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ABSTRACT

Indoor radon levels were measured in 221 homes located in 53 buildings, including 28 multi-occupant houses and 25 single-family terraced houses. The homes consisted of rented accommodation located in buildings recorded as being constructed before 2010 and after the year 1850. The radon level in homes was measured and the buildings were registered for a series of variables describing upgrades, facilities, building components, construction characteristics and used materials. In addition, the radon level was measured in the basement in 9 of the buildings. The mean year value of the indoor radon level was 30.7 (1–250) Bq/m^3. The indoor radon level exceeded 100 Bq/m^3 in 5.9% of the homes, all located in single-family terraced houses. The investigated variables explained 5.9% of the variation in indoor radon levels, and although associations were positive, none of these, besides homes in single-family terraced houses, were statistically significant. However, a number of the variables seem to characterise homes with a low radon level. Approx. 75% of homes exceeding 100 Bq/m^3 indoor radon level had levels between 100 and 200 Bq/m^3 and 25% had indoor radon levels exceeding 200 Bq/m^3. The risk of indoor radon levels exceeding 100 Bq/m^3 in homes in multi-occupant houses was found to be very low, but the risk was highest on the ground floor in a building constructed with slab on ground.

Keywords: *indoor environmental quality, radon, variables*

1. INTRODUCTION

Radon-222 develops from the radioactive decay of radium-226 and has a half-life of 3.8 days. This gas seeps through soil into buildings, and if it is not evacuated, there can be much higher exposure levels indoors than outdoors, which is where human exposure occurs. 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. 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. If people spend their whole life in a house with an average radon concentration in the indoor air that exceeds 200 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. Therefore, it is crucial to ensure a low radon level in the indoor air and to prevent radon from infiltrating into buildings. It is recommended that indoor radon levels in homes should be below 100 Bq/m^3.

In a national survey of radon in over 3000 Danish dwellings, the population-weighted average annual radon concentration was 59 Bq/m^3, which is more than twice the mean concentrations measured in the Netherlands and the UK, somewhat higher than the mean concentrations measured in Canada and the USA and about half the mean concentrations in Finland and Sweden.

In this study, radon levels in rented accommodation were measured in the winter of 2013/14 and again in the winter of 2014/15. The paper shows how well 221 homes for rented accommodation perform with respect to the recommendations for indoor radon levels, and to identify the association between indoor radon in these homes and floor level, multi-occupant houses, single-family terraced houses, and basements. The number of homes with radon levels exceeding 100 and 200 Bq/m^3 was determined.

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2. MEASUREMENTS

Measurements were carried out in 221 homes for rented accommodation and in 9 basements. 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 homes were located in 28 multi-occupant houses and 25 homes were located in single-family terraced houses. 221 families agreed to participate, and radon levels were monitored in their homes. The selected municipalities are located in regions where other studies have shown a 1-30% chance of finding detached single-family houses with radon levels exceeding 200 Bq/m^3. Three detectors (Gammadata Matteknik AB, Uppsala, Sweden) were distributed to each participant by mail in sealed aluminum-coated envelopes and returned after the integration period in a prestamped 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 (>25 cm from a wall and away from strong draughts and heat) and also instructed to clean and ventilate their homes as they usually would, so that representative levels were obtained. Information regarding year of construction, basement, crawl space, building and roof materials was gathered from the Danish Building and Housing Register. Information gathered from the Danish Building and Housing Register was used to make sure that homes represented typical rented accommodation in Denmark. In addition homes were registered for a series of variables describing the characteristics of the building where the accommodation was located. Registrations were carried out on site.

3. DWELLINGS

Homes were either rented accommodation located in buildings privately owned by land-lords or social housing owned by the Danish association of non-profit rented 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 today.

Buildings were grouped into three types, Type A, Type B and Type C. Type C included both multi-occupant houses and single-family terraced houses.

3.1 Type A

Multi-occupant house built between 1850 and 1920. Buildings were 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 were timber floor constructions.

3.2 Type B

Multi-occupant house built between 1920 and 1960. Buildings were 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 Type C

Multi-occupant house or single-family terraced house built in the period from 1960. Buildings were 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 floor against the ground were made of concrete cast on site.

4. EQUIPMENT

The detectors were closed passive etched track detectors, made from CR39 plastic film placed inside an antistatic holder (Gammadata Måtteknik AB, Uppsala, Sweden). During the integration period, alpha and its decay products cause damage to the film. Gammadata Måtteknik is ISO 17025 and ISO 14001 certified as well as EMAS (European Eco-Management and Audit Scheme) registered. 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

Radon was measured for a median duration of 90 days (min–max: 60 – 194 days). A single representative indoor radon concentration for each home was calculated as the arithmetic average of the three measurements and used in all statistical analyses.

Table 1 shows the distribution of the determined mean year values of the radon concentration grouped according to floor level in intervals of 50 Bq/m³. The minimum value was 1 Bq/m³, the maximum value was 250 Bq/m3. The standard variation was 38.3 Bq/m³, the median value was 18 Bq/m³ and the mean value was 30.7 Bq/m³. The ratio of homes with a mean year value of the radon concentration ranging between 100 Bq/m³ and 200 Bq/m³ was 4.5%. The ratio of homes with a mean year value of the radon concentration exceeding 200 Bq/m³ was 1.4%. The ratio of homes with a mean year value of the radon concentration exceeding 100 Bq/m³ was 5.9%.

Floor	0-50	51-100	101-150	151-200	>200	Number of homes
Ground floor	58	18	7	3	3	88
1st	50	0	0	0	0	51
2nd	38	0	0	0	0	38
3rd	30	0	0	0	0	30
4th	6	0	0	0	0	6
5th	8	0	0	0	0	8
Number of homes	190	18	7	3	3	221
Ratio in %	86.0	8.1	3.1	1.4	1.4	100

Table 1: The number of homes grouped according to the determined mean year values of the radon concentration is shown by their location, as the floor number, and in intervals of 50 Bq/m³.

Table 2 shows the distribution of the determined mean year value of the radon concentration in homes grouped in intervals of 50 Bq/m³ for homes located on the ground floor in multi-occupant houses.

	0-50	51-100	101-150	151-200	>200	Number of homes
Home over basement/crawlspace	42	5	0	0	0	47
Ratio i %	89.4	10.6	0	0	0	100
Home with floor on ground	9	7	0	0	0	16
Ratio in %	56.3	43.7	0	0	0	100

Table 2: The number of homes grouped by the determined mean year value of the radon concentration in intervals of 50 Bq/m³. Homes were located on the ground floor in multi-occupant houses.

Table 3 shows the investigated variables that homes were registered for describing the characteristics of the building where the accommodation was located.

Figure 1 shows the mean year value of the radon concentration for homes in a building with a basement that had not been fire protected. The mean year value of the radon concentration of the indoor air of the homes was 30.2 Bq/m³ determined with a standard variation of 37.4 Bq/m³ and a variation coefficient of 124%. Homes located in a building without a fire protected basement numbered 120.

Figure 2 shows the mean year value of the radon concentration for homes in a building with a basement that had been fire protected. The mean year value of the radon concentration of the indoor air of the homes was 17.4 Bq/m³ determined with a standard variation of 8.6 Bq/m³ and a variation coefficient of 50%. Homes located in a building with a fire protected basement numbered 62.

Variables	Radon [Bq/m³]	Std.var. [Bq/m³]	Var. [%]	Number of homes
Suspended floors of concrete	15.7	8.8	56	63
Suspended floors partly of concrete and partly of timber floor constructions	29.6	8.5	29	8
Suspended floors of steel and brick materials	26.3	40.7	155	26
Suspended floors of timber floor constructions	32.9	37.4	114	97
Bathroom with no outer walls	27.5	30.9	113	164
Bathroom with outer wall	7.5	2.6	34	8
Staircase connecting basement with home	20.3	19.4	96	144
Staircase without entrance to basement	36.3	21.9	60	28
Other entrance to home than staircase	50.0	67.4	135	24
Building without elevator	28.6	31.4	110	156
Building with elevator	11.3	6.4	56	29
Building without garbage chute	33.7	37.7	112	100
Building with garbage chute	18.4	20.9	114	94
Air change by grate mounted exterior wall	33.5	21.0	63	40
Air change without grate mounted exterior wall	25.8	34.9	135	139
Building without heat recovery	27.1	30.4	112	171
Building with heat recovery	7.5	2.6	34	8
Original floor construction in basement	26.2	30.2	115	170
Upgraded floor construction in basement	16	7.4	46	8
Floor drain in basement floor	18.2	12.8	67	105
Basement floor without floor drain	38.2	44	115	64
Visible gaps in suspended floors	26.2	18.1	69	90
Expected airtight suspended floors	22.1	30.9	140	45
Pipes drawn outside service shaft	26.2	35.4	135	104
Pipes drawn inside service shaft	25.2	19.0	76	66
Exterior basement walls of masonry	22.9	11.6	51	52
Exterior basement walls of concrete	17.6	21.3	121	105
Exterior basement walls of leca materials	55.7	52.1	93	37
Basement without fire protection	30.2	37.4	124	120
Fire protected basement	17.4	8.6	50	62
Cavity walls with thermal insulation	31.1	38	122	139
Cavity walls without thermal insulation	21.0	18.2	86	78
Retrofitted exterior walls	15.6	14.4	92	48
Original exterior walls (No retrofitting)	31.0	36.8	119	91
Windows with frames of plastic	26.0	40.9	157	97
Windows with frames of wood	26.6	18.2	69	97

Table 3: Mean year value of the radon concentration in Bq/m³, together with the standard variation in Bq/m³, the variation coefficient in per cent and the number of homes located in a building with the specific characteristic.

Other variables describing buildings with accommodation with a low radon level was: (radon concentration of the indoor air/standard variation/variation coefficient/number of homes)

- a building with an upgraded basement floor (16 Bq/m³/7.4 Bq/m³/46%/8)
- a building with homes with gaps around pipes going through the horizontal partition that was sealed and therefore the suspended floors were expected to be sufficiently airtight (22.1 Bq/m³/30.9 Bq/m³ /140%/45)

- a building with homes with suspended floors of concrete (15.7 Bq/m^3/ 8.8 Bq/m^3/56%/ 63)
- a building with homes with suspended floors partly of concrete and partly of timber floor constructions (29.6 Bq/m^3/8.5 Bq/m^3/29%/8)
- a building with an elevator (11.3 Bq/m^3/6.4 Bq/m^3/56%/29)
- a building with homes with a forced mechanical ventilation system connected to a heat recovery unit (7.5 Bq/m^3/2.6 Bq/m^3/34%/8).

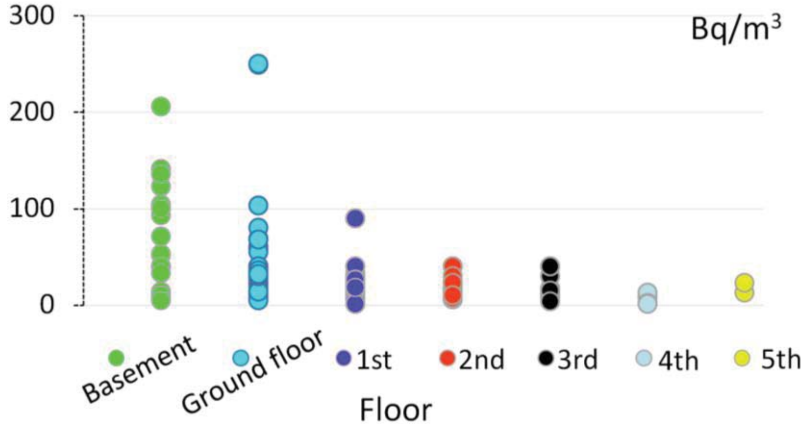

Figure 1: Mean year value of the radon concentration for homes in a building with a basement that has not been fire protected. Homes are located on the ground floor, 1st, 2nd, 3rd, 4th and 5th floors.

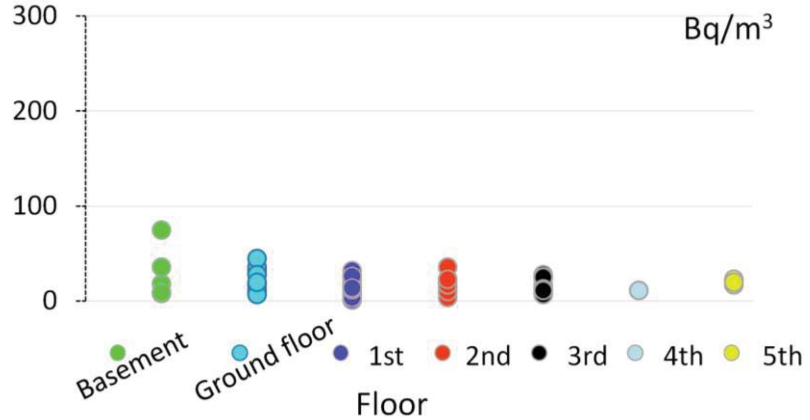

Figure 2: Mean year value of the radon concentration for homes in a building with a basement that has been fire protected. Homes are located on the ground floor, 1st, 2nd, 3rd, 4th and 5th floors.

6. DISCUSSION

This study found a mean year value of the indoor radon level of 30.7 Bq/m^3 ranging between 1 and 250 Bq/m^3. In total, 5.9% (13 of the 221) homes had indoor radon levels exceeding 100 Bq/m^3, all located in single-family terraced houses. The investigated variables explained 5.9% of the variation in indoor radon levels, and although associations were positive, none of these besides homes in single-family terraced house were statistically significant. However, the fact that the basement floor had been upgraded, that the basement was fire protected, that gaps around pipes going through suspended floors was sealed, that suspended floors was of concrete, that suspended floors were partly of concrete and partly of timber floor constructions, the presence of an elevator and forced mechanical ventilation connected to a heat recovery unit was observed to be variables of interest determining low radon levels in homes. Unfortunately the number of homes located in a building with these specific characteristics was limited and therefore not concluded to characterise homes with a low radon concentration in rented accommodation.

The mean year value of the radon level of 30.7 Bq/m^3 is somewhat lower than the population-weighted average annual radon concentration of 59 Bq/m^3 for all Danish homes. The population-weighted average annual radon concentration of 59 Bq/m^3 was based on 1-year measurements in 3012 single-family homes and 101 multifamily (apartment buildings) in Denmark, and measurements form the basis of a radon map covering Denmark.

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The present study found the indoor radon level exceeded 100 and 200 Bq/m^3 in 10 (4.5%) and 3 (1.4%) homes, respectively. Approx. 75% of homes with indoor radon levels exceeding 100 Bq/m^3 had levels between 100 and 200 Bq/m^3 and 25% had indoor radon levels exceeding 200 Bq/m^3. Significant differences in indoor radon levels were found in homes located in multi-occupant houses. The risk of indoor radon levels exceeding 100 Bq/m^3 in homes in multi-occupant houses is very low, but if there is a risk, it is most likely to be found in the lowest accommodation in a building with a slab on ground. A risk of indoor radon levels exceeding 100 Bq/m^3 was found in homes in single-family terraced houses.

The high levels in homes in single-family terraced houses may be explained by the possible deterioration of their radon protection due to the development of micro-cracks in individual materials, cracks in joints between building components, fissures associated with aging of the homes, alterations in air change rates, or some form of construction alterations made by home owners, which may penetrate the radon barrier.

The municipalities selected in the present study were previously characterised as having the highest levels of residential radon concentration indoors in Denmark (1–30% of homes with levels over 200 Bq/m^3). Measurements showed that the soil type was the main determinant of indoor radon levels. The present study did not include measuring radon levels in soil. The homes in this study were located on clayey/sandy to clayey soil, with 2–18% sand and gravel content, and although radon variation in these soils can be expected, this is not described at each specific home location.

The present study has several limitations including power constraints, which may affect the ability to detect associations. Furthermore, information on many other variables such as the specific radon protection measure used, interior wall and ceiling materials, radon ground concentrations, radon diffusion resistance, air permeability of the soil, air pressure differences, and air change rates in all homes were not acquired in the data acquisition process. These variables are all important in relation to the variation in radon levels indoors. More work is justified, and a more comprehensive study utilising an extended model including these variables should be considered in relation to the variation in indoor radon concentration in Danish homes.

7. CONCLUSION

This study found a mean year value of the indoor radon level of 30.7 Bq/m^3 ranging between 1 and 250 Bq/m^3. In total, 5.9% (13 of the 221) homes had indoor radon levels exceeding 100 Bq/m^3, all located in single-family terraced houses. Approx. 75% of homes exceeding 100 Bq/m^3 indoor radon level had levels between 100 and 200 Bq/m^3 and 25% had indoor radon levels exceeding 200 Bq/m^3. Significant differences in indoor radon levels were found in homes located in multi-occupant houses. The risk of indoor radon levels exceeding 100 Bq/m^3 in homes in multi-occupant houses is very low, but if there is a risk, it is most likely to be found in the lowest accommodation in a building with a slab on ground. A risk of indoor radon levels exceeding 100 Bq/m^3 was found in homes in single-family terraced houses. None of the other investigated variables explained the variation in indoor radon levels in homes. However, the fact that the basement floor had been upgraded, that the basement was fire protected, that gaps around pipes going through suspended floors were sealed, that suspended floors were of concrete, that suspended floors were partly of concrete and partly of timber floor constructions, the presence of an elevator and forced mechanical ventilation connected to a heat recovery unit were not significant variables characterising homes with a low radon concentration in rented accommodation, but seen to be variables that need to be further studied.

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