects (15)	Acute

Table 2. Summary of ICRP Recommendations

ICRP Publication	Homes (7000 hours/year)		Workplaces (2000 hours/year)		Total effective dose
	Effective Dose [mSv/year]	Radon activity concentration [Bq/m³]	Effective Dose [mSv/year]	Radon activity concentration [Bq/m³]	Max annual total effective dose [mSv/year]
65 (1993)	3 - 10	200-600	3-10	500-1500	20
103 (2007)	10	600	10	1'500	20
115 (2010)	10	300	10	1'000	20
126 (2014)	10	100-300	10	300	20

public exposures, it is intended that this same EDC applies to exposure in homes (20).

Derived reference levels for indoor radon

Once the reference levels (e.g. the effective dose values to be respected) have been chosen, the DRLs for indoor radon, expressed as radon activity concentration, are calculated using the EDC. This calculation is illustrated by Fig. 2.

The ICRP recommends using the same DRL in dwellings and in mixed-use buildings (e.g. schools, hospitals, shops, cinemas) that have access for both members of the public and workers, and, by extension, in workplaces without public access when indoor radon exposure is not considered as occupational (e.g. office buildings, typical workshops) (2).

Based on the new EDC, the reference level of 10 mSv/year corresponds to a DRL of 170 Bq/m³, assuming $F = 0.4$, a yearly exposure of 8,760 h (worst case scenario) and using Eq. 1.

Following the introduction of the new EDCs published in publication 137 ICRP (6), a question arises whether there is a need to review the DRLs range values recommended in ICRP 126 (100–300 Bq/m³) and by the World Health Organization (2, 21).

For a single DRL value of 300 Bq/m³ (without distinction between home and workplace), the effective annual dose does not exceed 20 mSv/year.

Let us try to demonstrate this with some practical examples.

Scenario 1 – dwelling and workplace (not occupationally exposed)

Workplace example (not considered to be professionally exposed to radiation)

Using Eq. 1 and assuming 2,000 h worked per year, an equilibrium factor of 0.4 and 300 Bq/m³, the result is 4 mSv/year, as shown in Eq. 2.

$$E = 1.67 \times 10^{-5} \times 0.4 \times 300\ (\mathrm{Bq/m^3}) \times 2{,}000 = 4\ \mathrm{mSv/year} \qquad (2)$$

Dwelling example

Using Eq. 1 and assuming a person stays at home for 6,760 h (8,760 h/year minus 2,000 working hours/year),

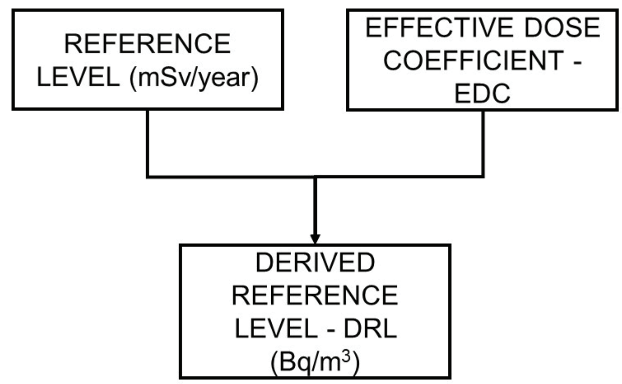

Fig. 2. Visual schematic of the DRL calculation.

an equilibrium factor of 0.4 and 300 Bq/m³, the result is 13.6 mSv/year as shown in Eq. 3. Summing the results from Eqs. 2 to 3, we have 17.6 mSv/year, as shown in Eq. 4.

$$E = 1.67 \times 10^{-5} \times 0.4 \times 300\ (\mathrm{Bq/m^3}) \times 6{,}760 = 13.6\ \mathrm{mSv/year} \qquad (3)$$

$$E_{total} = E_{dwelling} + E_{workplace} = 17.6\ \mathrm{mSv/year} \qquad (4)$$

Table 4 shows a summary of the results.

Scenario 2 – occupationally exposed workers

A worker exposed to an effective annual dose of more than 10 mSv/year (or 6 mSv/year in EU) must be considered a worker professionally exposed to ionising radiation (2, 4, 22). In the case of a professionally exposed worker, the dose limit value is set at 100 mSv averaged in 5 years (20 mSv/year) and the dose must be below 50 mSv/year (2, 4, 22).

Equation 5 shows the case of a professionally exposed person working 2,000 h/year receiving an allowed effective dose of 20 mSv/year in the workplace and assuming his dwelling has an average radon activity concentration of 300 Bq/m³. The results show that in this case, the effective dose (E_{total}) is 33.6 mSv/year.

$$E_{total} = E_{dwelling} + E_{occup.\ workplace} = 13.6 + 20 = 33.6\ \mathrm{mSv/year} \qquad (5)$$

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In this case, assessing the dose at the workplace is not enough. The overall dose value can be high. The contribution in the home must also be considered and the home value lowered or the exposure in the workplace reduced.

Conclusion about the two scenarios

Comparing scenarios 1 and 2, the effective dose in the dwelling is above 10 mSv/year, but, in the workplace (scenario 1), the effective dose is below this value. For the scenario 1, the sum of the two effective doses remains below 20 mSv, even if in the dwelling the effective dose is higher than the 10 mSv/year benchmark (2)

In the case of professionally exposed workers (scenario 2), the sum of the two effective doses is above 20 mSv/year. We believe that extending the effective dose calculation method to the dwelling is required to avoid excessively high doses, since the worker does not wear a dosimeter at home.

Table 3 shows the summary of the comparisons.

Reference levels versus limit

Some countries have regulated limits using the DRLs as benchmarks. Nevertheless, actual limits (legally binding) are not common worldwide. Some countries like Sweden, Norway and Estonia have set the radon activity concentration limit as 200 Bq/m^3 (11, 13, 23–25), compatible with the ICRP recommendations. In Switzerland, the citizens are not obliged to measure, but if they do so and the radon activity concentrations are higher than 300 Bq/m^3 (reference level), they must remediate the building (26).

In Germany, the DRL (300 Bq/m^3) is not considered a limit. The prerogative of using reference levels instead of limit values is explained by BfS (27), 'if there was a limit value for radon concentrations in buildings, it would be obligatory to implement measures there. These would include usage restrictions or obligatory mitigation measures in private buildings. International radiation protection experts consider that the measures required by a limit value would be unreasonable and are therefore in agreement that a reference value and not a limit value should apply to radon'.

Considering the risk for the health of citizens in some areas (e.g. the case study in 7.3), this agreement of using a DRLs involves the difficult balance between personal responsibilities and the States liability. We are changing the natural background by building houses with different radon trajectories and that leads to increased radon activity concentrations. In these cases, the situation can be remediated to lower the radon activity concentration indoor. Moreover, new buildings can be constructed with radon-proof materials and layout and Conscientization must happen about the risks of increased concentrations in buildings. These values are often much higher than the natural background due to the layout used.

Graded approach for dwellings and workplaces

According to ICRP 126 (2), a graded approach should be used for applying occupational protection requirements. Where workers' exposure to radon is not considered occupational (e.g. office buildings), the first step is to reduce the activity concentration of radon to As Low As Reasonably Achievable (ALARA) (2) that is below the same DRL for dwellings. It is essential to highlight that the Covid-19 pandemic made more people work from home, and this new situation may be permanent for some workers. Therefore, how the employers will approach the radon problem will determine if the implementation of the 2013/59/Euratom is successful (19).

The corresponding annual effective dose in the workplace is usually lower than that in dwellings because the

Table 3. Radon activity concentrations derived from effective doses (calculated using Eq. 1)

	Workplace	Home	Home[a]
	2,000 h/year	6,760 h/year	8,760 h/year
Yearly effective dose	C_{Rn-222}	C_{Rn-222}	C_{Rn-222}
[mSv/year]	[Bq/m^3]	[Bq/m^3]	[Bq/m^3]
1	75	22	17
6	448	132	102
10	746	221	170
20	1,493	442	341
50	3,731	1,104	852
100	7,463	2,208	1,704
250	18,657	5,520	4,260

[a]Full time at home scenario.

time spent in workplaces is usually less than the time spent at home. Therefore, using the graded approach also for dwellings is important to assess the radon risk properly. If difficulties are met in this first step, a more realistic approach is recommended as a second step, consisting of optimising protection using the actual parameters of the exposure situation, such as occupancy rate, together with a DRL of the order of 10 mSv/year of effective dose.

If despite all reasonable efforts to reduce radon, the exposure persists above the reference level expressed in effective dose, the workers should be considered occupationally exposed and, in dwellings, appropriate measures should be taken to remediate the building.

The approach for workplaces, which are classified as occupational or non-occupational, should be the same for dwellings as the radon source is the same. In the workplace, we can consider the situation as occupational or existing exposure, but for dwellings, we classify them only as existing exposure situation, independently of the dose and even if the doses are higher than for occupational exposure. Here we propose the use of an integrated approach for workplaces and dwellings.

Case study

In some parts of the world, radon values are much higher than the average, making it essential to take measurements to assess the risk to citizens as an emergency exposure situation could arise. It occurs in alpine countries where some regions have radon values causing significant effective doses in individual buildings, even higher than 100 mSv/year. Quoting ICRP 103 (5), 'exposures above 100 mSv, incurred either acutely or in a year, would be justified only under extreme circumstances, either because the exposure is unavoidable or in exceptional situations such as the saving of life or the prevention of a serious disaster'.

In these areas, carrying out measurements in all dwellings is needed to protect the health of citizens. Often, the rules do not oblige citizens to perform radon measurements even if the area is at significant risk. However, the government has the responsibility to inform citizens about the radon risk, most notably in radon prone areas, to demonstrate the importance of measuring radon at several points in the building to assess the risk properly.

Moreover, if the DRL in the dwellings is exceeded, we propose calculating the effective dose to which the occupants are exposed and also check if the reference level is exceeded.

The dose assessment approach applied to dwellings and non-occupational workplaces

Radon activity concentrations are essential to assess the danger of radon exposure.

The calculation of the total annual effective dose, demonstrates that occupants might be exposed to doses higher than 20 mSv/year, since 300 Bq/m^3, in the worst case scenario with an exposure of 8,760 h/year, corresponds to an annual effective dose of about 18 mSv (20), see Table 4. The calculation of the effective dose is simple but requires measurements in several rooms of the dwelling (at least the most used ones, e.g. the bedrooms and living room). The method to calculate the effective dose due to radon in dwellings and workplaces is the same as the one for occupational workplaces.

According to Table 5, assuming 8,760 h/year of exposure, and the EDC recommended by ICRP 137 (6), when the average indoor radon activity concentration exceeds 1,700 Bq/m^3 effective doses above 100 mSv/year are observed.

In practice, the times spent and the radon activity concentrations in each room should be considered to calculate the effective dose accurately. In the absence of measurements, estimations can be made to fill the gaps in the assessment.

A critical case

A particularly critical case, with high radon risk, is presented to illustrate the proposed method. This building is in the centre of a small town (Iragna) located in Switzerland (Canton Ticino), close to the Alps.

Following a 3-month measurement campaign during wintertime, carried out with trace dosimeters (CR-39), the effective dose to which the inhabitants of the building are exposed was evaluated. The results of the 3 months campaign (104 days) were extrapolated to give the exposure in 1 year.

Iragna dwelling

Table 6 presents the effective doses calculated according to the time spent by each member of the household indoor. The radon activity concentrations and the time spent in each room were considered. Moreover, it was assumed that the new-born spends all day at home (worst case scenario but very similar to the real situation), the child spends a few hours per day outside the dwelling, and the adult man and woman work 2,000 h per year outside the dwelling.
In the present case, the estimated effective doses received by the members of the household are more than 2.5 times

Table 4. Simulated effective doses for a person that works 8 h/day outside the dwelling (calculated using Eq. 1)

Location	Annual exposure [hours/year]	C_{Rn} [Bq/m^3]	Effective dose [mSv/year]
Dwelling	6,760	300	13.6
Workplace	2,000	300	4.0
Total	8,760	–	17.6

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Table 5. Yearly effective doses with varying Rn activity concentrations

	Workplace	Home	Home[a]
	2,000 h/year	6,760 h/year	8,760 h/year
C_{Rn-222}	Yearly effective dose	Yearly effective dose	Yearly effective dose
[Bq/m³]	[mSv/year]	[mSv/year]	[mSv/year]
100	1	5	6
170	2	8	10
221	3	10	13
300	4	14	18
341	5	15	20
400	5	18	23
442	6	20	26
500	7	23	29
600	8	27	35
700	9	32	41
746	10	34	44
800	11	36	47
852	11	39	50
900	12	41	53
1,000	13	45	59
1,104	15	50	65
1,200	16	54	70
1,300	17	59	76
1,400	19	63	82
1,493	20	68	88
1,600	21	72	94
1,700	23	77	100
1,800	24	82	106
1,900	25	86	112
2,000	27	91	117
2,208	30	100	130
3,000	40	136	176
3,731	50	169	219
4,260	57	193	250
5,000	67	226	293
5,520	74	250	324
6,000	80	272	352
7,000	94	317	411
8,000	107	362	470
9,000	121	408	528
10,000	134	453	587

(Shading legend)
- $E \le 20$ mSv/year recommendations for existing exposure situation in home + workplace (ICRP 126)
- $20 < E \le 50$ mSv/year (maximum annual dose for occupational exposure in exceptional cases)
- $50 < E \le 100$ mSv/year
- $100 < E \le 250$ mSv
- $E > 250$ mSv/year

[a]Full time at home scenario.

the maximum value of 100 mSv/year recommended by the ICRP (5), as shown in Table 6. In the case of the new-born, the annual effective dose is 350 mSv.

It is important to note that in the case of the new-born the effective dose after 3 months of measurements reach 100 mSv/year. The Iragna case is only an example of a

Table 6. Effective doses calculated for a new-born, a child, two adults with the same routine based on the habits of the occupants

		New-born		Child		Adults (woman and man with the same routine)	
Location	C_{Rn-222}	Usage	Effective dose	Usage	Effective dose	Usage	Effective dose
	[Bq/m³]	[hours/year]	[mSv/year]	[hours/year]	[mSv/year]	[hours/year]	[mSv/year]
Living room	4,582	547.5	16.8	365	11.2	1,643	50.4
Kitchen	8,174	0	0.0	0	0.0	730	40.0
Dining room	8,174	730	40.0	730	40.0	730	40.0
Bedroom	5,899	7,300	288.5	5,475	216.4	3,285	129.8
Bathroom	4,000[a]	182.5	4.9	182.5	4.9	365	9.8
Cellar	11,500	0	0.0	0	0	26	2.0
Total	–	8,760	350.2	6,753	272.5	6,779	272.5

Legend:

(grey shading) Average radon activity concentration measured with RadonMapper

[a]Estimated value.

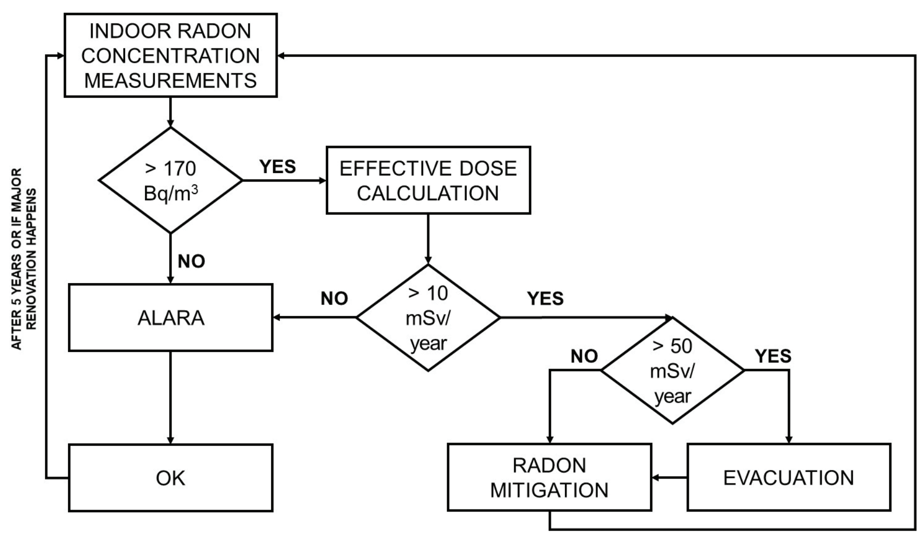

Fig. 3. Flowchart explaining the proposed method to assess radon risk indoor.

situation in which the effective doses exceed 50 mSv and 100 mSv yearly or acutely.

Radon mitigation

Exceeding of the limit value of the radon activity concentration, set by the legislation (country/region-specific or international recommendations) requires a mitigation intervention. Figure 3 shows the proposed method for evacuation and mitigation in any building. The concepts are explained in the following sections.

Evacuation

Assessing whether the condition can be characterized as an emergency exposure situation (5) is required before proceeding with the radon mitigation, as urgent actions are needed to reduce undesirable consequences. It is important to reinforce that ICRP 126 (2) does not exclude the possibility of radon exposure causing an emergency.

Generally, as indicated by ICRP 103 (236) (5), the effective dose of 100 mSv/year, or in a shorter time, represents a value not to be exceeded except for justified reasons in extreme conditions (e.g. saving lives). In analogy with the occupational workers, we consider the maximum effective dose of 50 mSv/year as a limit to evacuate the occupants from the premises or the building. As a point of comparison, the evacuees of Fukushima received an average effective dose of 68 mSv after the nuclear accident (14).

Coming back to the case study of the Iragna dwelling, with the annual effective doses being approximately 350, 272, 272 and 272 mSv/year, for the new-born, child, adult woman, and adult man, respectively, we recommend the immediate evacuation of the building based on the recommendation of ICRP previously explained. However, it is the responsibility of the homeowner to decide whether to leave and to implement remediation measures.

Radon mitigation target

The purpose of the mitigation intervention is to reduce radon activity concentrations below the DRL and, specifically, to ensure that the effective dose is below 20 mSv/year (workplace + dwelling). The mitigation intervention must use a target effective dose to calculate for how long the mitigation should be performed to prevent occupant exposure from reaching values higher than the maximum target effective dose.

There are no specific target effective doses for homes and workplaces not professionally exposed to radiation. The choice of the maximum target effective dose can be made by analogy with professionally exposed workers, who are subject to two constraints: the average effective dose must be below 100 mSv in 5 years, and the maximum exposure is set to 50 mSv/year. An effective dose of 100 mSv accumulated over 5 years corresponds to an average effective dose of 20 mSv/year, twice the recommended value for homes and workplaces not professionally exposed to radiation.

Radon mitigation deadlines

Mitigation interventions should be carried out within time limits that should be chosen to avoid occupants receiving critical effective doses.

According to ICRP 126 (55) (2), radon is not likely to give rise to an emergency exposure situation. However, the discovery of very high radon activity concentrations in a place can require the prompt (which means without delay) implementation of protective actions particularly when the exposure affect other occupants for whom the decision maker of a property has a duty of care.

Usually, there is a lack of radon mitigation regulations worldwide. In some cases, the deadlines to remediate are not enough to avoid high exposure for the occupants. For example, this occurs in Switzerland, where mitigation actions, even in areas with high activity radon concentrations, can take up to 3 years (22), which cannot be considered a prompt action (see Table 7).

Table 7 shows that even for radon activity concentrations over 1,000 Bq/m^3, which corresponds to an effective dose above 58.7 mSv/year, the radon mitigation can take up to 3 years, corresponding to a cumulative effective dose above 176.1 mSv. In the Iragna dwelling case study, where the annual effective dose is 350 mSv/year for the newborn, the radon mitigation can take up to 3 years, resulting in a potentially accumulated exposure over 1,000 mSv.

Table 8 shows the proposed radon mitigation deadlines for the radon activity concentrations in a determined range. This table is a simplification based on the average radon activity concentration, but as explained in the proposed effective dose calculation method, an accurate assessment of the time spent in each room and the actual radon concentrations measured in these rooms are significant for an individualised approach and determining the best radon mitigation deadline for each building. If the problem happens in only one specific room, the mitigation should be carried out in that room.

The graded approach enables us to determine the effective dose for every occupant of the building based on the time spent in the rooms. Exceeding the recommended effective dose value require intervening with radon mitigation.

The role of measurements

The only reliable way to assess the risk due to the presence of radon is to perform measurements inside the buildings.

Based on our approach, the measurements in the building should be made in the rooms where people stay the most, such as the living room, bedrooms, dining room and study room, to calculate accurately the effective doses.

Generally, the measured mean radon activity concentrations are then compared with the chosen DRL.

Table 7. Radon mitigation deadlines according to the radon concentrations in Switzerland.

Measured radon concentrations (Bq/m^3)	Maximum end of the radon mitigation in years		
	Places with a long stay of people[a]	Places with a short stay of people[b]	Uninhabited places[c]
> 300 up to 600	10	30[d]	No action needed
> 600 up to 1,000	3	10	
> 1,000[e]	3	3	

Source: Adapted from (22).
[a]Long stay > 30 h/week
[b]Short stay between 15 and 30 h/week
[c]Uninhabited place <15 h/week
[d]If before finishing the radon mitigation, a major renovation of the building is performed, radon mitigation should occur concurrently.
[e]Workplaces with more than 1,000 Bq/m^3 are considered 'radon risk workplaces' and workers are considered occupational exposed if the dose received is above 10 mSv/year. And they are subject to the disposition of article 167 ORaP.

Measurements should last for at least 1 year so that the annual dose can be calculated with better precision. However, in many critical areas, it may be sufficient to carry out a shorter measurement campaign during the cold period (90 days), which is generally the worst one, to establish whether the building needs to be evacuated and avoid unjustified exposure.

In critical cases, there is the possibility of having a first indication of the situation employing short-term measurement campaigns performed with electronic instruments (7 days).

Effective communication with the citizens

The information given to citizens is often not enough due to the lack of comparison terms enabling people to perceive the real problem related to radon presence in the dwellings. Since using terms of radon activity concentration is not useful, it is better to talk about the effective dose by using practical examples to make it an understandable situation (e.g. comparison with medical applications or nuclear accidents). It is not a question of scaring the population but of providing correct information to avoid a potentially dangerous situation.

The role of governments should be promoting radon awareness, funding researchers and training institutions and, in some cases, subsidising measurements and radon mitigation.

Conclusion

Effective doses, regardless of the origin, should be dealt the same way because there is no difference between the biological effects caused by the same effective doses received from natural or artificial sources.

The main conclusions derived from this work are:

- Natural radioactivity, primarily due to radon presence in the buildings, is not sufficiently considered. In some areas, however, the indoor exposure can be significantly high and poses risks to the population. The effective dose due to radon in homes can be higher than those used as limits to define a worker as occupational (e.g. 6 mSv/year in EU).
- With the revision of the EDCs values, the DRLs of 300 Bq/m^3, adopted by many standards, should be lowered to 170 Bq/m^3 if the goal is not to exceed an effective dose of 10 mSv/year in dwellings, as suggested by ICRP 126 (2). However, if we consider the sum of the effective dose for workplace and dwelling (20 mSv/year), the DRL can be maintained.
- For occupationally exposed workers, however, further studies are required to avoid critical situations, for example when they are also exposed to high radon activity concentrations in the dwelling.
- It is essential to measure radon activity concentration to avoid critical situations without the knowledge of citizens. Regulations generally do not oblige citizens to take measurements.
- It is crucial to inform citizens more effectively using, for example, concrete examples with effective doses.
- Finally, it is necessary to re-evaluate the radon mitigation deadlines by adjusting them to the effective doses using an approach like the one applied to the workplace.

Considering these conclusions, we believe developing a measurement protocol with the calculation of the effective dose is required, to standardise the methods for assessing the risk of radon exposure in dwellings and workplaces that are not professionally exposed.

Table 8. Proposed deadlines, in years and months, for radon mitigation purposes in buildings, considering the radon concentrations

Minimum Rn concentration	Maximum Rn concentration	Time limit	Minimum effective dose over the time limit	Maximum effective dose over the time limit
[Bq/m^3]	[Bq/m^3]	[months]	[mSv]	[mSv]
170	340	60	50	100
340	420	48	80	99
420	550	36	74	97
550	850	24	65	100
850	1,100	18	75	97
1,100	1,700	12	65	100
1,700	2,200	9	75	97
2,200	3,400	6	65	100
3,400	6,800	3	50	100
6,800	20,000	1	33	98
20,000	–	–	>100	>100

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For professionally exposed workers, we also propose an approach considering the exposure in the dwelling, in addition to the workplace.

In future work, the applicability and technical suitability of this protocol will be evaluated, considering more examples of practical cases.

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