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A 10-year follow-up study of yearly indoor radon measurements in homes, review of other studies and implications on lung cancer risk estimates

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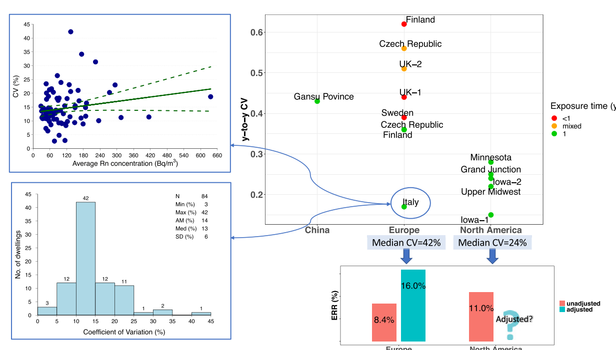
HIGHLIGHTS

- Indoor radon concentrations show year-to-year variations
- Uncertainty on long-term radon concentration can bias lung cancer risk estimates
- An Italian study estimated a 17% of yearly variability over a decade
- Studies in other countries estimated radon yearly variability from 15% to 62%
- Factors influencing yearly variability estimation were analysed and discussed

GRAPHICAL ABSTRACT



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ABSTRACT

Uncertainty on long-term average radon concentration has a large impact on lung cancer risk assessment in epidemiological studies. The uncertainty can be estimated by year-to-year radon concentration variability, however few data are available. In Italy a study has been planned and conducted to evaluate year-to-year radon variability over several years in normally inhabited dwellings, mainly located in Rome. This is the longest study of this kind in Europe; repeat radon measurements are carried out for 10 years using LR-115 radon detectors in the same home in consecutive years. The study includes 84 dwellings with long-term average radon concentration ranging from 28 to 636 Bq/m^3. The result shows that year-to-year variability of repeated measurements made in the same home in different years is low, with an overall coefficient of variation of 17%. This is smaller than most of those observed in studies from other European countries and USA, ranging from 15% to 62%. Influencing factors that may explain the differences between this study and other studies have been discussed. Due to the low yearly variability estimated in the present 10-year study, a negligible impact on lung cancer risk estimate for the Italian epidemiological study is expected.

1. Introduction

Results of epidemiological studies on lung cancer risk due to radon exposure in dwellings and in mines have prompted the introduction

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in recent years of more protective requirements into international recommendations and regulations (World Health Organization, 2009; Bochicchio, 2011; European Commission, 2014). The evaluation of uncertainty in radon exposure assessment in epidemiological studies, and the adjustment for it, is of utmost importance due to its impact on risk estimates.

There are several sources of error that may introduce uncertainty in residential long-term radon exposure assessment (Heid et al., 2004; Onishchenko and Zhukovsky, 2019), mainly related to temporal and spatial variations of radon concentration, to radon concentration measurement process itself, and to inhabited occupancy time in the measured dwellings.

A considerable source of uncertainty arises from use of current radon 1-year measurement as representative of the average radon concentration in a dwelling over a period of several (20−30) past years, thus assuming that measured annual average radon concentration has been constant in this long period. Uncertainty on long-term radon exposure can be experimentally estimated with studies on variations of annual radon concentration measured in the same dwelling over different years (year-to-year or yearly variations), often also including uncertainties due to the measurement process.

The uncertainty on long-term radon exposure has a large impact on lung cancer risk assessment in epidemiological case-control studies on radon in dwellings. The effect of radon exposure uncertainty due to year to year variability (including that due to the measurement process itself) has been estimated in the pooled analysis of the European collaborating study: ignoring this kind of uncertainty led to almost halve the excess relative risk (Darby et al., 2006; Darby et al., 2005) because of the multiplicative structure of the error, i.e. an error about proportional to the radon concentration level (Heid et al., 2004). This uncertainty can be evaluated by observed year-to-year variations, performing radon repeated measurements in the same dwellings over years.

Few studies (Lubin et al., 2005; Hunter et al., 2005; Zhang et al., 2007; Steck, 2009; Slezakova et al., 2013) were purposely designed to assess the radon yearly variability in domestic environment and, in these cases, most of the sources of additional variability were effectively controlled. In fact, these annual variation studies (hereafter called "AV studies") generally have the following characteristics: all the measurements are performed using the same protocols (i.e. same sampling times, same type of detectors, etc.); extra-exposures are made negligible; a quality assurance program is fully implemented; living habits of the inhabitants are under control.

These AV studies are quite different as regards the number and type of dwellings included in the study and as regards the number and the span of years covered by measurements. Furthermore, the studies differ in the number of monitored rooms, in the number of detectors placed in each room, in the duration of measurements in each year, and in the amount of data collected relative to the building, to the dwelling and to its occupiers.

Due to the different characteristics, these studies have different information content; the few studies specifically designed to evaluate the yearly variability are generally the most informative, covering many consecutive years and trying to control some factors that could have an impact on the results. All the available AV studies, with inclusion criteria specified in the *Methods* section, have been reviewed in this paper, and information on the factors that may influence the year-to-year variability of radon concentration have been collected and analysed.

Moreover, a discussion about results of the present study, compared with other AV studies, and about the impact of uncertainty in radon exposure assessment (mainly due to radon yearly variability) on lung cancer risk estimates is performed.

2. Methods

2.1. Evaluation of the year-to-year indoor radon concentration variability in an Italian region

2.1.1. Data collection

Systematic radon concentration measurements have been carried out since 1996 in a sample of dwellings owned, and generally inhabited, by voluntary workers of the Italian National Institute of Health (ISS). This choice was made to guarantee the feasibility of the study, since measurements repeated over many years were planned and detectors had to be exchanged twice per year. Moreover, the dwellings were chosen in order to cover as much as possible the territory of Rome, even if some dwellings were located in other towns of the Rome province. In the analysis presented in this paper, only dwellings with measurements for at least 3 years are included.

Information about dwelling characteristics, including heating or air conditioning system were collected through a questionnaire filled out by homeowners. Main relevant changes, potentially having an impact on radon concentration (e.g., dwelling structural modifications, or occupant modifications), occurred during the follow-up, were recorded as well.

The selected dwellings included different types of buildings (mainly multi-family buildings, but also some single-family houses) with different characteristics.

For each dwelling, at least two rooms, usually a living room and a bedroom, were monitored. In multi-storey dwellings, at least one room in each level was monitored. Non-inhabited rooms (e.g. cellars) were excluded from the analysis.

2.1.2. Experimental technique

Radon measurements were carried out with passive devices, each containing two alpha track detectors (LR 115 strippable films from Dosirad, France) placed in a 2-cm^3 diffusion box. Each box is enclosed in a plastic bag that stops entry of dust, radon and thoron daughters, reduce the entry of moisture, and strongly reduce the entry thoron (Bochicchio et al., 2009a). For each year and each dwelling, radon devices have been exposed for consecutive 6-month periods in the selected rooms.

After exposure, the detectors were chemically etched in a NaOH (2.5 N) solution at 60°C for 110 min. The residual thickness was measured by means of a micrometer and the tracks were counted using a spark counter with a 1 cm^2 electrode, at 500 V after two pre-sparking at 900 V.

These devices were calibrated in the radon chamber of the United Kingdom National Radiological Protection Board (NRPB), now named PHE (Public Health England), in years 1997, 2001, and 2005, and in the radon chamber of the ENEA-INMRI (Italian Institute of Ionizing Radiation Metrology) in year 2005, 2007, and 2008.

A total of 16 calibration exposures were used, ranging from 250 kBq/m^3·h to about 35,000 kBq/m^3·h, which corresponds to an average radon concentration ranging from 60 to 8000 Bq/m^3 for a 6-month exposure period. Half of these exposures (8) were below 1000 kBq/m^3·h with both low exposures (below about 300 kBq/m^3·h) and medium exposures (from 700 to 1000 kBq/m^3·h). The remaining exposures were higher than 1800 kBq/m^3·h.

A regression analysis was done to evaluate the best fitting calibration functions taking into account non-linearity of the LR 115 detector response at high exposures: i) up to about 700 tracks/cm^2, a linear calibration function was used with zero as intercept, i.e. it was used a single calibration factor; ii) between 700 and 4000 tracks/cm^2 a linear quadratic function was used; iii) over 4000 tracks/cm^2 a different linear-quadratic function was used. For all the detectors a mean background track density was subtracted to all measurements. For this technique, a quality assurance program has been implemented (Bochicchio et al., 2003a).

It should also be noted that the experimental technique (including detector typology) used in the present study was the same as that used in the Italian epidemiological study (Bochicchio et al., 2005), with the aim to reduce the additional uncertainties likely introduced by using different measurement protocols.

2.1.3. Annual radon concentration evaluation

In order to obtain the year-long radon concentration averages for each dwelling, several detectors were used. The two LR 115 detectors included in each passive radon device were averaged to obtain a six-month measurement for each room. Then, for each room, the year-long radon concentration value was obtained averaging the radon concentration in each 6-month period weighted with the number of corresponding days. Finally, the year-long radon concentration averages of the (two or more) rooms were averaged to obtain the radon concentration of the dwelling for that year.

Dwellings included in the analysis are those with annual radon concentration averages obtained on a time length within 365 ± 30 days.

2.1.4. Statistical methods

In this context, the parameter used to evaluate year-to-year variability is the coefficient of variation (CV) "within house", that is, the coefficient of variation of the repeated measurements (in different years) in the same place (the dwelling). The CV, generally expressed in percentage, is defined as the ratio of the standard deviation (SD) to the arithmetic mean (AM) of the annual measurements in the same dwelling. It is worth noting that the CV is affected by measurement error, depending on how many values are used to calculate it.

In order to estimate the CV, a log-normal distribution for the radon concentration data was assumed. Properties of the log-normal distribution was used, so the variance within house (σ_w^2, also called "variance-within") of the log-transformed data was evaluated with the aim to obtain a CV of the data on original scale (Heid et al., 2004; Lubin et al., 2005; Hunter et al., 2005; Hunter et al., 2009) by the means of the following formula (Corlett et al., 1957):

$$CV = \sqrt{exp(\sigma_w^2) - 1} \tag{1}$$

Moreover, using log-normal properties, we obtained confidence interval (CI) for the CV (Koopmans et al., 1964), computing the 95% CI for the parameter σ_w^2 under the simplified assumption that data are balanced (i.e. all the dwellings have the same number of monitored years). Finally, applying the (strictly increasing) function (1) to the confidence limits ($\sigma_{w,low}^2 - \sigma_{w,upp}^2$), a 95% confidence interval for the year-to-year coefficient of variation is obtained:

$$\sqrt{exp\left(\sigma_{w,low}^2\right) - 1} \le CV \le \sqrt{\exp\left(\sigma_{w,upp}^2\right) - 1}. \tag{2}$$

In order to obtain an estimate of σ_w^2, the following linear variance component model is applied:

$$y_{ij} = \log(x_{ij}) = \alpha_i + \varepsilon_{ij} \tag{3}$$

where y_{ij} represents the log-radon concentration measure during the jth year in the ith house. In this simplified model, each log-measurement is thought as a sum of two components: α_i which represents log-radon level in the ith house, and ε_{ijr} which represents random variation within the ith house between measurements and between years. It is assumed that those two components have a normal distribution, that is:

$$\begin{aligned} \alpha_i &\sim N(\mu, \sigma_B) \\ \varepsilon_{ij} \mid \alpha_i &\sim N(0, \sigma_w) \end{aligned} \tag{4}$$

where μ is a "long-term" (i.e., over many years) radon log-concentration average in a given district; σ_B and σ_w represent between and within (the same for all houses) house standard deviation, respectively. From these hypotheses, log-normality assumption for radon concentration derives. An estimate of both between-measurement-variability and between-year-variability combined is derived by σ_w, the standard deviation of residuals ε_{ij}.

Notably, in this approach, the lognormal hypothesis should be checked for each set of measurements relative to each house. In fact, overall log-transformed data do not satisfy i.i.d. (independent and identical distribution) normal hypothesis because of the structure of dependence of data within houses. Unfortunately, a small number of years is often measured in the houses, so it is not possible to perform a reliable test on the lognormal hypothesis (the power of tests made with few observations is very low, so the probability of false positive results is high).

Finally, it should be reminded that in this analysis (as well as for the other studies considered in this paper) the measurement error (variability due to the measurement devices) is included in the overall year-to-year variability.

The hypothesis about multiplicative structure of the error due to repeated measurements of radon concentration over years has been verified analysing the plot of the average radon concentration versus the CV of the measurements within each dwelling and testing the linear correlation between radon concentration and CV.

2.2. Methods used in the review of studies on year-to-year radon variability in dwellings

A systematic review of the published studies regarding radon yearly variability in other countries has been performed using the PRISMA methodology (Moher et al., 2010). The databases used were *Web of Science* and *Pubmed*.

The search strategy was to find all the scientific articles published in English up to November 2020 having: i) in the title, the words "radon", "year" (or "annual"), and "variation" (or "variability"); ii) in the abstract, the same words chosen for the title plus the words "dwelling" or "house". For all the words, with the exception of "radon", the asterisk character (*) was used as wildcard to find both the singular and plural forms of the words. For example, the query used for *Web of Science* was the following:

$$\begin{aligned} &(\mathrm{TI} = (\mathrm{radon})\ \mathrm{AND}\ (\mathrm{TI} = (\mathrm{annual} * \mathrm{OR\ year} *)\ )\ \mathrm{AND}\ (\mathrm{TI} = \mathrm{varia} *)\ )\ \mathrm{OR} \\ &\quad (\mathrm{TI} = (\mathrm{radon})\ \mathrm{AND}\ (\mathrm{AB} = (\mathrm{annual} * \mathrm{OR\ year} *)\ )\ \mathrm{AND} \\ &\quad (\mathrm{AB} = \mathrm{varia} *)\ \mathrm{AND\ AB} = (\mathrm{dwelling} * \mathrm{OR\ hous} *)) \\ &\qquad \mathrm{AND\ LANGUAGE} : (\mathrm{English})\ \mathrm{AND\ DOCUMENT\ TYPES} : \\ &\quad (\mathrm{Article}).\mathrm{Indexes} = \mathrm{SCI{-}EXPANDED, SSCI, A\&HCI, CPCI{-}S,} \\ &\quad \mathrm{CPCI{-}SSH, ESCI, CCR{-}EXPANDED, IC\ Timespan} = \mathrm{All\ years} \end{aligned}$$

A total of 188 papers were found after removing the duplicates from the 154 records of *Web of Science* and the 96 records of *PubMed*. After the screening of the titles and the abstracts of these papers, 179 papers were discarded since they did not deal with the issue of interest for the present review. The remaining 9 full text articles were further examined. The eligibility criteria were to include only studies in dwellings in which radon concentrations have been measured with passive detectors exposed for 2 to 12 months, thus excluding some studies involving short-term (i.e. few days or shorter) measurements. Furthermore, studies that involved less than 10 dwellings, as well as studies with measurements performed in not inhabited rooms (e.g cellars), were not included.

After full-text reading of these 9 papers, 6 of them met the eligibility criteria. In addition, searching in the references of these papers, 3 other articles were added in the final list of the papers included in the review (Fig. 1).

All the information relevant for the yearly variability assessment have been collected and summarized in Tables 2a and 2b. Those tables contain also information regarding some unpublished studies, reported

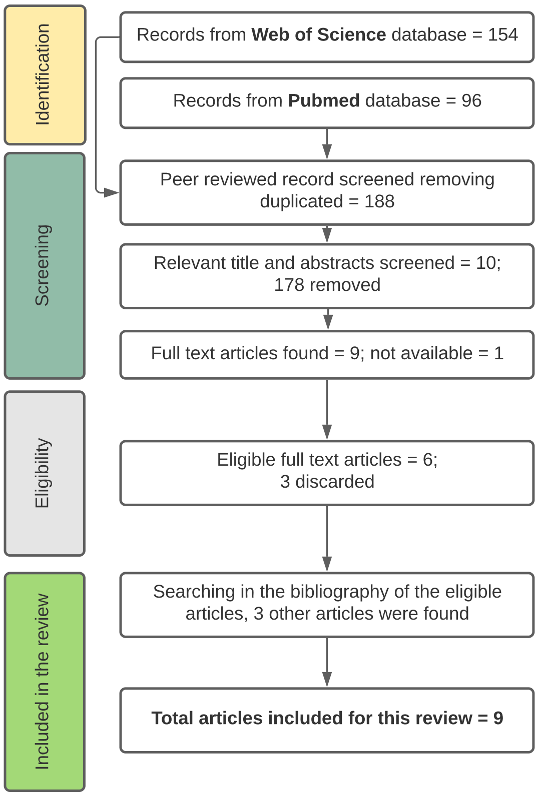

Fig. 1. PRISMA flowchart for the systematic review of studies on year-to-year radon variability in dwellings.

as personal communication in Table 30 of the paper by Darby et al. (2006).

In particular, the following factors have been considered in the analysis: information relative to dwellings involved in the study (selection criteria, number and type of dwellings; number of rooms measured in each dwelling); information regarding time of measurements (number of years with repeated measurements, time span, duration of measurement); number of detectors placed in each dwelling; radon concentration estimate.

Finally, for each study, the coefficient of variation of the repeated measurements (in different years) in the same dwelling has been computed and reported in the table.

In all the North American studies a different method was used to derive a CV estimate: a CV distribution is derived and a summary parameter (i.e. median or arithmetic mean) is considered. Moreover, in these cases asymptotically correct confidence interval for mean of CV can be obtained, under the hypothesis that the conditions of the Central Limit Theorem are satisfied.

It is worth noting that, in the European and Chinese studies that used the approach described in the subsection *Statistical methods*, the linear model applied to derive the variance within house (σ_w^2) is sometimes different from the linear model [2] adopted in this paper. The CV reported in the table was computed using the formula [1].

2.3. Criteria for comparison of radon measurements in AV and epidemiological studies

Some characteristics regarding the measurements carried out in the epidemiological studies have been compared to those regarding the measurements performed in the "corresponding" annual variation study. In some cases the "corresponding" AV study is the AV study on the basis of which the uncertainties used to adjust the long-term radon exposure assessment in the epidemiological study have been evaluated. In other cases, the "corresponding" AV study is that one performed in a geographic area close to that one of the epidemiological study (e.g., Winnipeg area and Minnesota).

Results of the comparison are collected in Table 3, where only the epidemiological studies with an available "corresponding" AV study have been reported.

3. Results

3.1. Year-to-year indoor radon variability in an Italian region over a decade (1996–2006)

In total, 100 dwellings have been involved in the study. During the years some dwellings have pulled out the study (because participants moved or stopped collaborating) and some new others have been included, for a total of 84 dwellings analysed. None of the dwellings included in the analyses were significantly renovated during the measurement period. The dwellings involved in the present study are mainly (83%) located in the Rome metropolitan city (and none of them in rural areas), in buildings with at least 10 housing units (61%) and at first or higher floors (74%), as shown in Table 1.

Information about heating and air conditioning system is available for 65 dwellings out of 84. All these 65 dwelling have a heating system (centralized or independent) and for only 2 the heating system is based on convectors; most of them do not have a conditioning system installed (Table 1).

The present analysis of data, collected over a period that covers the first ten years of the study, includes dwellings with at least three annual radon concentration measurements, with 55 of them (65%) having at least 8 years of annual measurements (see Table 1). A total of 173 occupied rooms were monitored (usually 2 rooms per dwelling), and 1393 year-long radon concentration values were obtained for these rooms, having excluded only 23 annual radon concentration averages that did not meet the inclusion requirement to be obtained over 365 ± 30 days. Considering the low difference between radon concentrations in different rooms of the same dwelling (probably because about 90% of the dwellings are single-storey), the average of such

Table 1
Characteristics of the dwelling included in the study.

Characteristic	Category	No. dwellings	%	Average Rn conc. (Bq/m^3)
Dwelling location	• Rome city	70	83	104
	• Other municipalities	14	17	123
Type of housing unit	• Single-family house	8	10	129
	• Two-family house	9	11	219
	• Flat in a small building (3–9 units)	16	19	105
	• Flat in a large building (≥ 10 units)	51	60	85
Floor	• Ground floor[a]	23	27	155
	• 1st floor	14	17	96
	• >1st floor	47	56	88
Air conditioning system	• No	54	64	117
	• Yes	11	13	72
	• Not available	19	23	101
Heating system	• Yes (central)	26	31	87
	• Yes (independent)	39	46	124
	• Not available	19	23	101
No. years of measurement	• Three	2	2	92
	• Four	9	11	148
	• Five	5	6	100
	• Six	5	6	48
	• Seven	8	10	109
	• Eight	9	11	128
	• Nine	7	8	88
	• Ten	39	46	106
Total		**84**		**108**

[a] Multi-storey dwellings that include ground floor were assigned to the ground floor.

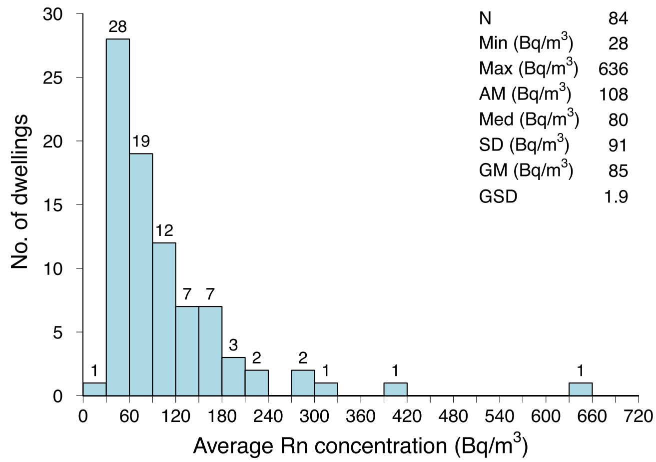

Fig. 2. Distribution of the measured annual radon concentrations averaged over one decade.

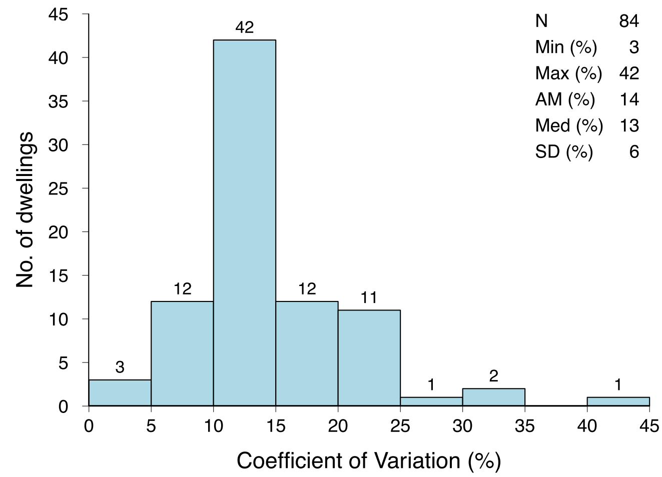

Fig. 4. Distribution of CV of the measured annual radon concentrations over one decade.

concentrations has been used for each dwelling and each year for this analysis. A total 678 year-long radon concentration values for the 84 dwellings have been analysed, with an average of 8 values per dwelling, as shown in Table 1. These values are generally consecutive, except in few cases: there are 19 missing values (regarding 14 dwellings) within the measurement periods, caused by failing of the inclusion requirement on the measurement duration (to be within 365 ± 30 days) and, in two cases, by the loss of detectors.

The distribution and a summary table of the long-term average radon concentration (i.e., the arithmetic mean of year-long radon concentrations for each dwelling) measured in the 84 dwellings are reported in Fig. 2. Values range from 28 Bq/m^3 to 636 Bq/m^3, with a geometric mean (GM) of 85 Bq/m^3 and a geometric standard deviation (GSD) of 1.9. The distribution of the standard deviation (SD) of annual radon concentrations is reported in Fig. 3, showing a median (Med) of 10 Bq/m^3. In six dwellings, for some years, radon concentration exceeded 300 Bq/m^3 (the maximum value of reference level for the annual average radon concentration in dwellings, on the basis of the new Directive 2013/59/Euratom). In two of these dwellings the excesses were observed for almost all of the years of measurement. All the dwelling owners have been informed about the radon concentration measured, including those with the highest measured values. However, at the time of the study (and until July 2020) the Italian regulation dealt only with the protection from radon in workplaces (including schools), and remedial actions were only required in workplaces with radon measurements exceeding 500 Bq/m^3 (value of the Italian action level at that time). To authors' knowledge, no remedial actions were performed in these dwellings; it can only be presumed that occupants' behaviour changed, improving ventilation by increasing window-opening duration per day.

The distribution of the coefficient of variation (CV), obtained as the ratio of standard deviation of year-long radon concentrations divided by the arithmetic mean of these concentrations for each dwelling (i.e., the long-term average radon concentration), is presented in Fig. 4 with a summary table. The CV for individual dwellings ranges from 3% to 42%, with a median value of 13%. The average value of CVs is 14.5% with a 95% confidence interval (CI) of 13.1%–15.8% (the CI is asymptotically correct, being derived using the Central Limit Theorem).

The CV estimate, obtained assuming a log-normal distribution for the radon concentration data (hypotheses [3]) and using the linear model [2], as described in the subsection *Statistical methods*, was estimated to be 16.6% with a 95% CI of 15.7%–17.6%.

In Fig. 5 the CV value for each dwelling is plotted against the average concentration over the decade in order to highlight a possible correlation. The slope of the regression line is not statistically different from zero (p-value ~8%), suggesting a multiplicative structure of the error of the repeated measurements. However, an additive error, representing a measurement error component that can have an impact especially at low concentrations (Hunter et al., 2011), could also be present, but it was not included in the simplified model [2].

The arithmetic mean, for each year, of the annual radon concentration values for the 39 dwellings with a complete set of measurements over 10 years is shown in Fig. 6 in order to identify a possible systematic

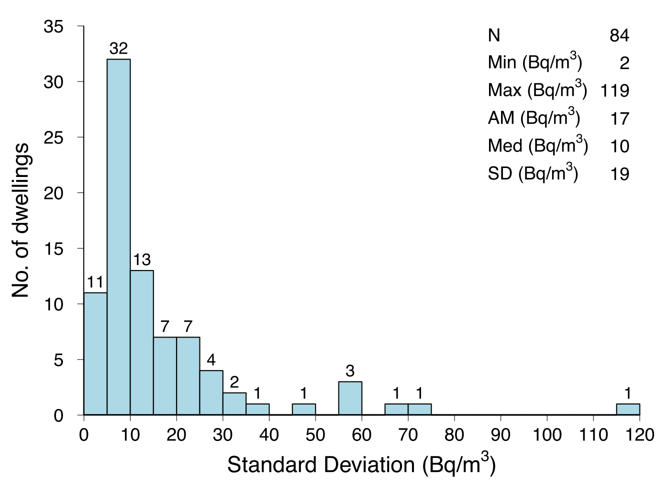

Fig. 3. Distribution of SD of the measured annual radon concentrations over one decade.

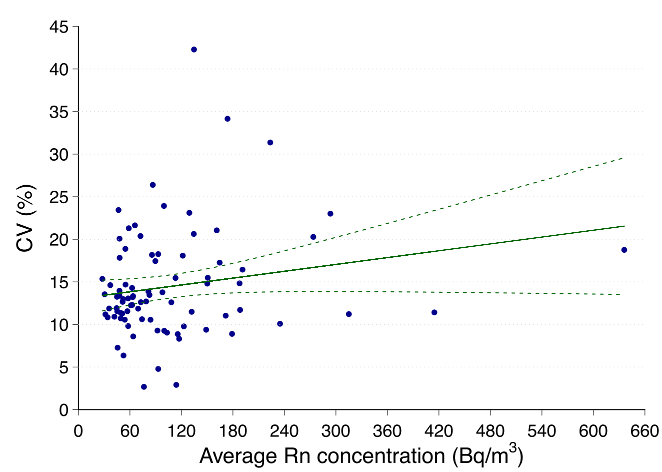

Fig. 5. CV of the measured annual radon concentrations vs average value over one decade.

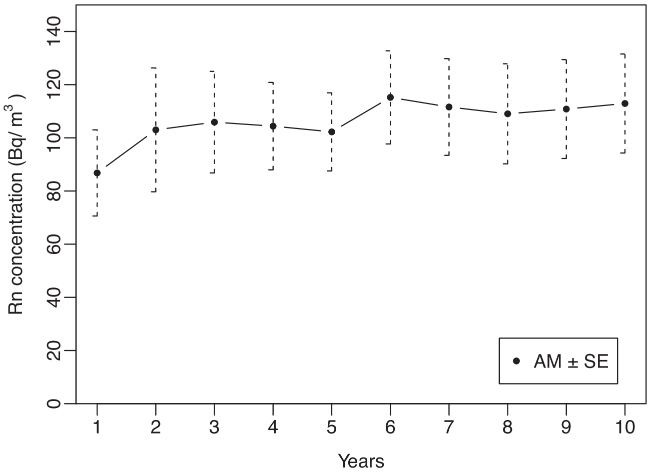

Fig. 6. Arithmetic mean, for each year, of the measured annual radon concentrations for the 39 dwellings with a complete set of measurements over 10 years (AM = arithmetic mean, SE = standard error).

component in the observed overall year-to-year variability. Some systematic radon concentration variability, and even a trend, can be observed in Fig. 5, particularly for the first 6 years. The data regarding these 39 dwellings were therefore analysed through a mixed linear model including a (linear) trend component in order to remove the contribution of systematic variations. The estimated residual year-to-year variability explained about the 80% of the overall year-to-year variability, meaning that the observed overall variability is only marginally explained by a systematic trend over years. It is worth noting that the average CV for these 39 dwellings is not significantly different from the average CV for the all 84 dwellings included in the study.

3.2. Review of the studies on the year-to-year radon concentration variability in dwellings

Results and main characteristics of the present and other studies on year-to-year variability of radon concentration in dwellings are reported in Tables 2a and 2b. The studies are grouped according to the geographic areas (i.e. Europe, North America and China) which the three main published pooled analyses of epidemiological case-control studies (Darby et al., 2006; Darby et al., 2005; Krewski et al., 2006; Lubin et al., 2004; Krewski et al., 2005) refer to. Overall, the CV estimates are quite different among the studies, ranging from 15% (for one dataset of the study carried out in Iowa (Zhang et al., 2007)) to 62% (for one dataset of the study in Finland (Darby et al., 2006)).

For the study performed in China, the CV is 43%; for the 8 datasets included in the 6 studies performed in Europe, the median CV is 42% and it ranges from 17% to 62%; for the 5 datasets included in the 4 studies performed in some North American country (or region), the median CV is 24% and it ranges from 15% to 28%.

Data collected in Tables 2a and 2b show that the studies considered are quite different with respect to the potentially relevant factors for the year-to-year variability evaluation.

As regards information relative to the dwellings involved in the studies, it can be observed that few studies (5 out of 11) are specifically designed for the estimation of the year-to-year variability (in this case most of the sources of additional variability could be better controlled), and the number of dwellings involved in the AV studies varies from 14 to 960 houses. Moreover, only in two studies ((Lubin et al., 2005) and the present study), more than two detectors per room are used, on average, to measure radon concentration; a larger number of detectors would produce a more precise annual radon concentration evaluation and, therefore, a lower year-to-year variation estimate.

As regards the duration of the measurement, in some studies 2- or 3- or 6-month long measurements have been performed and then, sometimes, seasonal (or temperature) correction factors have been applied; in other studies, the annual radon concentration value was obtained averaging the measurements relative to two consecutive 6-month periods, or using a 12-month integrated measurement. Furthermore, time elapsed from the first to the last repeated measurement ranges from 2 years (i.e. Czech Republic (Slezakova et al., 2013), Iowa (Zhang et al., 2007)) to 20 (Czech Republic (Slezakova et al., 2013)) years. If the CVs reported in Tables 2a and 2b are analysed taking into account the duration of the measurements used to compute the corresponding CV, it emerges that the CVs range from 17% to 43% (with median value of 25%) when considering the 9 datasets in which 1 year-long measurements were performed. On the other hand, among the 3 datasets for which the CVs have been obtained using measurements performed over a period shorter than 1 year, the CVs range from 39% to 62% (with a median value of 44%). We have excluded from this analysis the Czech study (Slezakova et al., 2013) carried out on 167 dwellings in a radon prone area and the UK study by Lomas and Green (1994) because for these studies the duration of the measurements was not homogeneous.

Regarding the number of years with repeated measurements, in addition to the extensive Italian study described in the present paper, only the study by Steck (2009), specifically designed to evaluate year-to-year variations of radon concentration, covers several (generally consecutive) years, ranging from 3 to 19 years, with a median of 10 years.

Regarding the time span of the measurements, some studies (e.g. Slezakova et al. (2013), Zhang et al. (2007)) evaluated radon yearly variation repeating the radon concentration measurement after few years (i.e., 2 years) and after many years (i.e., 6 and 20 years), obtaining a higher CV for the measurements repeated after a longer time span. Nevertheless, such correlation between the time span length and the year-to-year variability of radon concentration should be verified through an appropriate and more specific study.

Finally, the average radon concentration level ranges from 69 Bq/m^3 (median value in the study performed in Grand Junction – USA (Martz et al., 1991)) to 790 Bq/m^3 (geometric mean derived for the Czech study (Slezakova et al., 2013)) and this large difference may have an impact on year-to-year variability.

3.3. Radon exposure evaluation: comparison between year-to-year variability studies and epidemiological studies

In order to evaluate the adequacy of year-to-year variability studies to estimate the long-term exposure uncertainty in the epidemiological studies, the main characteristics of radon concentration measurements performed in epidemiological and corresponding AV studies have been compared and reported in Table 3.

Among the published AV studies, only the studies in Gansu Province of China (Lubin et al., 2005) and in Iowa (Zhang et al., 2007) were performed in a representative subgroup of the same dwellings where radon concentration was measured for the epidemiological study purposes. Furthermore, in these two AV studies and in the Italian one, the repeated radon measurements were performed with the same technique and procedures as those used in the corresponding case-control studies. In the other cases, the dwellings selected for the AV studies and for the epidemiological studies lay in different geographic areas and also the radon measurement protocols were different.

With respect to radon concentration distributions, in most AV studies radon concentration levels were higher than those found in the epidemiological studies: i) in Finland where in the AV study carried out in southern Finland a GM of 319 Bq/m^3 was found (personal communication in Darby et al. (2006)) versus a GM value of 80 Bq/m^3 found in the nationwide epidemiological study (Auvinen et al., 1996); ii) in Shenyang, China, where the GM obtained in the AV study (Lubin et al., 2005) carried out in Gansu Province was 348 Bq/m^3 while the GM computed in the epidemiological study (Blot et al., 1990) was 91 Bq/m^3; iii)

Table 2a
Summary of relevant information for the assessment of the yearly variability of indoor radon concentration in dwellings: studies conducted in Europe.

Study area (Reference)	No. (and type) of dwellings	Dwelling selection criteria	No. of years with repeated meas.	Time span (years from the 1st to the last meas.)	No. of det. used to estimate yearly Rn conc.	No. of rooms meas. for each house	Typical duration of meas. in each year	Meas. always in the same room	Rn conc. (Bq/m^3)	Year-to-year CV (CI)	Used to adjust the risk estimate
Czech Republic (Slezakova et al., 2013)	960 (mainly single-family houses with expected elevated indoor Rn conc)	From existing database	2	2	2	2	1 year (in some cases 2 months during the heating season or 6+6 consecutive months)	Yes	473 (GM)[(a)]	**36%** **(34%-37%)**	YesDarby et al., (2006)
	167 (in a radon prone area)	From existing database	2	20	2	2	1 year for the first measurements; 6 months for the second one, with seasonal corrections	No	790 (GM)[(a)]	**56%** **(50%-63%)**	No
Finland (Mäkeläinen, personal communication, in Darby et al., (2006))	301 (mostly single-family houses)	N.R.	N.R.	N.R.	N.R.	N.R.	Mostly 2 months during winter, but some 1 year	No	319 (GM)	**62%**	Yes
	80 (mostly single-family houses)	Selected to have small variability	N.R. [(b)]	N.R. [(b)]			Mostly 1 year, but some 2 months during winter		196 (GM)	**36%** **(33%-39%)**	No
Italy (present study)	84 (65 in multi-family buildings)	Specifically selected for AV study	8 (AM) 3–10	8 (AM) 3–10	8–16	Generally 2 (>2 in some cases)	6+6 consecutive months	Yes	106 (AM) 84 (GM)	**17%** **(16%-18%)**	Yes [(c)]
Sweden (Falk, personal communication, in Darby et al., (2006))	44 (mostly single-family houses)	N.R.	N.R. [(d)]	N.R. [(d)]	N.R.	N.R.	3 months in winter	Yes	178 (GM)	**39%**	YesDarby et al., (2006)
UK(Lomas and Green, 1994)	218 (mostly single-family houses)	From existing databases	2	Up to 10[(e)]	2	2	1 year for the first measurements; 3 months for the second one, with seasonal corrections	No	191 (AM) 107 (GM) second period	**51%** **(46%-57%)**	YesDarby et al., (2006)
UK(Hunter et al., 2005)	96 (houses selected with radon level around 100 Bq/m^3)	Specifically selected for AV study	6	8	2	2	3 months seasonal and temperature corrected	No	94 (GM) 110 (AM)	**44%**[(f)] **(42%-49%)**	YesDarby et al., (2006)

AM = Arithmetic mean; GM = Geometric mean; Med = Median; CI = confidence interval; N.R. = Not Reported in the reference; AV = Annual Variation

[a] This value has been obtained applying an equilibrium factor of 0.4 to the GM of the radon equivalent equilibrium concentration measurements reported in Table 1 of the paper by Slezakova et al. (2013)

[b] In table 30 of Darby et al., (2006) it is reported that measurements were carried out in “80 dwellings in 18 different years”. Details about the number of consecutive years per dwelling (and the time span) are not reported.

[c] The Italian value used by Darby et al., (2006) to correct the risk estimate was obtained analysing repeated measurements over five years(Bochicchio et al., 2009b)

[d] In table 30 of Darby et al., (2006) it is reported that measurements were carried out in “44 dwellings in 13 different years”. Details about the number of consecutive years per dwelling (and the time span) are not reported.

[e] The lapse between the first and second measurements generally was less than 4 y, but approximately 10% were in the 8-y up to 10-y interval.

[f] This value is obtained using seasonal corrected data

Table 2b
Summary of relevant information for the assessment of the yearly variability of indoor radon concentration in dwellings: studies conducted in North America and China.

Study area (Reference)	No. (and type) of dwellings	Dwelling selection criteria	No. of years with repeated meas.	Time span (years from the 1st to the last meas.)	No. of det. used to estimate yearly Rn conc.	No. of rooms meas. for each house	Typical duration of meas. in each year	Meas. always in the same room	Rn conc. (Bq/m^3)	Year-to-year CV (CI)	Used to adjust the risk estimate
North America											
USA (Grand Junction)(Martz et al., 1991)	40 single-family houses (30% built with uranium mill tailing)	Not specifically selected for AV study	Up to 6 [(a)]	6	1.5 (AM)	1.4 (AM)	1 year	Yes	92 (AM) 69 (Med)	**25%** [(b)(*)] **(21%-29%)**	No
USA (Upper Midwest)(Steck, 1992)	14 houses	Not specifically selected for AV study	2	2	2	2	1 year	N.R.	N.R.	**22%**	No
USA (Iowa)(Zhang et al., 2007)	196 (98 one story, 98 two- or three-story houses)	Specifically selected for AV study	2	2	2 (AM)	2 (AM)	1 year	Yes	176 (AM) second period	**15%** [(b)(c)(*)] **(14%-16%)**	No
	61 (31 one story, 30 two- or three-story houses) [(c)]	Specifically selected for AV study	2	5–6	2 (AM)	2 (AM)	1 year	Yes	184 (AM) third period	**24%** [(b)(d)(*)] **(20%-28%)**	No
USA (Minnesota) (Steck, 2009)	98 houses (mostly with basement partially below ground level)	Specifically selected for AV study	10 (Med) 3-19	13 (Med) 4-19	2(AM)	2 (AM)	1 year	Yes	120 (GM) 150 (AM)	**28%** [(b)(*)]	No
China											
Gansu Province (China)(Lubin et al., 2005)	55 (5 different types of single-family dwellings)	Specifically selected for AV study	3	3	9–36	2.8 (AM) 1-6	1 year	Yes	348 (GM) 356 (AM)	**43%** **(40%-46%)**	Yes

AM = Arithmetic mean; GM = Geometric mean; Med = Median; CI = confidence interval; N.R. = Not Reported in the paper; AV = Annual Variation
[a] More than a half rooms were measured for six years
[b] CVs were calculated for each site of the houses. So the average CV refers not to the houses, but to all sites measured.
[c] These 61 houses are a subgroup of the 196 houses for which a third measurement was carried out.
[d] CV was estimated for each floor level by house type.
[*] Arithmetic mean of the CV distribution

Table 3
Comparison between radon measurement characteristics in epidemiological (Epi.) and corresponding annual variation (AV) studies.

Epidemiological study	Corresponding AV study	Duration of measurements (months)		Radon dosimeter type		Radon concentration Bq/m^3 (GM)		AV study performed in a representative subsample of the Epi. study
		Epi. study	**AV study**	**Epi. study**	**AV study**	**Epi. study**	**AV study**	
Gansu Province (China) (Lubin et al., 2005)	Gansu Province (China) (Lubin et al., 2005)	12	12	CR-39	CR-39	176	348	Yes
Middle Bohemian Pluton region (Czech Republic) (Tomásek et al., 2001; Tomasek, 2012)	Middle Bohemian Pluton region (Czech Republic) (Slezakova et al., 2013)	12	12	LR 115 (open)	LR 115	448	327	No
Finland (nationwide) (Auvinen et al., 1996)	South Finland (Mäkeläinen[a])	12	Mostly 2 some 12	Makrofol	N.R.	80[(b)]	319	No
South Finland (Ruosteenoja et al., 1996)	South Finland (Mäkeläinen[a])	2	Mostly 2 some 12	Makrofol	N.R.	175[(b)]	319	No
Iowa (USA) (Field et al., 2000)	Iowa (USA) (Zhang et al., 2007)	12	12	CR-39	CR-39	89	130[(c)]	Yes
Winnipeg[d] (Manitoba, Canada) (Létourneau et al., 1994)	Minnesota[d] (USA) (Steck, 2009)	6+6	12	CR-39	CR-39	-	120	No
South west England (Darby et al., 1998)	UK(Hunter et al., 2005; Lomas and Green, 1994)	6 seasonally corrected	Either 12 or 3 seasonally corrected; 3 seasonally corrected	CR-39	CR-39	36[(b)]	107; 94	No
Sweden nationwide (Pershagen et al., 1994)	Sweden (Falk[a])	3 (in winter)	3 (in winter)	CR-39	N.R.	72[(b)]	178	No
Sweden never-smokers (Lagarde et al., 2001)	Sweden (Falk[a])	3 (in winter)	3 (in winter)	CR-39	N.R.	58[(b)]	178	No
Stockholm county (Sweden) (Pershagen et al., 1992)	Sweden (Falk[a])	12	3 (in winter)	CR-39	N.R.	119[(b)]	178	No
Lazio (mainly Rome) (Italy) (Bochicchio et al., 2005)	Rome (Italy) (present paper)	6+6	6+6	LR 115	LR 115	93[(b)]	85	No

Note: Only the epidemiological studies with a corresponding AV study have been reported in the table
GM = Geometric Mean; N.R. = Not reported; AV = Annual variation
[a] Personal communication from Table 30 in Darby et al., (2006)
[b] Time weighted average (TWA) of residential radon concentration from Table 5 in Darby et al., (2006)
[c] Weighted mean of the medians estimated for one- and two-story houses in Iowa (Table 2 in Zhang et al. (2007)
[d] Winnipeg lays in an area contiguous to Minnesota

in Sweden, where the GM obtained from measurements performed during the AV study was 178 Bq/m^3 (personal communication in Darby et al. (2006)) whereas the GM of radon concentration obtained from the two epidemiological studies (Pershagen et al., 1994; Lagarde et al., 2001) was 72 Bq/m^3 and 58 Bq/m^3.

With regard to the duration of radon concentration measurements, in some case-control studies measurements were carried out over a longer period than the period over which the measurements in the corresponding year-to-year variation study were performed. For example, in the nationwide case-control studies carried out in Finland (Auvinen et al., 1996) 12-month integrated radon measurements were performed, whereas the measurements for the corresponding year-to-year variation studies were mostly carried out over a period of 2 months (personal communication in Darby et al. (2006)). Similarly, in the UK 6-month integrated radon measurements were used in a case-control study (Darby et al., 1998) and generally 3 month-long measurements for year-to-year variation studies (Hunter et al., 2005; Lomas and Green, 1994), even if correction factors are used to obtain annual average values both for the case control study (Darby et al., 1998) and for the year-to-year studies (Hunter et al., 2005; Lomas and Green, 1994).

Regarding the dosimeter type, there are no differences between epidemiological and annual variation studies, at least for the studies where this information is reported.

4. Discussion

4.1. Year-to-year radon variability observed in the present study versus other studies

The present study, started in 1996, is currently the longest study, in terms of number of consecutive years of measurements, conducted in Europe and specifically designed to evaluate the year-to-year variations of indoor radon concentration in normally inhabited dwellings. The only other extensive and long study specifically designed with this aim is that carried out in Minnesota by Steck (2009).

In this paper, results relative to the first ten years of measurements of the Italian study are presented and discussed (results of the first five years were reported in a previous paper (Bochicchio et al., 2009b)). The analysed period of ten years allows evaluating annual variations of radon concentration over a period closer to that considered in epidemiological studies. Furthermore, these results are compared to other ones from AV studies carried out in some other European countries (Czech Republic, Finland, Sweden, UK) and in some non-European countries and regions (China, or some regions or States in North America) where epidemiological studies on residential exposure to radon were carried out.

The coefficient of variation estimated within the present study over one decade (17%) is considerably lower than that evaluated in all the studies carried out in other European countries (17% to 62%) and lower than that obtained in most of the studies carried out in North American states and regions (15% to 28%). This relatively low yearly variability may be explained taking account of the factors that appear to affect the year-to-year variability on the basis of the analysis of Tables 2a and 2b, due to the number of detectors used to perform the measurement, and the time length of the measurements. In fact, in the present Italian study a high number of detectors (8 to 16) was used for the measurement of the annual radon concentration in each dwelling, compared with the 2 detectors generally used in the other AV studies, and this reduces the variability due to measurement error, which is included in the overall observed year-to-year variability. Moreover, measurements were performed over one year, thus not requiring seasonal correction factors and not introducing their associated uncertainties. In fact, to extrapolate annual average radon concentration from a 3–6-month measurement, often a correction factor based on season or on outdoor temperature is applied (Miles, 1998; Miles et al., 2012). However, these factors are mean values, obtained from specifically designed surveys, and corrections for individual dwellings can differ considerably from such mean values.

The low yearly radon variability of the Italian study could be also due to the climate characterising the Rome metropolitan area, where most of the dwellings involved in the present study are located. Rome is characterized by a Mediterranean climate, with quite hot summer and quite warm winter, very different from the colder climate as in continental Europe or in the Nordic countries. Due to the temperate climate, natural ventilation is generally ensured all over the year (also considering that most of the dwellings do not have an air conditioning system installed), and this could partially explain the small fluctuations of radon concentration over the years. It can be reasonably presumed that studies performed in similar climate conditions would give similar results due to possible similar natural-ventilation conditions. On the contrary, in areas with colder climate conditions natural ventilation is not always assured (also due to insulation systems commonly installed), and results of indoor studies performed in these areas could be more influenced by natural-ventilation habits and climate changes.

It is believed that geological characteristics of Rome area have had a minor impact on the study results, both because sample of dwellings is spread all over the large territory of Rome (that encompass zones both with high, and low average radon concentration), and because 74% of the sampled dwellings are on the first or higher floors.

Other potential sources of radon variability (i.e., occupier changes or house renovation) have been avoided in the present study: only one of the sampled dwellings had occupier changes and none of the dwellings were significantly renovated during the study period. In order to evaluate if difference in house type could partially explain the lower year-to-year variability observed in the present study, a separate analysis for the 67 apartments and the 17 single/two-family houses was carried out, obtaining no significant difference in the year-to-year variability results. Few other studies investigated impact of these factors on the CV, concluding both that these changes do not result in significant differences in radon level (Hunter et al., 2005; Lomas and Green, 1994) and that they cause significant radon changes (Steck, 2009). However, in most AV studies analysed in this paper, including the Italian AV study, few dwellings have had occupier or building changes during the study period.

Finally, it is worth mentioning that the large impact of radon exposure uncertainty on the estimated risk has promoted the development of a different experimental approach to evaluate average radon concentration over a long period (20–30 years), as needed for epidemiological studies. This approach is based on retrospective techniques, i.e. on techniques that measure some quantities which is related with radon concentration over previous decades; alpha particles emitted from Po-210 (derived from the decay of short-lived radon decay products) implanted in the surface of glass objects (e.g. glass covering pictures and photographs). Two epidemiological studies have used this approach (Alavanja et al., 1999; Lagarde et al., 2002). However, theoretical and experimental studies have shown that large differences can occur in different dwellings in the ratio between radon exposure and the implanted Po-210 (Bochicchio et al., 2003b; Žunić et al., 2007). This issue, in addition to some practical limitations, probably explain why this approach has not been applied in more studies.

4.2. Potential impact of long-term radon concentration uncertainty on risk estimates from epidemiological studies

In ascertaining long-term radon exposure, one of the main sources of uncertainty is due to the use of one single radon measurement to represent radon concentration throughout many years. Uncertainty can affect lung cancer risk assessment in epidemiological case-control studies in dwellings, and, as a consequence, can have an impact on the evaluation of the burden of disease attributable to radon (Hunter et al., 2015).

Impact of error-prone exposures on epidemiologic analyses has been extensively discussed in a comprehensive paper by a STRATOS (STRengthening Analytical Thinking for Observational Studies Initiative) task group (Keogh et al., 2020), where methods available to adjust for such measurement error in continuous covariates used in regression models are also presented.

Under general circumstances (including nondifferential exposure mismeasurement and classical structure of measurement error), uncertainty on radon exposure leads to a bias of the effect estimate toward the null. This means that if there is an association between radon exposure and lung cancer, its strength is attenuated; moreover, the larger is the mismeasurement, the greater is the attenuation of the relationship. Intuitively, in case of dichotomous exposure, the dilution of the true effect is due to the fact that misclassification makes the exposed and non-exposed groups more similar. So, a correction for such uncertainty, if adequately evaluated, produces a quite higher risk than the observed one.

Moreover, classical measurement error decreases the precision of the risk estimate and results in loss of power to detect a true higher risk. As a consequence, in studies with substantial measurement error, a loss of power is observed, that is, the chance of detecting a significant effect of exposure is reduced.

In order to minimize the bias due to long-term radon exposure uncertainty, year-to-year variability of radon concentration has been used to correct the observed risk in the pooled analysis of the epidemiological studies carried out in European countries (Darby et al., 2006; Darby et al., 2005), as well as in some specific studies (i.e., Gansu Province of China (Lubin et al., 2005), south-west England (Darby et al., 1998), Sweden (Lagarde et al., 1997)). The correction for year-to-year uncertainty applied to the European collaborating study (Darby et al., 2006; Darby et al., 2005) (where the median CV, estimating year-to-year variability, is of 42%) lead to an increase of 100% of the risk estimates (ERR increased from 0.084 to 0.16 per 100 Bq/m^3). In the pooled analysis of 7 North American case-control studies, as well as in the pooling of 2 Chinese case-control studies, or in the more recent two Spanish pooling studies (Lorenzo-González et al., 2019; Lorenzo-Gonzalez et al., 2020), no formal adjustment for measurement error was attempted. However, from the comparative analysis performed in this paper, overall, year-to-year variability appears to be lower for studies performed in North American countries (median CV = 24%), with respect to those performed in Europe. Therefore, it can be supposed that adjusting the lung cancer relative risk for the radon exposure uncertainties derived from the year-to-year studies conducted in North-American countries would produce a lower ERR increase. Regarding the Chinese pooling, an AV study is available only for the epidemiological study carried out in Gansu, the larger of the two studies included in the pooling. It should be considered that in Gansu Province area high indoor thoron concentrations were found (Tokonami et al., 2004; Yamada et al., 2006), and the detectors used for both for the epidemiological Gansu study and the Gansu AV study are quite sensitive to thoron (Akiba et al., 2010), resulting in an over-estimation of radon exposure. Therefore, the presence of thoron could have impacted on both the estimate of annual variation and risk evaluation (Akiba et al., 2010; UNSCEAR 2006).

For the Italian data, a correction for yearly variability has been performed by Darby et al. (2006), using a CV value of 17%, based on preliminary results of the first 5 years of the present annual variation study. A negligible ERR increase (about 1%) was obtained. The low year-to-year variability estimated by the present 10-year study, confirms the results obtained in the first 5 years (Bochicchio et al., 2009b), consolidating the expectation of a negligible impact on lung cancer risk estimate derived from the Italian epidemiological study.

As previously mentioned, other uncertainties can affect results of epidemiological studies other than that due to temporal variations. In the

European pooled analysis radon exposure assessment is likely subject to additional uncertainty, even though some potential sources of uncertainty seem to be under control (for example, several studies included only persons with low residential mobility). Onishchenko and Zhukovsky (2019) evaluated the possible impact on risk estimates of the European pooling taking account of a wide range of uncertainty sources and estimated a possible increase of the excess relative risk of lung cancer incidence at least by 1.5 times. Therefore, in view of new pooled analyses, the evaluation of these other potential source of uncertainties in radon exposure assessment, and correction for them, should deserve consideration, as well as the influence of uncertainties on confounders typically used to adjust the risk estimates.

The analysis of different values of year-to-year variability reported and reviewed in this paper suggests that such correction should be done on a case-by-case basis, i.e. applying the most appropriate value to the risk evaluation result of each epidemiological study. In fact, there are often large differences in the radon concentration measurement characteristics (i.e., duration of measurements, occupier changes/building renewal) between studies on year-to-year variability and the case-control studies, whereas a study carried out to evaluate the year-to-year variability with the aim to adjust the risk assessment of an epidemiological study should have characteristics as similar as possible to the epidemiological study itself, otherwise other sources of uncertainties could affect the risk adjustment procedure. Ideally, the repeated radon measurements should be performed in a representative subgroup of the dwellings included in the corresponding epidemiological study (so that the radon distributions are as similar as possible, being derived from measurements in the same typology of dwellings and in the same geographic area); moreover, implementation of uniform radon measurement technique and procedures is strongly recommended.

4.3. Conclusion

A low year-to-year variability for the Italian data has been confirmed by the present 10-year annual variation study. It is expected that the correction for such low yearly uncertainty would produce a negligible effect on the lung cancer risk estimate for the Italian epidemiological study.

In general, uncertainty on long-term radon exposure in epidemiological studies has not always been characterized adequately, although having a large impact on the lung cancer risk evaluation. Therefore, more comprehensive studies aimed to evaluate long term radon exposure uncertainty, like the present study on year-to-year radon concentration variations, should be promoted. Moreover, also the other sources of uncertainty, that can have an impact on risk estimates, should be accounted for, and some effort should be deserved to control them as much as possible.

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CRediT authorship contribution statement

F.B. conceived and coordinated the study; M.A. collected the data and performed the experimental measurements; S.A. and G.V. performed statistical analyses; all authors interpreted the data; S.A. and G.V. wrote the first version of the paper; all authors commented on the manuscript; S.A. finalized the manuscript.

Declaration of competing interest

None of the authors has any actual or potential competing financial and non-financial interests to declare.

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