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# The risk of radon induced lung cancer in rental accommodation

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**Abstract.** The radon concentration in the indoor air was measured in 221 rental accommodations located in 53 buildings, including 28 multi-occupant houses and 25 single-family terraced houses constructed between 1850 and 2010. The overall annual mean value of the concentration of radon in the indoor air was  $30.7 \text{ Bq/m}^3$ . The annual mean value of the concentration of radon in the indoor air exceeded  $100 \text{ Bq/m}^3$  in 5.9% of the accommodations, all located in single-family terraced houses. For single-family terraced houses the annual mean value of the concentration of radon in the indoor air exceeded  $100 \text{ Bq/m}^3$  in 52% of the houses and 12% exceeded  $200 \text{ Bq/m}^3$ . Approx. 77% of the accommodations exceeding  $100 \text{ Bq/m}^3$  for the concentration of radon in the indoor air had a content between 100 and  $200 \text{ Bq/m}^3$  and 23% had a content exceeding  $200 \text{ Bq/m}^3$ . Significant differences in the concentration of radon in the indoor were found in accommodations located in multi-occupant houses. Additionally, the risk of the concentration of radon in the indoor air exceeding  $100 \text{ Bq/m}^3$  in accommodations in multi-occupant houses was found to be very low, but if any the risk was highest in accommodations on the ground floor in a building constructed with slab on ground.

## 1. Introduction

Radon-222 develops from the radioactive decay of radium-226 and has a half-life of 3.8 days. This noble gas seeps through soil into buildings, and if it is not evacuated, there can be much higher exposure levels indoors than outdoors [1], which is where human exposure occurs [2]. In this way, radon affects occupants through the indoor climate.

The World Health Organization recommends states to introduce requirements for the maximum concentration of radiation from natural sources in the indoor air. These recommendations are the result of the World Health Organization's evaluation of radon as being responsible for 3-14% of lung cancer incidents, depending on the average radon exposure in different countries [3]. Results show radon to be the second-largest cause of lung cancer (tobacco smoking is still the primary cause). Radon exposure must be taken seriously in the struggle against radon-induced lung cancer due to the large number of people who are exposed daily in buildings and especially in residential buildings [3]. If people spend their whole life in a house with an average radon concentration in the indoor air that exceeds  $200 \text{ Bq/m}^3$ , their risk of getting lung cancer is higher than 1%. This is far too high and higher than what in other contexts is acceptable for a single-factor risk [4]. Therefore, it is crucial to ensure a low annual mean radon concentration in the indoor air, by preventing radon from infiltrating into buildings and evacuate by diluting radon in the indoor air through ventilating indoors with outdoor air [5].

Since 2010, Danish buildings have been constructed to ensure a radon concentration in the indoor air below  $100 \text{ Bq/m}^3$ , estimated as the annual mean value [6]. For all other buildings including homes it is recommended that the annual mean radon concentration in the indoor air should be kept below  $100 \text{ Bq/m}^3$ , being the national reference level [7, 8].

In this study, the annual mean value of the radon concentration in the indoor air in rental accommodation was measured in the winter of 2013/14 and again in the winter of 2014/15. The paper

shows how well 221 homes for rental accommodation perform, with respect to the Danish Building Regulations for buildings constructed after 2010 and with respect to the national reference level, with regard to radon. Additionally, the association between the concentration of radon indoor in these rental accommodations and other studies on Danish accommodations, floor level, multi-occupant houses, single-family terraced houses, and the presence of a basement was identified. Furthermore, the number of accommodations with a concentration of radon indoor exceeding 100 and 200 Bq/m<sup>3</sup> was determined.

## **2. Measurements**

Measurements were carried out in 221 rental accommodations. Families and building owners were invited to participate in a radon-monitoring programme. The programme took place in the heating periods of 2013~2014 and 2014~2015 between November and May. 196 accommodations were located in 28 multi-occupant houses and 25 accommodations were located in single-family terraced houses. Accommodations were selected from regions where former studies have shown a 1-30% chance of finding detached single-family houses with a concentration of radon in the indoor air exceeding 200 Bq/m<sup>3</sup> [9]. Three detectors were distributed to each accommodation by mail in sealed aluminum-coated envelopes and returned after the integration period in a pre-stamped envelope. Each participant was asked to fill in a questionnaire regarding the date when exposure started and ended, as well as type of room in which the detector was placed. Participants were instructed regarding placement of the detectors [10] and instructed to clean and ventilate their homes as they usually would, so that a representative concentration of radon in the indoor air was obtained. Information regarding year of construction, basement, crawl space, and building and roof materials was gathered from the Danish Building and Housing Register [11]. Information gathered from the Danish Building and Housing Register was used to make sure that accommodations represented typical rental accommodation in Denmark. In accordance with Danish recommendations for radon measurements in private homes, the simplest assessment of radon concentrations is based on direct integrated measurements [10, 12, 13].

## **3. Dwellings**

Accommodations were either rental accommodation located in buildings privately owned by landlords or social housing owned by the Danish association of non-profit rental accommodation. Buildings were multi-occupant houses and single-family terraced houses. The buildings represented the building technique and commonly used building materials used in Denmark from 1850 until 2010. Buildings from this period were grouped into three types:

### *3.1. Multi-occupant houses built between 1850 and 1920.*

Buildings constructed with a solid brick wall founded on masonry foundations. Sometimes single natural stones might be included in the foundations and outer walls. Suspended floors at horizontal partitions were timber floor constructions and included timber beams. Solid floor against the ground were made of concrete, asphalt or soil.

### *3.2. Multi-occupant houses built between 1920 and 1960.*

Buildings constructed with solid brick walls or cavity walls founded on cast-on-site concrete foundations. Suspended floors were timber floor constructions or reinforced concrete suspended floors cast on site. Solid floors against the ground were made of concrete.

### *3.3. Multi-occupant houses or single-family terraced houses built in the period from 1960.*

Buildings constructed with load-bearing concrete constructions as prefabricated elements above the ground. Foundations and load-bearing basement walls were made of concrete cast on site. Suspended floors were made of reinforced concrete usually as prefabricated concrete elements. Solid floors against the ground were of concrete cast on site.

## **4. Detectors**

The detectors used were closed passive etched track detectors, made from CR39 plastic film placed inside an antistatic holder, manufactured by Gammadata Instrument AB (Uppsala, Sweden). Analysis

were carried out by an ISO 17025 and ISO 14001 certified as well as EMAS (European Eco-Management and Audit Scheme) registered laboratory. Measurement methods are accredited according to standards of SWEDAC (Swedish board of Accreditation and Conformity Assessment) and accepted in 18 European countries by the European Cooperation for Accreditation of Laboratories (EAL).

## 5. Results

The annual mean value of the radon concentration in the indoor air for every accommodation was calculated as the arithmetic average of three measurements. Radon was measured for a median duration of 90 days (min–max: 60 – 194 days). Measurements fulfil the requirements described by Rasmussen [10, 12].

Table 1 shows the distribution of the annual mean value of the radon concentration in the indoor air grouped according to floor level in intervals of 50 Bq/m<sup>3</sup>. The minimum value was 1 Bq/m<sup>3</sup>, the maximum value was 250 Bq/m<sup>3</sup>. The standard variation was 38.3 Bq/m<sup>3</sup>, the median value was 18 Bq/m<sup>3</sup> and the mean value was 30.7 Bq/m<sup>3</sup>.

**Table 1.** Number of accommodations grouped according to the estimated annual mean value of the radon concentration in the indoor air shown by their floor location, and in intervals of 50 Bq/m<sup>3</sup>.

<i>Location</i>	<i>Bq/m<sup>3</sup></i>					<i>number of accommodations</i>
	<i>0-50</i>	<i>51-100</i>	<i>101-150</i>	<i>151-200</i>	<i>&gt;200</i>	
ground floor	58	18	7	3	3	88
1st Floor	50	0	0	0	0	51
2nd Floor	38	0	0	0	0	38
3rd Floor	30	0	0	0	0	30
4th Floor	6	0	0	0	0	6
5th Floor	8	0	0	0	0	8
number of accommodations	190	18	7	3	3	221
ratio in %	86.0	8.1	3.1	1.4	1.4	100

Table 2 presents the same data as in Table 1 where the 45 buildings that do not have a basement or a crawlspace as the lowest level facing the ground have been excluded. The minimum value was 1 Bq/m<sup>3</sup>, the maximum value was 206 Bq/m<sup>3</sup>, the standard variation was 32.3 Bq/m<sup>3</sup>, the median value was 17 Bq/m<sup>3</sup> and the mean value was 26.2 Bq/m<sup>3</sup>.

**Table 2.** Number of accommodations, grouped by the estimated annual mean value of radon in the indoor air, for buildings with a basement or a crawlspace at the lowest level facing the ground.

<i>Location</i>	<i>Bq/m<sup>3</sup></i>					<i>number of accommodations</i>
	<i>0-50</i>	<i>51-100</i>	<i>101-150</i>	<i>151-200</i>	<i>&gt;200</i>	
ground floor	42	9	6	2	1	60
1st Floor	43	0	0	0	0	43
2nd Floor	34	0	0	0	0	34
3rd Floor	28	0	0	0	0	28
4th Floor	5	0	0	0	0	5
5th Floor	6	0	0	0	0	6
number of accommodations	158	9	6	2	1	176
ratio in %	89.8	5.1	3.4	1.1	0.6	100

Table 3 presents the same data as in Table 1 for the 45 buildings without a basement or a crawlspace as the lowest level facing the ground. The minimum value was 10 Bq/m<sup>3</sup>, the maximum value was 250

Bq/m<sup>3</sup>, the standard variation was 53 Bq/m<sup>3</sup>, the median value was 33 Bq/m<sup>3</sup> and the mean value was 50 Bq/m<sup>3</sup>.

**Table 3.** Number of accommodations, grouped by the estimated annual mean value of radon in the indoor air, for buildings with a slab on ground.

<i>Location</i>	<i>Bq/m<sup>3</sup></i>					<i>number of accommodations</i>
	<i>0-50</i>	<i>51-100</i>	<i>101-150</i>	<i>151-200</i>	<i>&gt;200</i>	
ground floor	15	9	1	1	2	28
1st Floor	8	0	0	0	0	8
2nd Floor	4	0	0	0	0	4
3rd Floor	2	0	0	0	0	2
4th Floor	1	0	0	0	0	1
5th Floor	2	0	0	0	0	2
number of accommodations	32	9	1	1	2	45
ratio in %	71.1	20.0	2.2	2.2	4.5	100

Table 4 presents the same data as in Table 1 for dwellings located on the ground where the 25 single-family terraced houses have been excluded.

**Table 4.** Number of dwellings grouped by the estimated annual mean value of radon in the indoor air for dwellings located on the ground floor in multi-occupant houses.

<i>Location: Ground floor</i>	<i>Bq/m<sup>3</sup></i>					<i>number of dwellings</i>
	<i>0-50</i>	<i>51-100</i>	<i>101-150</i>	<i>151-200</i>	<i>&gt;200</i>	
over basement/crawlspace	42	5	0	0	0	47
ratio in %	89.4	10.6	0	0	0	100
over slab on ground	9	7	0	0	0	16
ratio in %	56.3	43.7	0	0	0	100

## 6. Discussion

The presented study determines the annual mean value of the radon concentration in the indoor air in rental accommodation. Measurements were carried out in the heating period. A single value was estimated for each accommodation following the descriptions given by Rasmussen [10, 12].

The study found an average annual mean value of the radon concentration in the indoor air of 30.7 Bq/m<sup>3</sup> ranging between 1 and 250 Bq/m<sup>3</sup>. In total, 5.9% accommodations had an annual mean value of the radon concentration in the indoor air exceeding 100 Bq/m<sup>3</sup>, all located in single-family terraced houses. Furthermore, 1.4% of the accommodations exceeding 100 Bq/m<sup>3</sup> additionally exceeded 200 Bq/m<sup>3</sup>. The variable single-family terraced houses were statistically significant. For single-family terraced houses only the annual mean value of the concentration of radon in the indoor air exceeded 100 Bq/m<sup>3</sup> in 52% of the houses and 12% exceeded 200 Bq/m<sup>3</sup>. 77% of the accommodations with the annual mean value of the radon concentration in the indoor air exceeding 100 Bq/m<sup>3</sup> had levels between 100 and 200 Bq/m<sup>3</sup> and 23% had an annual mean value of the radon concentration in the indoor air exceeding 200 Bq/m<sup>3</sup>.

The annual mean value of the radon concentration in the indoor air of 30.7 Bq/m<sup>3</sup> was somewhat lower than the population-weighted average annual mean value of the radon concentration in the indoor air of 59 Bq/m<sup>3</sup> for all Danish accommodations [9, 14]. The population-weighted average annual mean value of the radon concentration in the indoor air of 59 Bq/m<sup>3</sup> is based on 1-year measurements in 3019 single-family detached houses and 101 dwellings in multi-occupant houses in Denmark. The aerometric annual mean value of the radon concentration in the indoor air in dwellings in multi-occupant houses is 18 Bq/m<sup>3</sup> and for single-family detached houses 77 Bq/m<sup>3</sup> [9, 14]. The same pattern was seen in the present

study included 25 single-family terraced houses and 196 dwellings in multi-occupant houses. The present study shows that the annual mean value of the radon concentration in the indoor air for 94% of the dwellings located in multi-occupant houses did not exceed 50 Bq/m<sup>3</sup> and 6% was in the interval of 51-100 Bq/m<sup>3</sup>.

Significant differences between individual detectors creating the annual mean value of the radon concentration in the indoor air were found in dwellings located in multi-occupant houses. The risk of an annual mean value of the radon concentration in the indoor air exceeding 100 Bq/m<sup>3</sup> in dwellings in multi-occupant houses was found to be very low, but if any, it was most likely to be found in dwellings on the ground floor in a multi-occupant building with a slab on ground.

The ratio of dwellings, with an annual mean radon concentration in the indoor air, lower than 50 Bq/m<sup>3</sup> is higher for dwellings located on the ground floor over a basement or a crawlspace than dwellings located on the ground floor over a slab on ground in multi-occupant houses. A basement or a crawlspace provides a protection factor against radon infiltration. The basement or the crawlspace provides protection by diluting the air with outdoor air, that contains a concentration of radon of approximately 5 Bq/m<sup>3</sup>. The diluted air that infiltrate the indoor environment from a basement or a crawlspace contains less radon and provides less radon than air infiltrating directly from the ground [15].

The municipalities where the accommodations are located were, in the present study, selected from areas previously characterised as having the highest annual mean value of the radon concentration in the indoor air in Denmark. In these municipalities, 1-30% of the single-family detached houses are assumed to have an annual mean value of the radon concentration in the indoor air exceeding 200 Bq/m<sup>3</sup> [9].

The annual mean value of the radon concentration in the indoor air in accommodations was measured in the heating period of the winter of 2013~2014 and again in the heating period of the winter of 2014~2015. Measurements were repeated in accommodations where the first measurements, carried out in the heating period of the winter of 2013~2014, showed results exceeding the annual mean value of the radon concentration in the indoor air of 100 Bq/m<sup>3</sup>. These accommodations were all located in single-family terraced houses. Results from the first measuring period correspond with the results from the second measuring period. However, seasonal variations and the use of the accommodations was seen to affect the results, however, marginally.

Since 2010 buildings constructed in Denmark must be constructed to ensure that the annual mean value of the radon concentration in the indoor air does not exceed 100 Bq/m<sup>3</sup> [6]. In addition, workspaces for humans despite that they are located in buildings constructed before 2010 exceeding an annual mean value of the radon concentration in the indoor air of 100 Bq/m<sup>3</sup>, must implement radon-reducing measures reaching an acceptable annual mean value of the radon concentration in the indoor air [7]. The Danish Health Authority define the acceptable annual mean value of the radon concentration in the indoor air. Assessments are based on the annual mean value of the radon concentration in the indoor air, the health-risk of workers and the costs to implement the necessary radon-reducing measures. In general, for buildings constructed before 2010, it is recommended that the annual mean value of the radon concentration in the indoor air should not exceed 100 Bq/m<sup>3</sup>. These initiatives are the latest initiatives laying down basic safety standards for protection against the dangers caused by exposure to ionising radiation where the exposure to radon concentration in the indoor air is the primary source. The initiatives and recommendations are the result of the implementation of the national reference level in Denmark following the council directive 2013/59/EURATOM of 5th December 2013. An ongoing study, of the annual mean value of the radon concentration in the indoor air, indicate a large impact from the implementation of the requirements on radon in the Danish Building Regulations. The ongoing study include measurements carried out in single-family terraced houses constructed before and after 2010 located in the same regions of Denmark.

## 7. Conclusion

The study found an average annual mean value of the radon concentration in the indoor air of 30.7 Bq/m<sup>3</sup> ranging between 1 and 250 Bq/m<sup>3</sup>. In total, 5.9% (13 of the 221) accommodations had an annual mean value of the radon concentration in the indoor air exceeding 100 Bq/m<sup>3</sup>, all located in single-family terraced houses (13). For single-family terraced houses only the annual mean value of the concentration

of radon in the indoor air exceeded 100 Bq/m<sup>3</sup> in 52% (13 of the 25) of the houses and 12% (3 of the 25) exceeded 200 Bq/m<sup>3</sup>. 77% (10 of the 13) of the accommodations exceeding 100 Bq/m<sup>3</sup> as the annual mean value of the radon concentration in the indoor air had values between 100 and 200 Bq/m<sup>3</sup> and 23% (3 of the 13) had an annual mean value of the radon concentration in the indoor air exceeding 200 Bq/m<sup>3</sup>. In municipalities where the accommodations are located, 1-30% of the single-family detached houses are estimated to have an annual mean value of the radon concentration in the indoor air exceeding 200 Bq/m<sup>3</sup> [9]. The municipalities are divided into regions having 1-10% and 10-30% single-family detached houses with an annual mean value of the radon concentration in the indoor air exceeding 200 Bq/m<sup>3</sup> [9]. A similar pattern was seen for rental accommodation in single-family terraced houses as well as for multi-occupant houses. However, A risk of an annual mean value of the radon concentration in the indoor air exceeding 100 Bq/m<sup>3</sup> was found in accommodations for rent in single-family terraced houses. The variable single-family terraced houses were statistically significant.

Significant differences in the annual mean value of the radon concentration in the indoor air were found in dwellings located in multi-occupant houses. The risk of an annual mean value of the radon concentration in the indoor air exceeding 100 Bq/m<sup>3</sup> in dwellings in multi-occupant houses was very low, but if any risk, it was most likely to be found in accommodations on the ground floor in a building with a slab on ground.

The council directive 2013/59/EURATOM of 5th December 2013 lay down basic safety standards for protection against the dangers caused by exposure to ionising radiation where the exposure to radon concentration in the indoor air is the primary source. Member states of the European Union are obligated to define and implement an acceptable national reference level for the concentration of radon in the indoor air. In Denmark, the reference level of the annual mean value of the radon concentration in the indoor air is 100 Bq/m<sup>3</sup>. Means reaching an acceptable level of radon in the indoor air includes the radon concentration in the indoor air in proportion to issues as the health-risk of users, the use of the building and the costs to implement the necessary radon-reducing measures. Since 2010 buildings must be constructed to ensure that the annual mean value of the radon concentration in the indoor air does not exceed 100 Bq/m<sup>3</sup> [6]. The national reference level in Denmark refers to workspaces. For all other buildings constructed before 2010 it is recommended that the annual mean value for the radon concentration in the indoor air does not exceed 100 Bq/m<sup>3</sup>.

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