ORIGINAL ARTICLE

Evaluation of radon exposure risk and lung cancer incidence/mortality in South-eastern Italy

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Keywords

Radon concentrations • Incidence • Mortality • Lung cancer • *Kriging*

Summary

Introduction. *Radon and its decay products may cause substantial health damage after long-term exposure. The aim of the study was to perform a spatial analysis of radon concentration in the Salento peninsula, province of Lecce (South-eastern Italy) in order to better characterize possible risk for human health, with specific focus on lung cancer.*

Methods. *Based on previous radon monitoring campaigns carried out in 2006 on behalf of the Local Health Authority (ASL Lecce) involving 419 schools and through the application of kriging estimation method, a radon risk map was obtained for the province of Lecce, in order to determine if areas with higher radon concentrations were overlapping with those characterized by the highest pulmonary cancer incidence and mortality rates.*

Results. *According to our data, areas at higher radon concentrations seem to overlap with those characterized by the highest pulmonary cancer mortality and incidence rates, thus indicating that human exposure to radon could possibly enhance other individual or environmental pro-carcinogenic risk factors (i.e. cigarette smoking, air pollution and other exposures).*

Conclusions. *The radon risk should be further assessed in the evaluation of the causes resulting in higher mortality and incidence rates for pulmonary cancer in Salento area vs Italian average national data. For these reasons, ASL Lecce in cooperation with ARPA Puglia and CNR-IFC has included the monitoring of individual indoor radon concentrations in the protocol of PROTOS case-control Study, aimed at investigating the role of different personal and environmental risk factors for lung cancer in Salento.*

Introduction

Radon (^{222}Rn) is a colorless, tasteless and odorless radioactive noble gas. It is constantly generated by some rocks of the earth's crust following the decay of radium (^{226}Ra), which in turn is progeny of uranium (^{238}U). There are two other radon isotopes (^{220}Rn and ^{219}Rn) resulting from the decay of elements ^{232}Th and ^{235}U, respectively. Although ^{220}Rn and ^{219}Rn are irrelevant, as determined by their short decay times, ^{222}Rn is more important from a radioactive point of view. Radon (^{222}Rn) has a half-life of 3.8 days and decays, emitting alpha particles, and generates a chain of unstable nuclei (radioactive lead, bismuth, and polonium), called "radon decay products". In particular, Polonium isotopes are alpha emitters and the particles emitted directly in contact with the lung tissues can contribute to radiation damage, even in the long-term (in particular the ^{210}Po has an average life of 140 days). Lead and bismuth are beta-emitters and their danger is lower, although ^{210}Pb (half- life 22 years) continues to be a continuous source of the most harmful ^{210}Po [1]. Radon emission is influenced by the geology (properties of rocks and soils) of a given region [2]. The amount of radon exhaled from the rocks depends essentially on two factors: their content in uranium and radio and their permeability [3-5]. As radon is a gas, outside it will then rapidly disperse in the atmosphere, but indoor (dwellings, schools and workplaces), radon can accumulate and results, in some instances, dangerous for human health, most notably causing lung cancer [6-8]. In 1988, radon and in particular its decay products (Polonium 218 and 214) are been assigned, by the World Health Organization's International Agency for Research on Cancer (WHO-IARC), in Group 1, as carcinogenic to humans [9]. Besides, the United States Environmental Protection Agency (US EPA) has classified radon as the second leading cause of lung cancer after cigarette smoking, and exposure to this gas is able to exponentially enhance the effect of other individual (smoking) or environmental exposures [10, 11].

Since radon leak up out of the ground and can enter buildings, the European Commission has required on Member States to establish a national action plan addressing long-term risks from radon exposures. They had to be identify "*radon prone areas*", zones where there is a high probability of finding high indoor radon concentrations [12, 13]. The European countries have defined the "*radon prone areas*" by developing different approaches: indoor radon measurements campaign-based approach, geology-based approach and integrated

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ones. Currently the most used is the last one, that integrates forecasts of radon exhalation related to the local geology, with the indoor radon measurements [14-17].
Over the last few decades, national indoor radon survey has been performed in Italy; in particular, a national survey to assess the indoor exposure of the Italian population was conducted by ISS (National Institute of Health) and ENEA (Italian National agency for new technologies, Energy and sustainable economic development), actually ISPRA (Higher Institute for the Protection and Environmental Research). The survey was organized by statistical areas of sampling to obtain representative samples of houses. Based on the average values found in 5,000 dwellings throughout national territory, Italy was assigned an average radon concentration of 77 Bq/m^3 and in particular Apulia region, a value of 52 Bq/m^3. More recent valuations assigned Italy an average radon concentration equal to 70 Bq/m^3 [18-20]. Considering that estimated world average radon value in 2000 was equal to 40 Bq/m^3, and the European average radon value is equal to 59 Bq/m^3, the average radon concentration of Apulia region can be considered medium-high, as well as the Italian one [21]. Therefore, in 2006, ASL (Local Health Authority) of the province of Lecce, in collaboration with INAIL (Italian Workers Compensation Authority), formerly ISPESL (National Institute for Occupational Prevention and Safety), Province of Lecce and University of Salento, in order to evaluate the radon concentrations in the Salento area (Apulia, South-eastern Italy), has performed a monitoring campaign in 91 municipalities of the province [22]. This monitoring was started because it was assumed that value radon concentration in Salento area could be higher than estimated average radon value for Apulia because of its karst features.
The aim of this paper was to perform a spatial analysis of the distribution of indoor radon concentration in the Province of Lecce (Apulia region, Italy), using data already available from the previous sampling campaign.
An ecological study was conducted to verify any overlap between the areas with the highest radon concentration and lung cancer mortality maps provided by Regional Epidemiological Observatory (OER) and incidence data published by Cancer Registry of ASL Lecce, accredited AIRTUM (Italian Association of Cancer Registries).
This in order to provide the public administrations with data useful for assessing the health risk attributable to radon for the resident population, taking into account that Salento area is characterized by an higher incidence of lung cancer in the male population (in the period 2003-2006: 88/100.000 inhabitant vs. an average rate of 73/100.000 and 64/100.000 in Northern and Southern Italian regions, respectively) [23].

Methods

In 2006 the ASL Lecce with INAIL, Province of Lecce and University of Salento has conducted a huge monitoring campaign to assess the indoor radon levels in schools. The present study starts from the results obtained by that survey.
Indoor radon concentration was investigated as activity of its radioisotope ^{222}Rn and expressed in Bq/m^3 (Becquerel per cubic meter), using NRPB/SSI type passive radon dosimeters with CR-39 TASTRAK plastics (TASL, UK) as nuclear track detectors. After exposure, passive devices were returned to the INAIL laboratory by express mail for analysis [22].
In this paper were considered only the schools in which the measure had been carried out on the ground floor, owing to their high exposure to radon sources (direct contact with the soil and, thus, with a natural radon source).
A total of 419 schools were monitored: 332 schools were monitored for two consecutive six-month periods in order to obtain the average annual radon concentration; while, in 87 schools, the results of only a single six-month period were available. In the last case, the radon concentration measured was corrected using the "seasonal correction factor", estimated equal at 1.23, as described by Trevisi et al., 2012 [22].
Starting from this radon monitoring campaign, an ecological study was conducted, and the radon concentration values were grouped by macro-areas corresponding to the boundaries of the Social-Health Districts, considering that the report published by the Cancer Registry of ASL Lecce grouped the incidence of lung cancer by district, while the mortality data were made available for each municipality by the OER.
The study was divided into three distinct phases:

a. analysis of the distribution of indoor radon concentration and its possible spatial representation;
b. analysis of lung cancer incidence data, published by Cancer Registry of ASL Lecce, and lung cancer mortality data provided by Regional Epidemiological Observatory, in order to verify possible overlaps between health data and geographical areas with higher concentrations of radon;
c. analysis of the correlation of geological parameters with the distribution of indoor radon concentration.

To represent the data, conventional maps and thematic maps were used in four main types:

1. maps of points that allow to represent discrete or observed quantities at different points, with dimensions proportional to the value of the quantity. Different colors and shapes have been used to represent qualitative differences;
2. maps of lines, which represent quantities distributed along linear elements, using different thickness, colour and type of the lines;
3. maps of areas, which represent variables in two dimensions, and use different texture and colour to discriminate qualitative differences;
4. maps of values, to represent numerical quantities that vary depending on the position (i.e. elevation, temperature, density), using more intense colours and/or denser textures for the higher values.

According to this methodology, have been indicated on the map the radon concentrations measured in the sam-

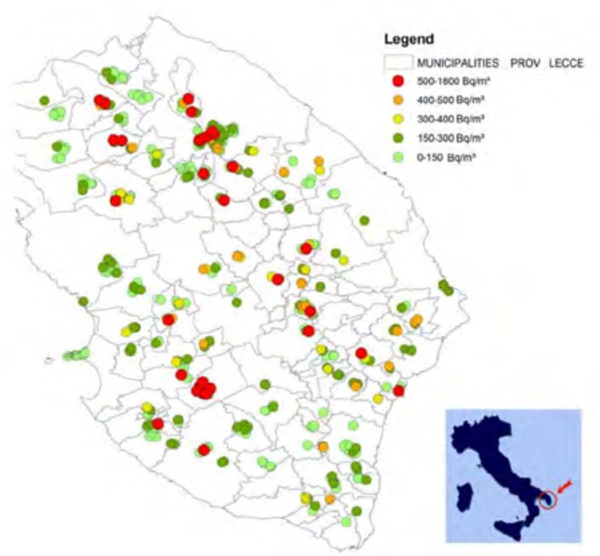


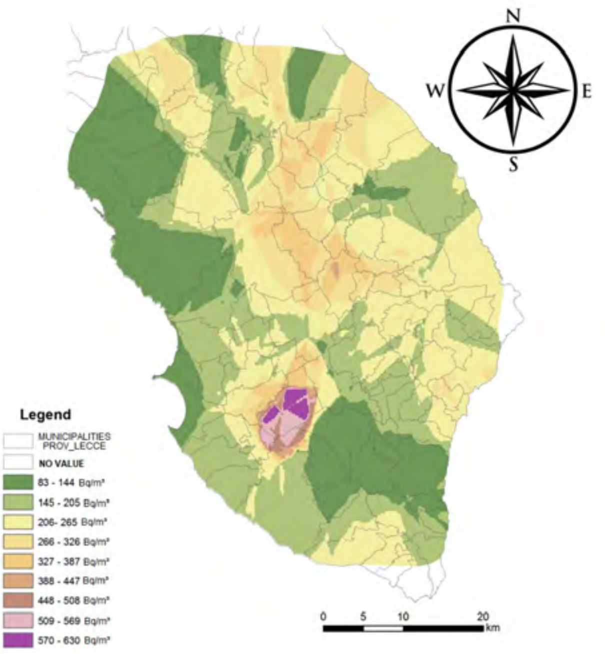
Fig. 1. Spatial distribution of samples on the territory of the Province of Lecce, classified according to radon concentration.

pling campaign in 2006 in the province of Lecce. The spatial distribution of data was not organized according to a regular grid, revealing areas of the Province with low density of points (rural areas) and others, characterized by an high density of point (typically urban areas). Furthermore, were present isolated points, in the areas with low density, not usable for the geostatistical analysis. On other hand, in the monitored area, the density of data was sufficient for highlight any significant variations of concentrations in regional territory and the analysis of these data could be useful for a future set up of maps, with the aim of define "*radon prone areas*", implemented with data collected according to a regular grid.
A spatial distribution of the data, based on the radon concentration, was performed (Fig. 1). In this map, there is a spatial continuity in the data related to the indoor radon concentration, as observed in most of the environmental phenomena. Neighbouring samples are more likely to have similar values than samples that are distant: low values tend to be close to other low values and high values to other high values.
Finally, was done an overlap of radon concentrations measured in 2006 and the geological map of Province of Lecce, showing formations of carbonate rocks.
Aimed to interpolate the radon concentration values on the provincial territory, it was used the *kriging* estimation method (already used for the estimation of mineral deposits or hydrocarbons in the subsoil). The advantages of *kriging* method of interpolation are principally: possibility of a prediction on a regular grid even where there aren't values; modelling anisotropy (directionality) and estimation of measurement error variance [24]. For that purpose, it was necessary to observe the spatial distribution of the samples and to consider the descriptive statistics indexes calculated on the data. As already highlighted, some areas are clustered, and this aspect should be taken into consideration to carry out the interpolation of data for its implications in the parameter estimation: high clustering is the cause of the "nugget effect", source of short-term variability and readable in the variogram like a discontinuity at the origin, with a leap from zero to the a first value of function.
For the calculation of *kriging*, a search radius of 7000m was used and the interpolation grid was fixed in meshes of 200 m x 200 m. Therefore, a radon risk map was obtained for the province of Lecce, where subsequently were highlighted the boundaries of the municipalities (for which the mortality data provided by the OER were available) and the boundaries of the social-health districts of the ASL (for which the incidence data published by the Cancer Registry of ASL Lecce were available). Radon risk map was overlapped with maps reporting the standardized incidence and mortality rates per 100,000 persons (in the resident population aged 0-74).

Results

The annual average concentrations of radon, measured in 419 schools of the province of Lecce, were in a very wide range, with values from a minimum of 21 Bq/m³ to a maximum of 1608 Bq/m³. On 419 school buildings, 28 schools presented annual values between 400 and 500 Bq/m³ (equal to about 6.7% of the schools involved) and 32 had values higher than 500 Bq/m³ (equal to about 7,6%). About 86% of school buildings had average annual radon values below 400 Bq/m³. The arithmetic mean of radon concentrations in the schools analysed was 214 Bq/m³ ± 191 S.D., with a median equivalent to 155 Bq/m³. The schools of the municipalities of Casarano, Barbarano, Galugnano, Corigliano d'Otranto, Giorgilorio, Melpignano and San Donato di Lecce had higher overall radon levels than others.
Using the *kriging* method, was obtained a radon risk map for the province of Lecce. In Figure 2, with different shades of colours (from less to more intense), the trend of the radon risk level in the Province of Lecce was represented, calculated using data related to the average annual radon concentrations measured in each municipal territory on the ground floors of school buildings in 91 of the 97 municipalities. From the interpolation map, some areas with the highest radon concentration are highlighted.
Figure 3 shows on maps, detailed at the municipal level, respectively, the radon concentrations and the lung cancer mortality rates per 100,000 person, from 2000 to 2005, the latest data available at the time of this study. The mortality data were obtained from the Regional Nominative Causes of Death Register (ReNCaM) of Apulia and made available from the Regional Epidemiological Observatory (OER) [25]. So there would be overlap between areas with a higher radon concentration and areas with higher Mortality Rates for lung cancer.
Similarly, data on incidence of lung cancer in the Province of Lecce, collected by the AIRTUM Cancer Registry of ASL Lecce (Report 2010, latest one available

Fig. 2. Radon risk map for the province of Lecce.



at the time of the study) highlight interesting aspects to be examined (Tab. I). Data refer to incidence during the period 2003-2004, grouped by macro-areas corresponding to the Social-Health Districts of the Province [26].

Graphic representation of the areas with highest radon concentration (red and orange areas) shows a possible overlap with the Local Health Districts that have the highest incidence of lung cancer (respectively Galatina, Casarano, Poggiardo and Maglie); while the four Districts with low incidence of lung cancer (Martano, Nardò, Gallipoli and Gagliano del Capo) coincide with the green areas that have a lower radon concentration (Fig. 4).

Tab. I. Standardized lung cancer Incidence Rates, for the Local Health Districts of Province of Lecce, from 2003 to 2004, per 100,000 person, in the resident population of age 0-74 years.

Local Health Districts (Province of Lecce)	Standardized incidence rates
Galatina	114
Casarano	93
Poggiardo	91
Maglie	90
Campi Salentina	86
Lecce	83
Gagliano del Capo	80
Gallipoli	72
Nardò	69
Martano	56

Finally, from dataset of the measurements related to the ground floor of the sampling schools, 60 values of average annual radon concentration have been extrapolated, of which 28 between 400 and 500 Bq/m³ and 32 higher than 500 Bq/m³ (data with the higher contribution of exhalation from soil). To correlate the spatial data distribution of radon concentrations with the geological characteristics of the territory (presence of faults facilitating radon emissions from the depths of the karst subsurface of Salento), the geological data were overlapped with

Fig. 3. Standardized lung cancer Mortality Rates for the Province of Lecce during the years 2000-2005 (A) and the map of radon concentrations (B).

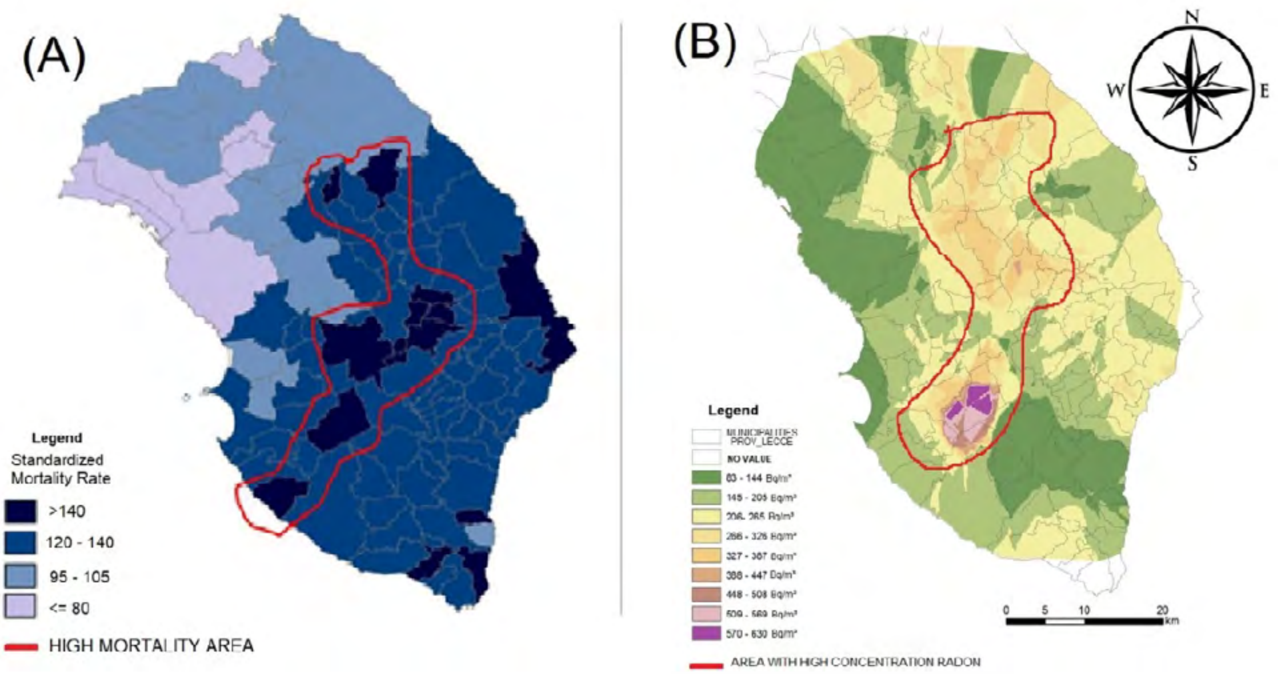
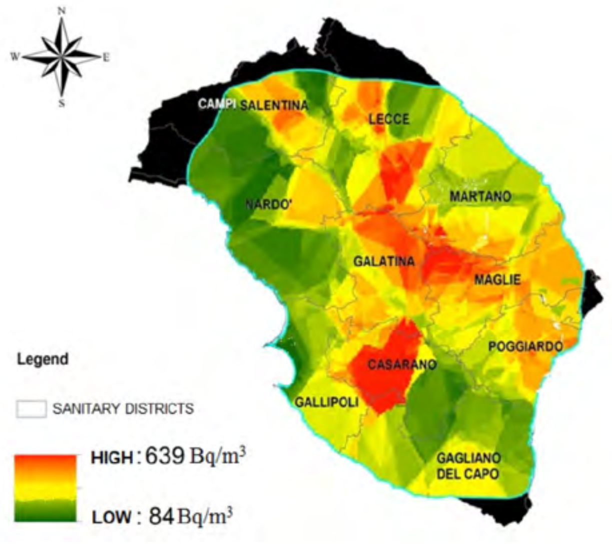


Fig. 4. Map of Radon Concentrations for Local Health Districts: in the red and orange areas radon concentrations exceed 400 Bq/m³.



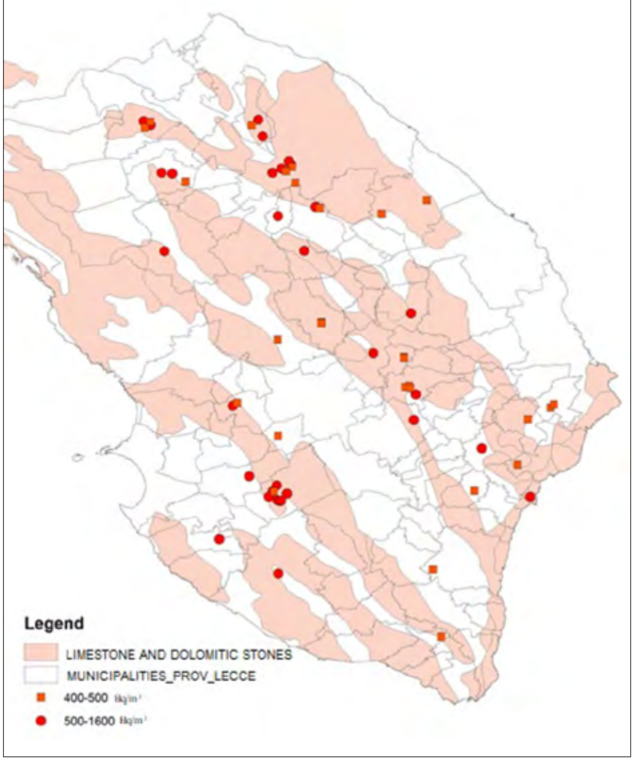
georeferencing data of average annual radon concentrations between 400 and 500 Bq/m³ (indicated with orange squares) and above 500 Bq/m³ (indicated with red circles). Figure 5 shows 44 points of colours orange and red (73.3% of the total 60) that are located on the borders of formations of carbonate rocks (at the foot of the "serre") where, due to karst phenomena, there is a high probability of structural discontinuity; in fact, there are faults and fractures conveying large quantities of radon gas from considerable depth.

Discussion

In addition to the presence of uranium in the subsoil, radon concentrations in the air also depend on numerous physical or meteorological parameters, such as site geomorphology, atmospheric pressure, temperature, humidity and the season of year. Radon is released from the ground in gaseous form, reaches the surface and mixes quickly with atmosphere, in a concentration of 10 Bq/m³. On the other hand, the situation for buildings is different, where higher values are normally obtained. Of course, it is not possible to build buildings totally protected by radon, while it's possible to design buildings with characteristics that minimize the radon entry or make the monitoring of the radon presence in already existing buildings in order to plan any interventions [27-29]. Relevant has been the national indoor radon survey performed in Italy in the last few decades, that attributed to Apulia an average radon concentration value of 52 Bq/m³ (average value in Italy: 70 Bq/m³; average value in Europe: 59 Bq/m³). The same survey identified a geographically very different situation for Italy, with extremely variable average regional concentrations: the highest averages were attributed to Lombardy (111 Bq/m³), Lazio (119 Bq/m³), Friuli Venezia Giulia (99 Bq/m³) and Campania (95 Bq/m³) [19, 20]. Literature has always confirmed that the soil is the main source of indoor radon, while the influence of building materials, as well as the water, has often been completely negligible [30, 31]. Therefore the limit of the national survey could consist in the approximation to regional medium situations of any specific territorial particularities. In fact, from the geological point of view, Salento peninsula is a karst territory [32-34], consisting of a series of carbonatic formations which, due to their solubility, facilitate the instauration of fractures and faults in the rocks favouring exhalation of radon from the subsoil [35]. This research through the spatial distribution of radon concentrations and the correlation with the geology of the study area, provides more information to better understanding of the phenomenon. Radon exhalation is not related just to the local soil lithology, but also to other factors, such as geological structure, porosity and the presence of faults and fractures in the territory. It is evident that the high radon concentrations detected are influenced by the particular geological situation of the subsoil and the karst phenomena influences significantly the process of radon exhalation. In fact, the radon transported in the underground karst networks by water and gases, can travel great distances and be directed outside by the presence of numerous faults, as shown also in other regions [36]. Therefore, also calcareous rocks, characterized by a relatively low content of uranium, can release significant amounts of radon.

Overall, the average annual radon levels measured in schools were in a wide range, with values between 21-1608 Bq/m³. Furthermore, of a total of 419 school build-

Fig. 5. Georeferencing data of average annual radon concentrations between 400 and 500 Bq/m³ and above 500 Bq/m³ correlated with the geomorphological characteristics of the province of Lecce.



ings, 28 schools showed annual values between 400 and 500 Bq/m³ (about 6.7% of the sampling schools) and 32 schools (equal to about 7.6%) had higher values than 500 Bq/m³, the Italian action level for workplaces (Leg. Decree n. 241/00) [12].
The results reported in this paper represents the prerequisites for continuing the study of radon spatial distribution, which requires uniform measurement method throughout the national territory, in order to compare the data of different surveys on the same territory. Moreover, in this study a comparison was performed between areas with highest radon concentration and the health data related to incidence and mortality due to lung cancer and according to our data, areas at higher radon concentrations seem to overlap with those characterized by the highest pulmonary cancer mortality and incidence rates. Certainly, the study presents the limits of an ecological study, due to not being able to measure individual exposures to radon and to control for individual lifestyles or habits, history of disease, socioeconomic status, etc. [37]. Therefore, radon risk should be further assess in the evaluation of the causes resulting in higher mortality and incidence rates for pulmonary cancer in Salento area vs. Italian average national data.

Conclusions

The identification of areas with great probability of high concentrations of radon in confined spaces play a crucial role for a right control strategy for existing buildings and for prevention policies. The average radon concentration in monitored schools of the province of Lecce is equal to 214 Bq/m³, a value greater than four times of the Regional average (52 Bq/m³) and greater than three times of the National average (70 Bq/m³). According to new European Directive 2013/59/Euratom and to Apulia Regional Law no. 30/2016, that identify the reference value of 300 Bq/m³ for home and public buildings [13, 38], many of the schools monitored, on the basis of the data resulting from this research, exceeded the limit of radon concentration and the relative Municipalities should therefore provide for further monitoring measures for evaluate the radon indoor concentration, for possible remediation measures and new building regulations. The georeferencing of 60 values, higher than 400 Bq/m³, highlighted a strong correlation with the geology of the Salento territory. It was found that the 73,3% of georeferenced values are placed on the sites characterized by karst phenomena, important faults and fractures, potentially favouring the exhalation of radon from the subsoil. The overlap between map of the radon concentrations and map of incidence and mortality for lung cancer in province of Lecce give information on which it is opportune to investigate in more detail, as human exposure to radon could possibly enhance other individual or environmental pro-carcinogenic risk factors (i.e. cigarette smoking, air pollution and other exposures).
Further studies are needed, given the intrinsic limitations of ecological studies; for these reasons, ASL Lecce, in cooperation with Regional Agency for Environmental Prevention and Protection (ARPA Puglia) and National Research Council-Institute of Clinical Physiology (CNR-IFC), has included the monitoring of individual indoor radon concentrations in the PROTOS Study, a huge case-control study on the risks factors for lung cancer in Salento, involving about 2000 people (420 pulmonary cancer cases and 1500 controls), whose results will soon be available.

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Conflict of interest statement

The authors declare no conflict of interest.

Authors' contributions

GM, PP, AI, FS, IFC, ADD, GDF contributed to conceive, write and revise the paper. TT, BT, MM, APC participated in the analyses and interpretation of the findings. AM, BV, AR were involved in critically revising the article. All authors have read and approved the final version of manuscript.

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