# Radon 1. Information

This article is a 'work in progress' incorporating new information whenever time permits.

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# Radon

Radon is considered the second cause of lung cancer and the first in those who have never smoked (Torres-Durán 2013, Choi & Mazzone 2014, Laurier & Gay 2015, Choi 2016). Hinojosa de la Garza (2014) reported that it was evident that lung cancer mortality was directly associated with locations with high levels of radon. Their study took into account a population which had been stable for more than 25 years, which they believe suggested spatial clustering of lung cancer deaths due to indoor radon concentrations. Geologic unit, well water, community, weather and unconventional natural gas development were associated with indoor radon concentrations (Casey 2015). Stopping smoking at age 50 years decreases the lifetime risk due to radon by around a half relative to continuing smoking, but the risk for ex-smokers remains about a factor of 5-7 higher than that for never-smokers.

In an Irish study of people with lung cancer (Smyth 2017), 21 % of patients had radon levels recorded above the national reference level. Only 5 % of patients were aware of the association between radon gas and lung cancer. Smokers were significantly less likely to engage fully in radon testing. In another study from Ireland (Dowdall 2016), it is estimated that approximately 7% of the national housing stock have radon concentrations above the Reference level of 200 Bq $m^{-3}$.

Radon mitigation used to reduce radon concentrations in homes can also have a substantial impact on lung cancer risk, even for persons in their 50's. Smokers in high-radon homes should both stop smoking and remediate their homes (Hunter 2015). In a study of lung cancer in never-smokers, by Torres-Durán (2015), the median residential radon concentration was 195 Bq $m^{-3}$, higher than the action levels recommended by the World Health Organisation.

Alpha particle emissions from inhaled radon decay products, and not radon itself, cause lung cancer. Alpha particles, which can only penetrate a short distance into bronchial epithelium, induce more biological damage than beta or gamma radiation, and can induce DNA base mutations and chromosomal strand breaks (Melloni 2014).

Radon and its decay products are the cause of 50% of the total radiation dose from natural sources. Thoron gas is one of the most common isotopes of radon. Indoor radon and thoron concentrations are not correlated, though thoron levels are comparatively low, between 0.5 and 6% of the radiation dose.

Public Health England recommends that radon levels should be reduced in homes where the average is more than 200 Bq $m^{-3}$. This recommendation has been endorsed by the Government. The Target Level of 100 Bq $m^{-3}$ is the ideal outcome for remediation works in existing buildings and protective measures in new buildings. If the result of a radon assessment is between the Target and Action Levels, action to reduce the level should be seriously considered, especially if there is a smoker or ex-smoker in the home. Axelsson (2015) suggested that 35-40% of the radon attributed lung cancer cases can be prevented if radon levels higher than 100 Bq $m^{-3}$ are lowered to 100 Bq $m^{-3}$.

Worldwide, 3-20 % of all lung cancer deaths are likely caused by indoor radon exposure (SH Kim 2016). Lung cancer deaths induced by radon was slightly higher among females than males. If all homes with radon above 100 Bq/m(3) were effectively remediated reports Kim, studies in Germany and Canada found that 302 and 1704 lung cancer deaths could be prevented each year, respectively. 5 % of all cases of lung cancer in South Korea might be attributable to radon. Studies in Germany, France, and Switzerland reported indoor radon concentrations similar to those in South Korea (Kang 2016).

In Canada, the estimated average thoron concentration is 9 becquerels per metre cubed (Bq $m^{-3}$), and the average radon concentration is 96 Bq $m^{-3}$, more than double the worldwide indoor radon concentration (Chen 2014). A study in Canada (Rauch & Henderson 2013) concluded "The radon potential map of Canada may communicate potential radon risk, but it was not designed for epidemiologic exposure assessment. Overall, the potential map classified 34 LHAs as higher than observed, and 10 LHAs as lower than observed. The potential map should only be used to inform exposure assessment in conjunction with observed radon concentrations." The results of a study by Branion-Calles (2015) contribute evidence supporting the use of a reference level lower than the current guideline of 200 Bq $m^{-3}$ for the province of British Columbia.

Increased probabilities of high residential radon vulnerability were associated with cold and dry winters, close proximity to major river systems, and fluvioglacial and colluvial soil parent materials (Branion-Calles 2016).

Several investigations in **Estonia** during 1996-1999 have shown that permissible level (200 Bq/$m^3$) of radon (222Rn) in indoor air is exceeded in 33% of the inspected dwellings. This makes Estonia one of the five countries with highest radon risk in Europe (Petersell 2017).

The Environmental Protection Agency (EPA) in the USA and Public Health England (PHE) estimate that there are 22,000 radon-related deaths in the USA each year and over 1,100 in the UK as a result of inadequate preventative measures and poor detection methodologies. The Environmental Protection Agency (EPA) announced a strategy in 2015 for preventing 3,200 lung cancer deaths annually by 2020, by reducing radon levels in five million homes, schools and childcare centres.

In **Kosovo**, in two villages affected by depleted uranium, radon levels ranged from 82 to 432 Bq $m^{-3}$; the value of 400 Bq $m^{-3}$ was exceeded in 2 of the 25 homes measured (Nafezi 2014). At least 15% of homes in Finland (Valmari 2014) were found to exceed their reference levels of 400 Bq $m^{-3}$.

In the **USA**, the results of the 1992 EPA National Radon Survey estimated that 1 in 15 homes (about 5.8 million) had an elevated radon level (Keith 2012).

In a study of **Shiraz**, Iran (Yarahmadi 2016), the concentration of radon in 5.4% of the houses was found to be greater than 100 Bq/m(3), which is above the level allowed by the World Health Organization (WHO). Since radon is the second leading cause of lung cancer, it seems necessary to increase the public's awareness of this issue and to take action to reduce radon in homes when the concentrations are above the WHO's guideline.

The radon levels obtained in most assessed offices in Obafemi Awolowo University in **Nigeria** were found to be within the permissible reference levels. It was recommended that mitigation measures should be put in place in the few offices above permissible levels (Afolabi 2015).

In places of high radon concentration 222Rn daughters adhere to clothes, skin and hair, adding some radiative concentration to that due to radon and its progeny (Martín Sánchez 2013).

A survey by Nursan (2014) concluded that there was a necessity to inform the public about significant environmental risks such as radon gas. Well-educated middle-aged parent of high school students seemed to be inadequately informed. Signorelli & Limina (2002) said that due to the populations' low risk perception (caused by unawareness of the problem) radon is undoubtedly the environmental pollutant which has the most impact on public health. In Italy 4,000 cases of lung cancer are attributable to radon (about 11% of total lung cancer) have been estimated per year.

A survey of 40 homes, 31 elementary schools and 5 kindergartens in **Macedonia** (Stojanovska 2016) found measured values varied from 22 to 990 Bq/m$^3$ for indoor radon concentrations. It seems that the variation in level of radon exposure suggests that it would be worth measuring field levels and taking remedial action where necessary.

**Serbia**n radon levels depended on the geological background, with elevated levels in areas with vulcanite and granitoid rocks (Bossew 2013). A study by Zunić (2014) confirmed the strong influence of geological factors in the **Balkan** region on the variability of indoor radon, and large differences of radon concentrations could be found in different rooms of the same house and significant difference in radon concentrations in one season. Extensive measurements of radon in the town of Xanthi in northern **Greece** show that the part of the town overlying granite deposits and the outcrop of a uranium ore has exceptionally high indoor radon levels, with monthly means up to 1500 Bq m$^{-3}$. 40% of the properties in this part of the town exhibit radon levels above 200 Bq m$^{-3}$ while 11% of the houses had radon levels above 400 Bq m$^{-3}$ (Kourtidis 2015).

The European Council directive of 5 December 2013 on basic safety standards for protection against the dangers arising from exposure to ionising radiation (2013/59/Euratom) tightened up the radon levels allowed in the workplace and exposures in homes are regulated for the first time (Bochicchio 2014). Barros (2015) concluded that *"Because of the percentage of workplaces with elevated radon concentrations, additional surveys of workplace radon concentrations are needed, especially in areas of high radon potential, to assess the contribution of workplace radon exposure to an individual's overall radon exposure."*

## Building materials

The most dominant source of indoor radon is the underlying soil, so the enhanced levels of radon are usually expected in mountain regions and geology units with high radium and uranium content in surface soils (Forkapic 2017). One of the most important indoor pollutants is radon from soils and building materials (Schram-Bijkerk 2013, Kumar 2013, Borgoni 2014, Singh 2016). In a study in Romania, the main source of radon was the building sub-soil and the soil near the house (Cosma 2015). Indoor radon levels are lower in flats than houses, and in buildings with concrete foundations (Kropat 2013).

Radon levels were investigated in homes in **Turkey** where construction materials had included many different sorts of building materials. The levels were between 23 and 1141 Bq m$^{-3}$ (Aykamis 2013, Kayakökü 2016). Carbonate rock tends to produce higher levels of indoor radon, whereas sedimentary rocks can produce only low levels (Kropat 2013). The Iranian study by Pirsaheb concluded that granite stone and adobe coverings could not be recommended for construction purposes.

Pirsaheb (2016) reported that internal building materials and ventilation type affect indoor radon and thoron concentrations. The use of proper materials and adequate ventilation can reduce the potential human exposure to radon and thoron. This is of utmost importance, particularly in buildings with a high density of residents, including hospitals.

Many people are using ornamental rocks as garden features. The radionuclide concentrations in 180 rock samples reached a wide range of values: $^{222}$Rn concentrations and inhalation and external doses were estimated to range from 0.1 to 13 Bq m$^{-3}$, from 0.01 and 0.26 mSv yr$^{-1}$ and from 0.01 and 0.61 mSv yr$^{-1}$, respectively (do Carmo Leal & da Costa Lauria 2016). The authors of the study highlight the necessity of considering the properties and use of the materials.

## The effect of changes in building construction techniques

It can accumulate in residential buildings. Breathing radon and radon progeny for extended periods can be hazardous to health and can lead to lung cancer. Air change rate, indoor temperature and moisture have significant effects on indoor radon concentration. Minimum radon levels were obtained at temperatures between 20 and 22°C and a relative humidity of 50-60% (Akbari 2013). Kropat (2013) found higher levels of radon at higher temperatures.

Modern energy-efficient architectural solutions and building construction technologies in combination with effective insulation reduce the air permeability of the building. As a result, the air exchange rate is significantly reduced and conditions for increased radon accumulation in indoor air are created. A study by Mohery (2013), short-lived radon decay products were measured in poorly ventilated living rooms. The maximum radon deposition fractions were found in the upper bronchial airway. In Russia, Yarmoshenko (2014), found a remarkable increase in the indoor radon concentration level in energy-efficient multi-storey buildings compared with older properties. Zhukovsky & Vasilyev (2014) also found radon concentration over 200 Bq $m^{-3}$ when ventilation rates were low. Vasilyev & Yarmoshenko (2017) found that in comparison with 2000, as a result of energy-efficient measures in building construction, average radon concentration is likely to increase by a factor of 1.42 by 2030, the percentage above the reference level of 300 Bq/$m^3$ may increase by a factor of 4.

Radon levels were higher in the basement of houses undergoing 'weatherization' (Francisco 2017).

Radon levels in homes of people with lower socio-economic status are, on average, only about two thirds of those of the more affluent. The reasons for this is not known with certainty, but may be connected with greater underpressure in warmer and better-sealed homes (Kendall 2016).

Jiránek & Kaćmařikova (2014) found that replacing existing windows by new ones decreased the annual energy need for heating 2.8 times, but also reduced the ventilation rate. As a consequence, the 1 year average indoor radon concentration values increased 3.4 times. The additional risk of lung cancer in the thermally retrofitted house increased to a value that is 125 % higher than before conversion.

Houses in Brittany that had undergone a thermal retrofit had a higher average radon concentration than those that had not, which may have been due to a decrease in air permeability of the building envelope following rehabilitation work that did not systematically include proper management of the ventilation (Collignan 2016).

## Occupational exposures

Radon activity was measured in 34 workplaces in Algiers nuclear research centre between March 2007 and June 2013. The indoor radon levels ranged from 2 to 628 Bq $m^{-3}$ (Ait Ziane 2014). With no intervention on occupational radon exposure, estimated lung cancer mortality by age 90 was 16%. Lung cancer mortality was reduced for all interventions (Edwards 2014).

Duan (2015) found a dose-response association between occupational environmental radon exposure and the risk of lung cancer. The increased risk is particularly apparent when the cumulative exposure to radon is beyond that resulting from exposure to the recommended limit concentration for a prolonged period of time.

Workers in the granite industry in Spain were exposed to an annual mean value of radon concentration in the indoor air of 33 Bq $m^{-3}$. However, during granite processing works the radon concentration could increase up to 216 Bq $m^{-3}$, due to mechanical operations (sawing, polishing, sanding,etc). This radon concentration was below the 600 Bq $m^{-3}$ reference level for action in working places (Tejado 2016).

In a study by Rossetti & Esposito (2015), as a result of 8695 measurements in underground workplaces, it was found that the mean radon concentration is higher than that from previous maps elaborated for dwellings and a significant radon concentration was also found in regions traditionally considered as low-risk areas. Elevated levels of radon in public workplaces in Brisbane, Australia were largely found in basements and ground floor levels and in rooms with concrete flooring (Alharbi & Akber 2015).

In Castañar cave, in Spain, cave guides received a total effective dose of 6.41 mSv in 4 months. Public visitors would receive about 12% of the total effective dose permitted at each visit in autumn and about 8-9% in summer (Alvarez-Gallego 2015).

In Polish caves which are open to tourists, as well as providing jobs, it was found that in 67% of the routes the average concentration of radon exceeded 300 Bq $m^{-3}$ and in 22 underground routes it exceeded 1000 Bq $m^{-3}$ (Olszewski 2015). This may be an organizational, legal and health problem. It is necessary to develop a program of measures to reduce radon concentrations in underground routes, especially routes located in the former mines. In Romanian caves, the highest values were recorded in show caves, ranging from 1.15 to 6.15 mSv/year, well above the European recommended limit, thus posing a potential health hazard upon cave guides, cavers, and scientists (Cucoş Dinu 2017).

Radon exposure was determined in the Saqqara region in Cairo (El-Kameesy 2016), in tombs and pyramids. Solutions were proposed to protect the health of those who work inside the tombs for long periods of time.

The radon exhaled from radioactive mineral collections exhibited in five Polish geological museums may influence its total indoor concentration. Radon concentrations measured in the exhibition halls do not pose a risk for visitors or museum staff. However, air exceeding the ICRP (2007) action limit for workers (equal to 300Bq/$m^3$) was noted in the storage rooms of two museums. Significant radon activity concentrations were measured inside lead containers where radioactive minerals were stored (Dlugosz-Lisiecka 2017).

A Chinese study of 3 different kinds of mines were monitored throughout a year (D Fan 2016). The results showed that the individual exposure to radon significantly varied with types of mines and work. Compared with the exposure to coal miners, the exposure to copper miners was much higher. The results indicate that the individual monitoring of radon is necessary for an accurate assessment of radon exposure to miners. An increased risk of lung cancer and a dose-response relationship was observed with cumulative radon exposure in uranium miners (Navaranjan 2016).

Eleven cohorts of miners occupationally exposed to relatively high concentrations of radon showed a statistically significantly high risk of lung cancer, in a Korean study by Oh (2016). The authors recommended that preventive policies are needed in order to actively reduce radon exposure and lung cancer incidence in non smokers.

Radon activity concentrations (in water and in air) were measured at 13 selected locations at the Avalon Springs thermal spa resort in Montagu (Western Cape, South Africa) to estimate the associated effective dose received by employees and visitors (Botha 2016). The most significant potential radiation exposure identified is that due to inhalation of air rich in radon and its progeny by the resort employees.

### Ground disturbances (earthquakes, etc.)

Tectonic movement and meteorological events are accompanied by radon release. Not only magnitude of earthquakes but also distance from the measurement site should be used for identifying radon anomalies (Içhedef 2014, Briestensky 2014, Zhou 2015). Residents in Fukushima were concerned about radon exposure as well as other sources of radiation following the Nuclear accident at Fukushima in 2011 (Tamari 2016).

The results of indoor radon measurements in dwellings of two villages lying on the fault zone of Malá Magura in the Horná Nitra region of Central Slovakia showed values that were lower than those commonly observed on the Slovak territory, ruling out any negative health impact on population (Mojzeš 2017).

Areas of high radon activity were located near areas of high flow accumulation showing new submarine groundwater discharge (Rapaglia 2015).

Geologic unit, well water, community, weather, and unconventional natural gas development were associated with indoor radon concentrations (Casey 2015).

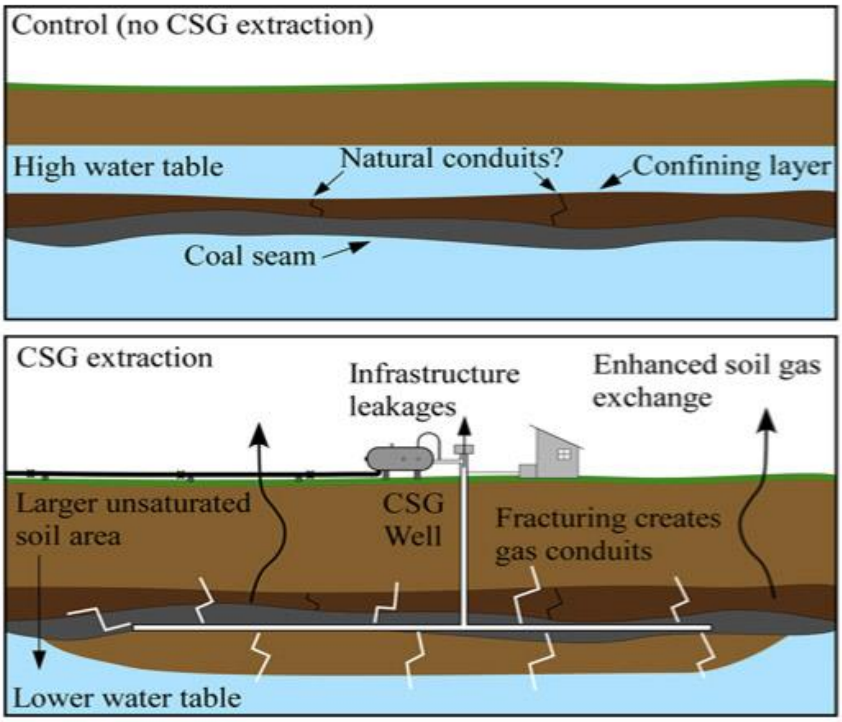
Large local radon anomalies may be an indicator of a clandestine underground nuclear explosion (Carrigan 2016).

### Fracking

Domestic gas supplied by the controversial process of fracking will increase levels of radioactive radon in people's homes, public health experts have warned. A risk assessment by Public Health England (PHE) shows that shale gas would result in individual exposures to radon that are 15 times higher than through existing supplies of natural gas.

A US health study has found that the hydraulic fracking of unconventional rock formations can liberate and accelerate the release of radon, a highly carcinogenic gas (Casey 2015). US homes in Pennsylvania have been on the rise ever since fracking of the Marcellus shale began in 2004. Buildings in areas of the most active shale gas mining had significantly higher readings of radon compared to buildings located in areas of low well density and fracking activity. Averaged over the whole study period, houses and other buildings using well water had a 21 percent higher concentration of radon than those using municipal water. Houses and buildings located in rural and suburban townships, where most of the gas wells are, had a 39 percent higher concentration of radon than those in cities. In the past decade buildings have been more tightly sealed, potentially trapping radon that gets inside and leading to increased indoor radon levels.

The US findings collaborate and strengthen earlier studies by Australian researchers at Southern Cross University as well as recent shale gas research in Colorado. In 2013 Tait reported that the radon air levels above the heavily fracked Surat Basin in Queensland, Australia were three times greater than those observed in a non-fracking region. (A separate and earlier study also showed that methane and carbon dioxide levels in the air were three times higher in the mined landscape.) See model below.




Shallow fracking of coal seams radically changed "the geological structure" of the ground by cracking rock, removing water and lowering pressure in the formation. The fracturing of the ground structure simply created more pathways for radon and other gases to leak up through the soil.

The mechanism for releasing radon into the atmosphere in fracked landscapes may be similar to that caused by earthquakes, added the researchers. Atmospheric levels of radon will typically increase fivefold prior to an earthquake due to stress changes in rock which, in turn, opens new fractures and pathways to the surface.

In 2012 Health Canada found that more than seven per cent of the homes measured in Calgary, Peace River, David Thompson and Aspen regional health districts had dangerous levels of radon (200 becquerels per cubic metre). High levels of radon have also been found in northeast B.C. That geographic region has also witnessed intense shale gas activity over the last decade.

## Weather and seasonal changes

Long-term measurements of radon levels in the soil shows a high variability in concentration depending on the daily changes in atmospheric pressure. It was also found that typical annual radon activity concentration in the soil air was disturbed by mild winter and heavy summer precipitation (Műllerova 2014). Vasilyev & Zhukovsky (2013) confirmed the seasonal variations of radon concentrations. In a study by Moreno (2016) it was found that radon measurements presented a wide range of values. The highest soil radon levels in the vicinity of the Amer fault were found close to the fractured areas and showed very important fluctuations repeated every year, with values in summer much higher than in winter. Indoor radon measurements were taken during and after Superstorm Sandy on the US East Coast, and from the normal level of 70 Bq $m^{-3}$ it increased up to 1500 Bq $m^{-3}$ during the storm. The outdoor radon concentration was not significantly affected (Kotrappa 2013).

The season of radon variation seems to be different in different countries, possibly due to the nature of the soil. The measured soil gas radon activity concentration around fault lines near the

North Anatolian Fault Zone in Turkey shows seasonal variation in a highly permeable sandy-gravelly soil with definite seasons without obvious long transitional periods. The summer is characterised by 1.8 times higher average soil gas radon activity concentration than the winter (Yakut 2017). In a study by Kikaj (2016) of radon levels in **Kosovo**, the results showed seasonal variations of the measured soil gas radon concentrations with maximum concentration in the spring months.

Indoor radon in houses in Slovakia, Hungary & Poland shows the typical radon behaviour, with a minimum in the summer and a maximum in the winter season, whereas in 32% of schools the maximum indoor radon was reached in the summer months (Műllerová 2016). This could possibly be due to ventilation?

The following conclusions were drawn as a result of a study on vegetable growing circumstances by Li (2016): Firstly, the average radon levels in typical months in Shouguang county are all much higher than that in ordinary dwellings in China, diurnal and seasonal variations in radon levels are observed inside greenhouses. Secondly, temperature and relative humidity may play a role indirectly through affecting soil moisture and other factors.

### Water supplies

A **Turkish** study showed that some spa waters contained radon at higher levels than our action levels. If people bathe indoors in such spa waters the levels of radon they inhale could add significantly to their exposure (Oner 2013, Akkaya 2016). Radon-contaminated drinking water from private wells in the **USA** was felt to present a significant public health concern (Cappello 2013). Significantly high levels of radon gas were found in **Iran**ian water (Pirsaheb 2013). Yang reported (2014) that wells within 5 km of granitic intrusions are at risk of containing high levels of radon.

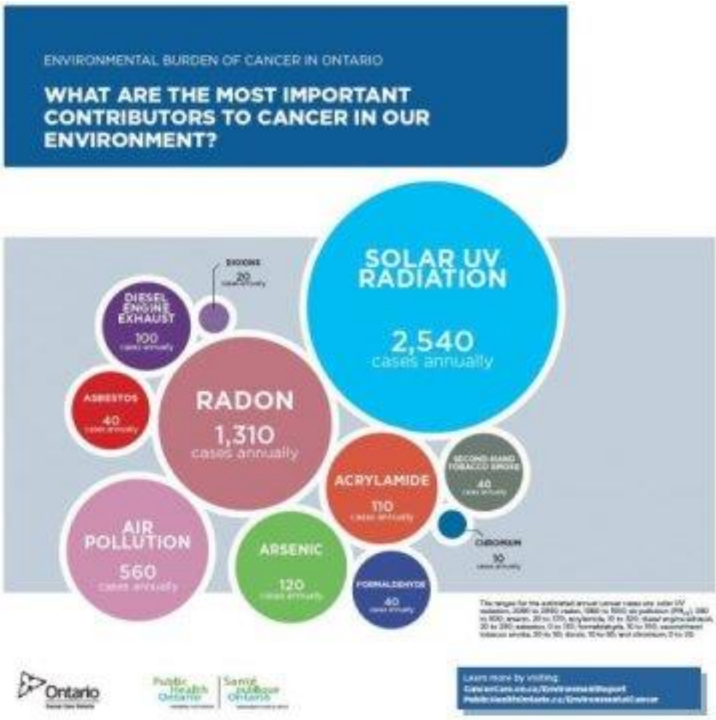
At least 10% of people living in the **Czech Republic** are supplied with water from private sources (wells and boreholes). The official guideline limit does not apply to private sources of drinking water. Radon in water influences human health by ingestion and also by inhalation when radon is released from water during showering and cooking (Otahal 2014, Moldovan 2014).

Groundwater radon is associated with increased risk for lung and stomach cancer (Messier & Serre 2017) in North Carolina, USA.

Inhalation of escaping radon from groundwater comprises the largest part of radiological hazard from groundwater. Groundwater containing 3 kBq dm radon activity concentration supplied an ordinary bathroom of 15 m in a home. Using the showerhead, atmospheric levels of radon activity in the bathroom exceeded 100 kBq m within a period of about 1 h (Søstrand 2016).

### Health Effects

Between 3,540 and 6,510 new cancer cases in Ontario each year result from environmental factors, says a report in August 2016 from Cancer Care Ontario and Public Health Ontario (PHO). Dr Ray Copes, chief of environmental and occupational health for PHO says "Interestingly, three main carcinogens stand out as being particularly important -- ultraviolet (UV) radiation from the sun, radon gas, and fine particle (PM2.5) air pollution." The report finds that 1,080 to 1,550 new cancer cases are associated with radon exposure. See http://www.publichealthontario.ca/en/eRepository/Environmental_Burden_of_Cancer_in_Ontario_2016.pdf




Radon and its progeny have been confirmed as being a category I carcinogenic agent. Data from a study by Liu (2016) demonstrated that p53-associated metabolic pathways may be altered in radon-mediated malignant transformation.

Radon changed a total of 208 genes in lung cells, 32% upregulated and 68% downregulated and depended on the dose. Further analysis showed them to be involved in biological processes related to cell cycle control/mitosis, chromosome instability and cell differentiation (Chauhan & Howland 2014).

Residential radon might increase the risk of hospital admissions in patients with chronic obstructive pulmonary disease (COPD) with women at a higher risk than men (Barbosa-Lorenzo 2017).

Chen (2013) found that among those people living in homes with very high radon concentrations, it is typically parents of young children that demonstrate a great deal of concern. They want to know the risk of developing lung cancer when a child has lived in a home with high radon for a few years. The results of the study demonstrated clearly that the higher the radon concentration, the sooner remedial measures should be undertaken. There is a critical need to raise parental awareness about child health related to home exposure to radon and secondhand smoke (Huntington-Moskos 2016). Public health nurses can create promote home testing for radon and low-cost resources to reduce risk.

A study by Larionov (2016) suggested that particular types of DNA damage found in children with long-term exposure to radon could be linked to a sensitivity to radiation.

The highest rogue cell (RC) frequency was present in children environmentally exposed to radon. In 85% of RCs, double minutes, observed in a large number of human tumours, were present (Druzhinin 2016).

Exposure to radon is the second leading cause of lung cancer, especially for women in developed countries (Serke 2013), and the risk is significantly higher for smokers than for nonsmokers. Bräuner (2012) found a positive association between radon and lung cancer risk. Lung cancer in those who have never smoked accounts for between 9 and 28% of all lung cancer cases (Hubaux

2012, Truta 2014). Exposure to radon can lead to genetic and epigenetic alterations in tumour genomes, impacting genes and pathways involved in lung cancer development.

A study by Bräuner (2013) found significant associations and exposure-response patterns between long-term residential radon exposure in a general population and risk of primary brain tumours. Another study (Bräuner 2015) found that long-term residential radon exposure may contribute to development of basal cell carcinoma of the skin, though radon levels were calculated rather than measured and more follow-up is recommended.

In Spain, 14% of Galician municipalities had radon concentrations above the United States Environmental Protection Agency (USEPA) action level. There was a significant correlation between residential radon and oesophageal cancer mortality for males (Ruano-Ravina 2014).

Professor Denis Henshaw suggests 5% of childhood leukaemia is linked to radon, which diffuses into open air and a house can trap radon gas.

Bräuner (2010) suggested that air pollution from traffic might enhance the effect of radon on the risk of childhood leukaemia, and Pedersen (2014) suggested that distance to powerlines together with domestic radon levels may impact the risk of childhood leukaemia. Schwartz & Klug (2015) found that incidence rates for chronic lymphocytic leukaemia (CLL) were significantly correlated with residential radon levels. Laurent (2013) concluded that there could be a link between radon, ioising radiation and leukaemia in French children, though further research was needed due to some uncertainty about the level of risk. A large, prospective study suggest residential radon may be a risk factor for lymphoid malignancies among women but not men (Teras 2016).

A large proportion of radon-attributable lung cancer deaths in Ontario are from exposures below the Canadian guideline. Peterson (2013) felt that testing and remediation may prevent a portion of radon-related lung cancer deaths.

In the first study of residential radon and birth defects, Langlois (2016) found significant associations with cleft lip with or without cleft palate and cystic hygroma / lymphangioma. They also found non-significant associations with three skeletal defects, Down syndrome, other specified anomalies of the brain, and other specified anomalies of the bladder and urethra.

A high percentage of the houses included in a study of Lucrécia city in Brazil had indoor radon concentrations over 100 Bq $m^{-3}$. The mean annual effective dose from Lucrécia houses was six times higher than observed in a control region. The levels of exposure in most of the Lucrécia houses were classified as middle to high. The residents of the city suffer from a high cancer rate (Marcon 2017).

## Remediation

Lantz (2013) strongly supports public communication efforts that promote residential radon testing and remediation. A questionnaire study of 23 European countries found that approximately 26,000 homes have been remediated, but millions have not yet been done. The number is increasing due to the rare use of radon prevention.

Radon concentrations in dwellings above 200 Bq $m^{-3}$ are very rare in the Netherlands (Smetsers 2016). As a result, relatively simple and inexpensive measures in existing Dutch single-family dwellings will be sufficient to reduce indoor radon concentrations above the proposed national reference level of 100 Bq $m^{-3}$ to values well below.

A study by the Health Protection Agency (Howarth 2013) determined the long term effectiveness of commonly used radon remedial methods over 15 years. The overall failure rate was 63%, with roughly equal rates for passive and active type systems. It was also found that all types of remedial measure can last more than 10 years, but also found examples for all measures that failed in less than 5 years. The HPA advises that homes should be retested every 5-10 years.

## Radon levels in the home, school and workplace

In **Albania**, where an initial 10% of homes were measured, the indoor radon concentrations ranged from 14 to 1238 Bq $m^{-3}$ (Tushe 2015).

In British Columbia, **Canada**, some homes which lie outside of the radon-prone areas have radon levels above the Canadian guideline, which is the reason Health Canada recommends that all homes should be tested (Cheng 2016).

**Hungary**, **Poland** and **Slovakia** have higher radon levels than the world average. Radon concentrations are more than 200 Bq $m^{-3}$ in about 87% of cases. Homes with radon concentration of about 800 Bq $m^{-3}$ were found in Poland and Slovakia (Műllerova 2014). In **Turkey**, indoor radon concentrations were found between 1 and 1400 Bq $m^{-3}$ (Celebi 2015).

Radon was measured in three nurseries and a primary school in a rural area with nongranite soil in north **Portugal.** Radon concentrations surpassed by severalfold the recommended guidelines and thresholds, and excessive levels of health concern were sporadically found (Sousa 2015). Radon concentrations were measured in 45 classrooms from 13 public primary schools located in Porto, **Portugal**. In all schools, radon concentrations ranged from 56 to 889 Bq $m^{-3}$. The results showed that the limit of 100 Bq $m^{-3}$ established by WHO IAQ guidelines was exceeded in 92 % of the measurements, as well as 8 % of the measurements exceeded the limit of 400 Bq $m^{-3}$ established by the national legislation (Madureira 2015). The geometric mean of radon activity of 91 dwellings located at the Vila Pouca de Aguiar pluton in northern **Portugal** is 568Bq$m^{-3}$, exceeding that of other northern Portuguese granites (Martins 2016). Measurements carried out during a winter season, indicate that 62.6% of the analysed dwellings yield higher indoor radon average values than the Portuguese legislation limit of 400Bq$m^{-3}$.

In some towns in central and South Serbia, 26.7% of dwellings had radon concentration higher than 100 Bq $m^{-3}$ (Vuckovic 2016).

Kitto (2014) measured radon levels in 186 schools in New York State. Some rooms in the schools had more than 740 Bq $m^{-3}$. Short-term radon measurements in the schools showed little correlation to basement and first-floor radon results from single-family homes in the towns.