SEASONAL VARIATION OF RADON CONCENTRATION IN DWELLINGS IN FRANCE

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INTRODUCTION

Indoor radon concentrations are subject to seasonal variation with a maximum in winter and a minimum in summer. Due to the constraints of time placed on an epidemiological study, it is not always possible to perform radon measurements over one year, and thus there is a need for seasonal correction in order to make measurements comparable with each other and to calculate annual concentrations. In France, a national radon campaign has been carried out since 1982. Besides, a series of measurements have been made as part of an indoor radon case-control study carried out in 5 regions (Auvergne, Ardennes, Brittany, Languedoc, Limousin). With all these data, seasonal correction factors have been estimated using the methodology of Pinel et *al* (1). In this paper the derivation of these correction factors is described and they are compared with existing factors published elsewhere (1, 2).

MATERIAL AND METHODS

Data

Radon national campaign

A radon national campaign has been carried out by the Institute for Radioprotection and Nuclear Safety (IRSN) in collaboration with the Ministry of Health since 1982 in French departments (French administrative entities of about 5000 km^2 each). The main objectives were to identify radon affected areas in France, to estimate the percentage of dwellings above action levels, and to investigate factors affecting radon concentrations (3, 4). To ensure a homogeneous geographical distribution of the measurements, each department was squared by a grid of 36 to 49 km^2, depending on the area of each department. In the squares having cities with more than 1500 inhabitants, a second measurement location was selected. Volunteers were mainly recruited through contacts in the local administrations who placed and collected the detectors.

Indoor radon measurements were carried out with one Kodalpha LR 115 detector over two months. The readout was performed according to a technique described elsewhere (5). To each measurement was associated a questionnaire designed to trace some of the factors that may influence radon concentrations (dwelling type, building date of the dwelling,...) (6).

Indoor radon case-control study

For the French indoor radon case-control study (7, 8), measurements of radon were performed in the present and past dwellings occupied by each subject. Measurements of radon concentrations were performed during a period of 6 months, using two Kodalpha LR 115 detectors, one in the living room and one in the bedroom. The detectors were placed and collected by local assistants who asked current occupants to fill in a questionnaire about housing characteristics and their way of life (ventilation habits, heating, ...). At each dwelling, the radon concentration was estimated by the average of the measured radon levels in bedroom and living room.

Statistical model for seasonal variation

The objective of the analysis was to estimate geometric means of monthly radon concentration and then to use these estimates to derive seasonal correction factors.

The measurement, m_i, of radon concentration for each dwelling i was in Bq.m^{-3} both for the indoor case-control study and for the national campaign.

The mean concentration of radon for each month was calculated as

$$x_j = \frac{1}{N_j} \sum_{i \in T_j} \log(m_i)$$

where $i \in T_j$, $j = 1, \ldots, 12$ with the middle day of measurement period for dwelling i falling between the middle of the month j-1 and the middle of the month j. This ensures the measurement duration is symmetrical around the month it is assigned. N_j is the number of measurements in the jth month. The most appropriate central measure for a log-normal distribution is the geometric mean, which was used throughout the modelling procedures to estimate the average radon concentration. The geometric mean concentration for each month was calculated as

$$d_j = \exp(x_j)$$

A sine-cosine curve was fitted to the geometric mean monthly concentrations (1) as

$$\hat{m}_j = \hat{\beta}_0 + \hat{\alpha}_1 \sin\left(\frac{\pi j}{6}\right) + \hat{\beta}_1 \cos\left(\frac{\pi j}{6}\right) \quad \text{(Equation 1)}$$

Seasonal correction factors are derived from Equation 1. If a dwelling is measured for t months (t=2 for the national campaign and t=6 for the case-control study) beginning on month j, an estimate of the correction factor $f_{j,t}$ will be (1)

$$f_{j,t} = \frac{t}{12} \frac{\sum_{k=1}^{12} \hat{m}_k}{\sum_{k=j}^{j+t-1} \hat{m}_k} \quad \text{(Equation 2)}$$

with the convention that $\hat{m}_{12+k} = \hat{m}_k$.

Seasonality is partly a function of the magnitude of variation in local climatic conditions, and the severity and length of seasons differ substantially across France. Therefore, it seems reasonable that seasonality in levels of radon concentration may vary across the case-control study regions and the national campaign regions. Mean monthly radon concentrations were calculated separately for each of the five regions of the case-control study. Mean monthly radon concentrations were also calculated for the five regions cited above and for the whole France when using the data of the national campaign.

RESULTS

Available data

Measurements were performed over 2 months (national campaign) and over 6 months (indoor radon case-control study) but the actual measurement periods varied for a number of reasons. In all, 1706 dwellings from the national campaign were measured for less than one month or more than three months, 755 dwellings from the indoor-radon case-control study were measured for less than five or more than seven months. These data were excluded from the present analysis leaving 11186 measurements of approximately two-month duration (national campaign) and 2181 measurements of approximately six-month duration (case-control study), Table 1.

Table 1: Summary of measurements performed in France.

Category	Number	%
Indoor radon case-control study		
Measured dwellings(*)	2968	100.0
Missing dates of detectors placement	32	1.1
Detectors not in place for 5-7 months	755	25.4
Total measurements analyzed	**2181**	**73.5**
Ardennes	329	
Auvergne	315	
Brittany	656	
Languedoc	294	
Limousin	587	

Category	Number	%
Radon national campaign		
Measured dwellings(**)	13144	100.0
Missing dates of detectors placement	252	1.9
Detectors not in place for 1-3 months	1706	13.0
Total measurements analyzed	**11186**	**85.1**
Ardennes + Auvergne + Brittany + Languedoc + Limousin	*2503*	

(*) All dwellings with at least one radon measurement were included in this analysis without any exclusion criteria on the period of occupation by the study subject. Radon concentration less than 5 Bq/m^3 were considered as missing data.

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Considering the French indoor radon case-control study, the measurements analysed (n=2181) were distributed evenly throughout the year, whereas the measurements analysed from the radon national campaign (n=11186) have been performed mainly in winter (Figure 1).

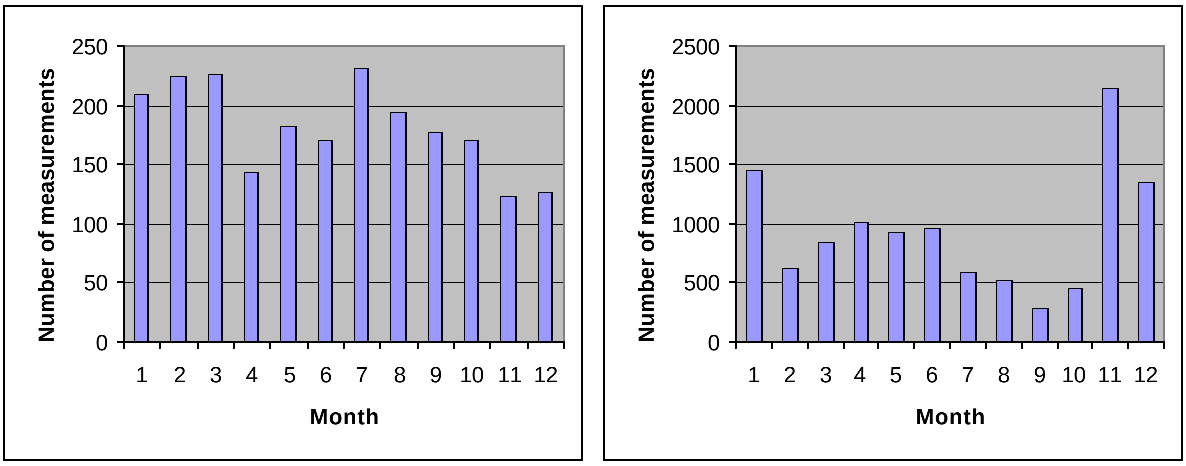

Figure 1: Number of measurements according to the middle month of the measurement period for indoor radon case-control study (on left side) and for radon national campaign (on right side).

Prior to seasonal correction the arithmetic means of measurements performed respectively as part of French radon case-control study and radon national campaign were 132.58 Bq.m^{-3} and 89.40 Bq.m^{-3} (Table 2). Regional arithmetic means, prior to seasonal adjustment, ranged from 52.31 Bq.m^{-3} in Languedoc to 183.06 Bq.m^{-3} in Limousin.

Table 2: Annual average concentrations of radon in Bq.m^{-3} (not seasonally adjusted).

Region	Number	Arithmetic mean	Geometric mean	Min	Max
Indoor radon case-control study					
Auvergne	315	163.73	101.10	6.00	1998.00
Ardennes	329	58.76	40.14	6.00	733.00
Brittany	656	145.46	89.21	7.50	2609.00
Languedoc	294	52.31	41.00	8.50	506.00
Limousin	587	183.06	115.26	11.50	4605.50
All 5 regions	2181	132.58	77.47	6.00	4605.50
Radon national campaign					
5 regions*	2503	131.76	75.35	5.00	4964.00
Whole France	11186	89.40	53.76	5.00	4968.00

(*) All 5 regions of the indoor radon case-control study

Seasonal variation

The geometric mean for measurements with period with middle day falling between the middle of month *j*-1 and the middle of month *j* and the estimated geometric mean based on the assumption that seasonal variation follows a sine wave of period 12 months are listed in Table 3. There was a tendency for measurements with the middle day in the summer months to be less high than those with middle day in the winter months, but there was also a month to month random variation.

Table 3: Number of measurements N_j, geometric mean radon gas concentrations d_j for measurements with middle day falling between the middle of month *j*-1 and the middle of month *j*, and estimates $\hat{m}_j$ of monthly geometric mean concentrations (in $Bq.m^{-3}$).

		Indoor radon case-control study (n=2181)			Radon national campaign (n=11186)		
j	**Month**	N_j	d_j	$\hat{m}_j$	N_j	d_j	$\hat{m}_j$
1	January	210	84.14	88.99	1446	47.21	58.69
2	February	225	92.74	86.81	624	50.51	56.59
3	March	226	88.86	82.28	846	65.20	53.67
4	April	143	68.91	76.60	1017	55.04	50.73
5	May	183	67.02	71.30	934	47.54	48.54
6	June	171	68.02	67.79	967	53.01	47.69
7	July	231	76.72	67.02	597	39.95	48.41
8	August	194	64.31	69.20	523	36.19	50.51
9	September	178	72.77	73.73	280	63.29	53.42
10	October	170	79.95	79.41	462	65.24	56.37
11	November	124	85.46	84.71	2147	64.26	58.56
12	December	126	87.17	88.22	1343	55.15	59.41

Seasonal correction factors

Seasonal correction factors for a detector in place for 6 months (case-control study) and for 2 months (national campaign) are listed in Table 4 and plotted in Figure 2. The proportion of variance in the data explained by each model (R^2) is reported.

For 6-month measurements, the model fit the data well, with 73 % of the variance explained when the 5 regions were included. Models fitted for each region separately gave a lower fit. The correction factors varied from 0.92 to 1.10 without any significant difference between regions. These correction factors were close to those obtained by the UKCCS as part of an epidemiological analysis of the association between indoor radon and the incidence of childhood cancer (2) but the range was less than the range of coefficients derived by Pinel et *al* (1).

For 2-month measurements, the model on radon national campaign data had a low fit (19 % of variance explained for whole France). The correction factors varied from 0.91 to 1.11. The lower range of 2-month seasonal correction factors in comparison with the range of 6-month seasonal correction factors was not expected.

Table 4: Seasonal correction factors and model fit for a six-month (case-control study) or a two-month (national campaign) placement of the detector.

		Month in which measurement commences											
	R^2	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
SIX-MONTH PLACEMENT (case-control study)													
Auvergne	*0.15*	0.94	0.98	1.03	1.07	1.10	1.10	1.06	1.02	0.97	0.93	0.92	0.92
Brittany	*0.53*	0.98	1.04	1.09	1.12	1.11	1.07	1.02	0.96	0.92	0.90	0.91	0.94
Languedoc	*0.53*	0.98	1.05	1.11	1.14	1.13	1.08	1.02	0.96	0.91	0.89	0.90	0.93
Limousin	*0.25*	1.04	1.07	1.07	1.06	1.03	0.99	0.96	0.94	0.93	0.95	0.97	1.01
Ardennes	*0.27*	1.01	1.04	1.07	1.07	1.06	1.03	0.99	0.96	0.94	0.94	0.95	0.97
All 5 regions	***0.73***	**0.99**	**1.04**	**1.08**	**1.10**	**1.09**	**1.06**	**1.01**	**0.97**	**0.93**	**0.92**	**0.92**	**0.95**
Pinel (1)	-	0.88	0.99	1.14	1.29	1.35	1.30	1.16	1.01	0.89	0.82	0.79	0.81
UKCCS (2) *	*0.51*	1.04	1.08	1.09	1.08	1.05	1.01	0.97	0.93	0.92	0.93	0.95	0.99
TWO-MONTH PLACEMENT (National campaign)													
All 5 regions	*0.09*	1.02	1.12	1.19	1.20	1.16	1.07	0.98	0.90	0.86	0.86	0.88	0.94
Whole France	***0.19***	**0.93**	**0.97**	**1.03**	**1.08**	**1.11**	**1.11**	**1.08**	**1.03**	**0.98**	**0.93**	**0.91**	**0.91**
Pinel (1) **	-	0.74	0.79	0.91	1.10	1.34	1.55	1.56	1.36	1.12	0.92	0.80	0.74

(*) The United Kingdom Childhood Cancer Study
(**) For three-month placement

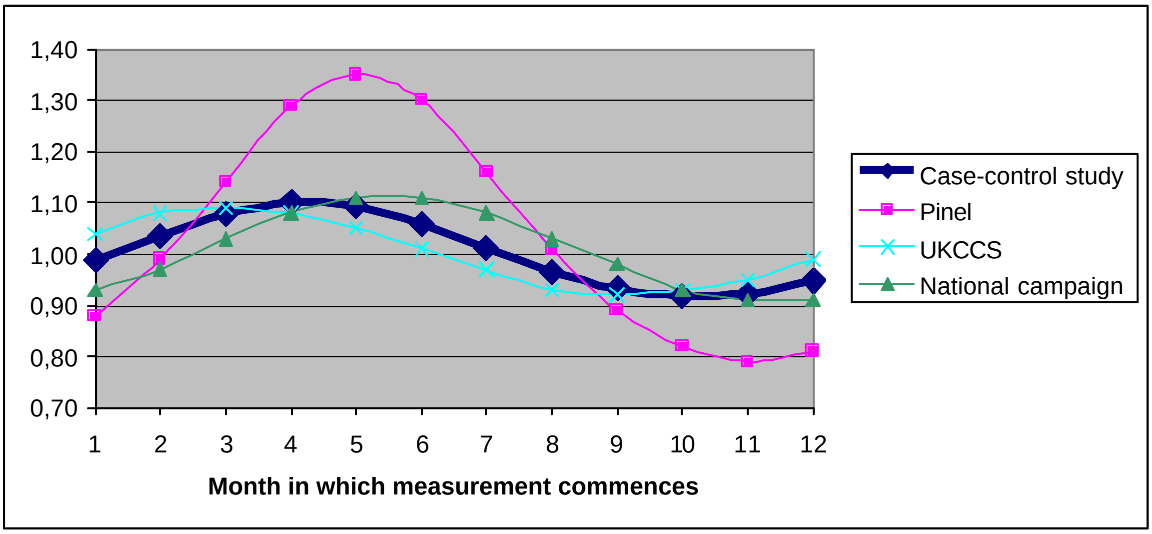

Figure 2: Seasonal correction factors for a six-month (case-control study and literature) and two-month (national campaign) placement of the detector.

DISCUSSION

Since 1982, IRSN has collected radon measurements for a large number of dwellings, performed as part of the national radon campaign and as part of an indoor radon case-control study. These measurements were linked to information about housing characteristics (type of dwelling, period of construction, building materials…) and about conditions of measurement (starting and ending dates of measurement, room where the dosimeter was placed…) that may influence radon concentration.

Seasonal variations of indoor radon concentrations may depend on a number of factors, including geological and meteorological factors, dwelling characteristics and habits of the occupants (1, 3). For example, different levels of heating and ventilation throughout the year cause radon to fluctuate by season. In temperate climates most dwellings show a seasonal variation of the indoor radon concentration with a maximum in winter and a minimum in summer. Average radon concentration over a 12-month period is generally considered as the best estimate of the long-term average radon concentration. However, due to constraints of time, radon detectors were in place for 6 months (indoor radon case-control study) and 2 months (radon national campaign) and therefore a multiplicative factor is required to correct for seasonal variation.

For six-month measurements, correction factors were derived from measurements performed as part of an indoor radon case-control study carried out in 5 regions (Auvergne, Ardennes, Brittany, Languedoc, Limousin). The data were examined regionally to see if seasonal patterns in radon concentrations may vary across the country because of differences in climate and way of life. Nevertheless, the best model fit (R^2=0.73) was obtained when data from all 5 regions (n=2181 measurements) were introduced in the analysis.

In order to check the appropriateness of the model, the measurements performed as part of the indoor radon case-control study were split into two halves according to whether the measurement was above or below the median and the estimation process was repeated for each half separately (1). The geometric means in the two subsets were 36.8 $Bq.m^{-3}$ and 167.4 $Bq.m^{-3}$ respectively. The resulting six-month correction factors estimated in both subsets were very similar to each other, and to those obtained on the global dataset (not shown). These results suggest a good stability in these coefficients. Besides, they were consistent with the factors obtained by the UKCCS as part of an epidemiological analysis of the association between indoor radon and the incidence of childhood cancer (2).

For two-month measurements, correction factors were derived from measurements performed as part of the radon national campaign. The low model fit (R^2=0.19) may be due to the fact that the measurements were not distributed evenly throughout the year. Measurements in a given region were all performed at the same period therefore it was difficult to distinguish seasonal variation from geographical variation. In addition, a lower range of 2-months seasonal correction factors in comparison with the range of 6-months seasonal correction factors was observed. This result was not expected and suggested some bias in the estimation. To obtain better correction factors for two-months measurements, one method will consist in using Equation 2 together with estimates $\hat{m}_j$ from data of all 5 regions of the indoor radon case-control study (1).

CONCLUSION

Procedures to correct for seasonal variation are necessary in order to get unbiased estimates of annual average concentration from data based on short-term measurements. In order to obtain such correction factors, we apply the model developed by Pinel et *al* (1) to the French database of indoor radon measurements (measurements performed as part of the indoor radon case-control study and the radon national campaign). These correction factors might be applicable when assessing indoor radon concentrations in regards to action levels.

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