Radon

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Radon is a radioactive gas that emanates from uranium-bearing soil and porous rock. Although radon is most highly concentrated in areas of high uranium concentration, the presence of trace amounts of uranium in most ground sources means that all humans are exposed to radon to some degree. Radon migrates out of soil and rock into the surrounding air, resulting in accumulation in poorly ventilated or closed areas. Such areas represent the primary environments in which humans are exposed to radioactivity from radon to experience detrimental health effects.

There is no convincing evidence that any cancers other than lung cancer are associated with exposure to radon. There is, on the other hand, consistent evidence of a substantially elevated risk of lung cancer among Canadians exposed to radon in certain occupational settings, particularly uranium mining. While the combined evidence for a positive association between residential radon exposure and lung cancer is less compelling, the inherent methodological difficulties in mounting such studies may render it impossible for any single study to detect the relationship more conclusively. The best available evidence to date from pooled analyses indicates a positive, but weak association between residential radon and lung cancer risk.

Residential radon is of critical importance because it is ubiquitous; a small excess risk that may exist in relation to radon exposures encountered in a residential setting translates into the potential for a far greater number of excess cancers in the general population than does exposure of a relatively small number of miners, even though the latter may be exposed to much higher levels of ionizing radiation. Fortunately, a number of techniques are available to homeowners to reduce radon concentrations in their homes.

Introduction

Radon-222 is a radioactive gas that is a daughter product in the radioactive decay sequence of uranium-238 and its daughter product radium-226. It is the gaseous nature of radon that makes it of particular interest to epidemiologists. Although radon is most concentrated in the atmosphere above ground with high uranium concentration, the presence of trace amounts of uranium in ground sources means that all humans are exposed to radon, to some degree, due to its emanation from uranium-bearing substrate. This property allows it to migrate out of soil and porous or broken rock, into the surrounding air, resulting in accumulation in poorly ventilated or closed areas. Such areas represent the primary environments in which humans are exposed to sufficient levels of radioactivity from radon (alpha particles) to experience detrimental health effects.

The adverse health effects associated with exposure to radon were recognized even before the discovery of the radioactive properties of radium by Becquerel and Curie in the late 1890s. Schüttmann[1] gives an excellent historical account of the identification of "Schneeberg lung disease" in the mines of the Saxony area of Germany as early as the 16th century. This "miners' disease" was described as a progressive illness, with symptoms of increasing cough, expectoration and shortness of breath. It resulted in the early deaths of a large proportion of miners who had worked in the mines of the Saxony area. Schneeberg lung disease later came to be recognized as a form of lung cancer and, over time, evidence mounted that it was associated with mines where pitchblende (uranium-bearing waste) was extracted. It was later discovered that mines in the Saxony area were associated with levels of radon among the highest in the world, and that this factor seemed to be more strongly associated with the development of Schneeberg lung disease than with other potential exposures such as silica. Schneeberg lung disease, which had already come to be known as lung cancer, was first listed as an occupational disease in 1925.[1] This led to the first organized attempts to protect miners from the deleterious effects of radon through use of ventilation in the mines to reduce the concentration of radon in the mine air.

Most of the adverse health effects identified as associated with exposure to radon relate to development of malignant disease (though cardiovascular disease has been studied in recent years as well). In the sections that follow, we describe the biological basis for the mechanisms by which radiation, and radon in particular, are thought to cause cancer, the epidemiological evidence for the association between cancer and radon, and potential health implications in Canada.

The biological basis for radon-induced malignancy in humans

Radiobiology of cancer

The potential for radiation to induce malignant transformation in mammalian cells has been extensively studied and some of the biological mechanisms have been elucidated.[2] When radioactive materials decay, photons (gamma rays), high speed electrons (beta rays) or nuclear fragments (charged particles or neutrons) are ejected from the radioactive atoms. These ejected particles can then interact with other materials, including mammalian cells, with which they may come in close proximity. For biological damage resulting in malignant potential to occur, the ejected particles must pass into a cell and deposit some or all of their energy within the cell. The relationship between the amount of energy deposited and the track length over which it is deposited is known as the linear energy transfer (LET).[3] Generally speaking, high LET radiation is more effective at inducing cell damage than low LET radiation.

The types of radiation emitted from radioactive materials such as radon are referred

to as ionizing radiation. The term "ionizing" refers to the mechanism by which the radiation interacts with matter through which it passes. Whether passing through air or water or solid material, ionizing radiation interacts with matter at an atomic level through deposition of energy and the resulting ejection of electrons from the atoms. This leaves the atom ionized and changes its chemical properties. This in turn can result in breakage of chemical bonds between atoms. Ionizing radiation can also result in changes to the nucleus of atoms in which it is deposited.

Mammalian cells are mostly water, which means that in tissues, the energy deposition is mainly in water. In this medium, ionizing radiation can cause formation of negatively charged hydroxyl radicals (OH-) through fragmentation of water molecules. Because of the instability of these "free radicals", they have a high propensity to bind with other molecules, changing the chemical properties of these molecules.[3]

From the standpoint of malignant transformation of cells, the most important molecules within the cell that can be affected by ionizing radiation are the double-helix DNA (deoxyribonucleic acid) molecules. These can be damaged by either direct or indirect processes. Direct damage involves breakage of chemical bonds between base pairs by the ionizing radiation itself. Indirect damage entails alteration of base pair chemistry and resulting loss of chemical bonds between base pairs through interaction with hydroxyl radicals created by the ionizing radiation.

Damage to DNA strands can result in a number of outcomes: the breaks may be repaired by the normal repair mechanisms of the cell, resulting in a normal DNA molecule; there may be loss of a base, resulting in permanent change in the DNA; there may be a break in the strand on one side of the double-helix molecule, or there may be breaks in both strands. Any of the latter three may result in mutations that can give rise to malignant potential.[2]

Malignant potential is only significant if the cell divides, the offspring cells survive the cell division, and the mutation which confers the malignant potential is passed on to one of the offspring. Furthermore, the cells which result will only give rise to malignancy if the mutation is of a type that changes the cell in some way or ways that lead to an altered phenotype capable of tumour formation. Typical changes, among others, that lead to such phenotypes include activation or deregulation of oncogenes and loss of tumour suppressor genes.[4]

Biological effects of radon related to cancer

Radon decays into Polonium-218 through emission of an alpha particle. Polonium-218 itself emits an alpha particle as it decays. Another radon daughter, Polonium-214 also emits an alpha particle in decaying to Lead-210. Both Polonium isotopes have very short half-lives and both, unlike radon itself, are solid rather than gaseous elements. It is believed that these solid elements, in aerosolized form, or, in their charged state, attached to other particulate matter, result in most of the biological damage attributed to exposure to radon.[5] Damage results when these radioactive elements come into close proximity to lung tissue, particularly in the larger airways of the lung, where they have a propensity to settle out. This is supported by evidence that miners exposed to moderate to high levels of radon have a higher ratio of central to peripheral lung tumours than non-miner smokers, whose carcinogen (tobacco smoke) tends to settle out in more peripheral airways.[6]

There is evidence of radon-associated mutations in both tumour suppressor genes and oncogenes. Taylor et al.[7] described a series of lung cancer samples from 52 uranium miners of the Colorado plateau, which showed mutations in the p53 tumour suppressor gene in 55 to 73% of lung cancers, depending on histological subtype. Of particular interest was that 16 of 29 mutation-positive cancers had the same transversion mutation, potentially indicating that this was a specific hotspot for p53 mutation induced by radon exposure. Vähäkangas et al.[8] failed to find this same mutation, but did report that other types of mutation in the p53 tumour suppressor gene occurred in 37% of tumour samples in their series. Furthermore, there was another difference between the types of mutations in their series and those series reporting non-radon related lung tumour mutations: namely, that 22% of the mutations were deletion mutations, whereas other series had rarely reported this type of mutation in lung tumours. Subsequent series[9,10] failed to confirm the findings of Taylor et al. with respect to a specific hotspot for p53 mutation caused by radon, but these studies involved individuals for whom the exposures to radon were lower than those in the Taylor series. A further analysis of lung adenocarcinoma specimens from the Colorado plateau miners by McDonald et al. did not find a specific p53 hotspot.[11]

Both Vähäkangas et al.[8] and McDonald et al.[11] also examined rates and types of mutation in the K-ras oncogene commonly found in lung tumours. Whereas Vähäkangas reported finding zero out of 19 tumours containing K-ras mutations, McDonald reported 9 out of 23 (37%) containing such mutations. However, McDonald et al. concluded that the rate and pattern of K-ras mutations in their series of adenocarcinomas in the Colorado plateau miners was similar to the rate found in smoking-induced adenocarcinomas.

Thus, although the molecular biology evidence for mutation-induced malignant transformation is consistent with mechanisms postulated above, the published literature is not clear on this issue.

The inverse-dose-rate effect

Another important consideration regarding the biological mechanisms by which exposure to radon results in carcinogenesis, relates to a phenomenon known as the inverse-dose-rate effect. This concept has as its central tenet that the same dose of radiation will be more effective in causing cancer if it is delivered over an extended period of time rather than as an acute dose. Thus, for a given dose of radiation, a lower dose rate is more effective in causing cancer. The biological rationale for this is that cells are more susceptible to genetic damage during specific parts of their cell cycle.[12,13] When exposed to an acute dose of radiation, only a small proportion of cells will be at a point in their cycle where they are susceptible to genetic damage. When a more protracted dose is delivered, a higher

percentage of the cells have the potential to be affected during a sensitive part of their cell cycle. This results in a higher chance of malignant transformation. However, a dose rate effect is only plausible when the total dose is sufficiently high that multiple traversals of individual cell nuclei are likely. In other words, a cell which experiences only a single "hit" by an alpha particle cannot express a dose rate effect.[12] There is evidence in support of this effect in the literature dealing with miners exposed to radon.[14-16]

This theory has a direct bearing on the interpretation of studies that involve very low dose rate and total dose from radon. In such exposures (as may be experienced in the residential setting), the exposure may be so low that the inverse-dose-rate effect disappears. This is important in understanding the epidemiological literature which has, more than occasionally, attempted to infer the risk associated with very low exposure to radon, as may occur in residences, from the data corresponding to much higher exposure rates and levels associated with uranium mining. Inferences of risk associated with one set of exposure conditions may be associated with large errors when applied to other exposure conditions. If the inverse-dose-rate effect is real at low doses, then simply extrapolating doses at levels typically found in association with occupational risk will result in an underestimate of true risk of residential exposure, whereas the reverse happens if the inverse-dose-rate effect is not real at dose levels found in residences.[13]

The linear no-threshold theory

Based on the empirical evidence and biological considerations, the Biological Effects of Ionizing Radiation (BEIR) Committee, in their fourth report (BEIR IV), proposed a model for relative risk of lung cancer mortality associated with radon exposure.[17] The model was based on earlier work, some of which related to chemical carcinogenesis.[18] This model implies that relative risk is linearly related to radon exposure in Working Level Months (WLM). A WL is any combination of radon progeny in one litre of air that results in the average emission of 1.3 x 10^5 MeV of alpha energy. A WLM is the product of a WL and time (M) in working months (170 working hours).[5] The model postulates that there is no threshold below which the risk of lung cancer associated with exposure to radon is zero. This model generated a great deal of controversy in the literature, most of which relates to data from some of the ecological studies of cancer risk from radon exposure that are discussed below. The discussion about the merits of this model has been ongoing since the BEIR Committee adopted it.[19-29]

In a later report (BEIR VI),[30] the BEIR Committee used cellular and molecular evidence, in conjunction with epidemiological evidence, to update the specification of its model. The result was an Excess Relative Risk (ERR) model of a linear relationship between ERR and past exposure to radon. Consistent with the available data, the model also contains a parameter to explain the decrease in ERR with increasing age. Most recent studies of radon and risk of lung cancer have assumed or are consistent with this model. The most recent report (BEIR VII) supports the application of the linear no-threshold concept at low doses.[31]

Epidemiological evidence for the association between radon and malignant lung disease

Miner studies: Canada

The evidence for a relationship between occupational radon exposure and risks to health come from studies of a number of miner cohorts in a variety of countries. As mentioned above, the first evidence for a detrimental health effect of radon came from the Saxony area of Germany where miners were exposed to radon in pitchblende. More recently, health effects of exposure to radon have been studied in miners in Canada, the United States, France, Sweden, Finland, Czechoslovakia, Italy and China. Although exposures are highest in cohorts exposed in uranium mines, miners in certain non-uranium mines have also had moderate to high exposures.

In Canada, one of the earliest studies was conducted by Muller et al.[32] using data from the Mining Master File held by the Ontario Ministry of Labour. This study examined exposure and outcome data for Ontario miners who were classified as either uranium or non-uranium miners. The uranium miner cohort contained a total of 17,102 men who worked in the mines between 1955 and 1977. Unlike more recent studies that excluded subjects who had mined for less than one or two years, this study included miners who had worked for more than half a month. After exclusion of miners with known asbestos exposure or those who worked in uranium mines outside Ontario, the cohort consisted of 15,984 men. Exposures prior to 1968 were estimated using measures taken in each of the mines in individual calendar years and time spent in the mines on a calendar year basis for individual miners. Subsequent to 1968, personal exposure data were available for individual miners.

Muller et al.[32] found a significantly elevated standardized mortality ratio (SMR) for carcinomas of the trachea, bronchus and lung of 1.81 (119 observed deaths, vs. 65.8 expected, $p < 0.01$). This elevated risk was demonstrated in both of the main subcohorts of miners based on location of mining activity (Bancroft mines: SMR 2.41; Elliot Lake mines: SMR 1.62). No increases in other types of malignancies were seen in this cohort. Among the non-neoplastic diseases, only silicosis and chronic interstitial pneumonia were associated with elevated SMRs, and only in the Elliot Lake mines (SMR 5.60).

Muller et al.[32] stated that the mean cumulative exposure in this cohort, to radon progeny, was 53.5 WLM. The somewhat lower mean cumulative exposure, compared to that found in many other studies, was because uranium mining was a relatively new industry in Ontario in 1955 (when individuals became eligible to be included in the cohort). Also, they state that most men entered the study in the early years of uranium mining and worked for short periods only (median 1.5 years).

Muller et al.[32] used the exposure data to quantify the ERR per additional WLM (ERR/WLM). This was calculated to be 0.015. Each additional WLM of exposure added 0.015 to the relative risk estimate. No attempt was made in this study to account for the effects of potential

confounders such as smoking history, exposure to arsenic, mineral fibres or silica. This is one important limitation of the study (in addition to relatively small sample size). However, the effects of exposure to mineral fibres were partially controlled for by eliminating miners with previous asbestos exposure from the cohort.

An updated study of this cohort[33] found a significantly elevated mortality from lung cancer in Ontario uranium miners (SMR 2.25, 95% Confidence Interval (CI): 1.91-2.64). Kusiak et al. reported the excess risk of dying from lung cancer in uranium miners was greatest in those exposed 5 to 14 years prior to diagnosis, and in men less than 55 years of age. This study also concluded that a part of the excess risk of lung cancer was due to exposure of some members of this cohort to arsenic while employed as gold miners previous to their employment as uranium miners. The ratio of small cell carcinomas to other histological types was also greater in the uranium miners than in the general population.

In 1996 Finkelstein[34] reported a study of lung cancer in Ontario uranium miners at the Elliot Lake mines. The study determined how risk of lung cancer due to radon exposure was modified by other factors, including smoking, silicosis, clinical symptoms, lung function and temporal pattern of radon exposure. Among 1,043 eligible uranium miners, 967 agreed to participate in the study and 733 had complete records. This included a respiratory health questionnaire, lung function tests and chest radiograph from 1974. These records contained information on smoking status as well as the other modifiers of risk under study. Data for individual miners were linked to the Ontario Mortality Database and the Ontario Cancer Registry up to the end of 1992. Both standardized incidence ratios (SIRs) and SMRs were calculated using the Ontario population as the standard. After controlling for confounders in Cox proportional hazards models, risk was found to be modified by older age at exposure, poorer lung function and exposure to radon in a time window 4 to 14 years before diagnosis. This study did not find smoking to be an effect modifier with respect to radon exposure.

Another attempt at determining the relative importance of silicosis as a modifier of the risk associated with exposure to radon in Ontario miners was published by Finkelstein in 1995.[35] This was a case-control study of the role of potential confounders of the link between lung cancer risk and silicosis. Miners with radiographic evidence of silicosis, identified through the Ontario Silicosis Surveillance Database, were matched by year of birth with three miners from the database who did not have evidence of silicosis. Miners with silicosis had a SIR for lung cancer of 2.55 (95% CI: 1.43-8.28). Smoking differences were considered unlikely to account for the difference in lung cancer risk. In a conditional logistic regression analysis, where radon and silicosis were added as variables, the effect of silicosis (Odds Ratio (OR) 6.99, 95% CI: 1.91-25) appeared to completely overwhelm the effect of radon as a risk factor (OR 1.00, 95% CI: 0.986-1.004). One limitation of this study was that the exposure of non-uranium miners was assumed to be the same as background and assigned a value of zero WLM, which may have introduced some differential misclassification.

A study of 7,057 gold miners in Ontario by Muller et al.[36,37] detected a significantly elevated risk of lung cancer in this cohort (SMR 1.40, $p = 6 \times 10^{-6}$) relative to similarly aged Ontario males. However, it was not possible to attribute this risk to radon exposure due to lack of data regarding radon exposure levels in the mines for the period of study. Other factors, such as arsenic exposure, may have played a role in the increased lung cancer mortality of these miners. Smoking may have also influenced the SMR as expected greater prevalence of smoking among miners than general population.

Subsequently, Kusiak et al.[38] reported that radon measurements made in Ontario gold mines after 1961 (most in the 1980s) showed levels of radon in inactive areas to average 0.3 WL or greater, while levels in active gold mines averaged 0.02 WL. Kusiak[38] estimated that the levels in the inactive mines would have been the upper limit of exposure for miners working in gold mines prior to 1945, while exposures after 1945 were estimated from measurements in the active work areas and the individual work histories of the miners. The study found a statistically significant elevated risk of dying from lung cancer in miners who started mining gold before 1945 and who never mined nickel. Poisson regression analysis found that both arsenic and radon had regression coefficients that were significantly different from zero, when analysed in the same model. The interaction term between radon and arsenic was not significantly different from zero. The authors concluded that the increased incidence of lung cancer in Ontario gold miners was due to the independent effects of arsenic and radon exposure.

Howe et al.[14] have reported results of a study of lung cancer mortality in uranium miners employed at the Beaverlodge uranium mine in Saskatchewan. This cohort was comprised of 8,487 miners who mined between 1948 and 1980. A statistically significant SMR of 1.90 was found, relative to the general population. They also found a significant dose-response trend and determined that the ERR/WLM was 0.0328. This represents one of the largest dose-response relationships published to date and was thought to be due to the relatively low exposures experienced by this group of miners, who mined primarily in an era when the mine was ventilated. A reanalysis of the exposures of cohort members by SENES Consultants[39] concluded that the original exposure estimates were underestimated by about 50% and that a significant number of miners had exposures other than at Beaverlodge that were not accounted for in the original estimates.

Further analysis of this cohort by L'Abbé et al.[40] was performed to determine the relative importance of other potential modifiers of the risk-exposure relationship, particularly cigarette smoking and non-Beaverlodge mining experience. In this study, next of kin were traced for 46 of 89 men who died of lung cancer after working in the Beaverlodge mine between 1949 and 1980. Data on smoking and other mining experience were collected and compared to interviews of next of kin for 95 male controls who worked at the Beaverlodge mine and died of other causes. The cases in this study included 24 who had worked at the Port Radium mine in the

Northwest Territories in addition to the Beaverlodge mine. Their conclusion, based on logistic regression modeling of the confounding effects of smoking and other mining experience, were that neither of these variables appeared to substantially confound the relationship between risk and exposure. L'Abbé et al.[40] further concluded that the relatively high risk coefficients found in the original study cannot be explained by confounding by these two variables. However, the study was very limited since it represented only a small fraction of the original Beaverlodge cohort (N = 125 compared to N = 12,000 for the entire cohort) and it employed the original rather than the revised exposure estimates.

Howe et al.[15] also reported results of studies involving a cohort of 2,103 uranium miners employed at the Eldorado Port Radium mine in Port Radium, Northwest Territories, Canada. These miners were employed at an earlier period than the Beaverlodge miners (1942-1960), during an era when the mine was not ventilated and they were therefore exposed to much higher levels of radon than the Beaverlodge miners. As with most other studies, this study found a highly significant relative risk (RR 3.37) associated with exposures greater than five WLMs. The risk of death was highest in the group of miners exposed five to nine years prior to diagnosis (RR 16.78) and declined in miners exposed for longer periods before diagnosis.

In contradistinction to the Beaverlodge cohort risk coefficient (0.0328), the ERR/WLM from Port Radium workers was 0.0027. The order of magnitude difference in these coefficients was explained by Howe et al.[15] on the basis of the inverse-dose-rate effect. The average annual exposure rates for the Beaverlodge and Port Radium cohorts were five WLM and 109 WLM respectively. At the lower exposure rate of the Beaverlodge mine, the inverse-dose-rate effect would predict that similar cumulative doses received in the Beaverlodge mine would be associated with higher excess risk (and therefore higher risk coefficients) than would be those in the Port Radium mine. However, the Beaverlodge ERR would be reduced under the revised dose estimates discussed above.

The data for the Port Radium cohort were also consistent with a decrease in risk coefficient as age at observation increased. Howe et al.[15] reported that those aged 70 or older showed no increase in risk over the general population, while no relationship was found between age at first exposure and risk.

Another group of miners who were exposed to high levels of radon in Canadian mines were the workers at the fluorspar mines of Newfoundland.[41] It was noted in the 1950s that these miners had a growing number of lung cancer deaths. Measures of radon concentration, which were first recorded in the mines in 1960, revealed radon levels as high as 190 WL.[41] It was found that the radon was entering the mines in ground water, presumably after the radioactive gas had leached into ground water in uranium-bearing rock nearby. Ventilation was introduced into the mines in 1960, after which the radon concentrations dropped to an average of 0.5 WL.

Morrison et al.[41] examined the lung cancer risk in a cohort of 1,772 fluorspar miners. One hundred thirteen lung cancers were observed, compared to an expected number of 21.5 (RR 5.25, 95% CI: 4.33-6.32). The dose-response trend was highly significant, with an associated relative risk for miners exposed to > 2500 WLM of 33.6 (95% CI: 22.47-48.18). No significant increase in risk was noted for the first ten years after exposure. For miners exposed to moderate (100-1000 WLM) or high (1000 + WLM) exposures, the risk was highest 10 to 19 years after exposure and declined thereafter. This pattern of declining risk after an initial latency period was consistent with results reported above for other groups of miners.[14,15] Morrison et al. also found a decrease in attributable risk coefficient after age 70, as did the Beaverlodge cohort studies.[14]

The added strength of internal cohort comparisons, relative to SMR-related analyses may be noted. Also, a fundamental issue of these studies is trying to estimate exposures retrospectively; for the most part, the highest exposures occurred prior to monitoring.

Miner studies: Other countries

The Colorado Plateau uranium miner cohort[42] has been followed since the 1950s.[43-45] Roscoe[44] provided the latest update to the mortality experience of 3,238 white miners in the cohort, with vital status being ascertained until 1990. Occupational, medical and smoking histories were obtained in health surveys between 1950 and 1970. As in most other studies, exposures were estimated from a variety of methods, including actual measurements, and interpolation or extrapolation in time. For earlier time periods in the study, estimated doses were based on geographic features of the mines and ventilation practices. There were 371 deaths from lung cancer in the cohort members, which represented an SMR of 5.8 (95% CI: 5.2-6.4). In those who died from lung cancer, the average exposure to radon progeny was 1,574 WLMs. The test for trend for the relationship between exposure and risk of lung cancer was strongly positive ($p < 0.002$). In calculating the standard rate ratios (SRRs) for lung cancer, an internal comparison group (those with lifetime exposure < 120 WLM) was used. Duration of employment was found to be an important factor in the risk-exposure relationship, with those working longer than 15 years having a 3.1-fold increase in risk of lung cancer over those working less than five years.

A subsequent analysis of the Colorado Plateau cohort by Hornung et al.[43] examined the effects of age and smoking on the risk-exposure relationship. This analysis found no statistically significant interaction between radon exposure and smoking, which was contrary to the results of some studies, described below, that generally found a sub-multiplicative interaction between smoking and radon exposure.[46] However, a significant interaction was found between radon exposure, attained age and smoking. The meaning of this interaction is difficult to interpret due to the complexity of the relationship between the three variables, but Hornung et al. stated that it was consistent with a sub-multiplicative radon/smoking interaction that depended on attained age. The analysis was also consistent with other studies that showed an inverse-dose-rate effect that disappears at very low exposures (e.g., no dose rate effect below

10 WL). Significant interactions were also found between cumulative radon exposure and attained age, and age at last exposure and relative risk of lung cancer, also consistent with findings of other studies.

An interesting subgroup of the Colorado Plateau cohort consisted of miners of Navajo descent. Roscoe et al.[45] analysed the mortality data for this subgroup of 757 miners known to be light smokers (446 never smoked, 106 ex-smokers, 174 smoked < 1 pack/day). Consistent with other groups, a statistically significantly elevated SMR was found for lung cancers in the Navajo miners (SMR 3.3, 95% CI: 2.3-4.6). The relative risk of lung cancer for those in the 400-1000 WLM total exposure category was 6.9 (relative to those in the < 120 WLM category) while those in the > 1000 WLM category had a relative risk of 18.9 (both were statistically significant). Exposure rate was found to be inversely related to relative risk, with an increase of 10 WL in exposure rate being associated with a relative risk of 0.51. The SMRs for Navajo miners were lower for all categories of cumulative exposure than for the white miners. Roscoe et al.[45] interpreted this as consistent with the lower smoking exposures of the Navajos when compared to the white miners.

A cohort study was also done on New Mexico uranium miners,[47] who began working in an era when ventilation practices in the mines were becoming commonplace. The exposures received by the 3,469 miners in this cohort were less than those of the Colorado Plateau miners. Consistent with other studies, a significant excess of lung cancer deaths occurred (SMR 4.0, 95% CI: 3.1-5.1). After adjusting for smoking, relative risk in the highest exposure category (> 1000 WLM) was 12.3 times that of the lowest exposure category (< 100 WLM). Relative risk of lung cancer rose more steeply in those with attained age less than 55 years of age than in those 55 or older. Samet et al.[47] also found a decreasing risk with increasing time since last exposure, and that the relationship between ERR and WLM was 0.018 ERR/WLM, which was similar to other studies.

A brief report of a cohort of French uranium miners was published in 1992.[48] The reported exposures were less than those of the US miners, with exposures in the range of 1-4 WLM, except in the first ten years of operation of the mine (1946-1955). The lung cancer mortality for these miners was significantly elevated (SMR 2.13, $p < 10^{-4}$). Both the high exposure (those exposed before 1956) and the low exposure (those exposed after 1955) groups had significantly elevated SMRs (2.38 and 1.84, respectively). An interesting feature of the cohort study of French miners was that the relative risk estimates in the pre-ventilation era were about tenfold higher than in the post-ventilation era, which suggests that ventilation may be important in reducing risk.

Tomášek et al.,[49] following on earlier studies,[50] reported the mortality experience of uranium miners in West Bohemia. This was a cohort of 4,320 miners with relatively high exposure to radon (average 219 WLM) for whom detailed radon exposure measurements were available from shortly after the opening of the mine. The relative risk of lung cancer mortality in the cohort was 5.08 (95% CI: 4.71-5.47) when compared to the general Czech population. Consistent with other studies reporting a declining risk with increasing time since first exposure, this study found the greatest risk among miners 10 to 14 years from first exposure (RR 9.17, 95% CI: 7.5-11.1) and that it declined thereafter. No data regarding potential confounders, effect modifiers or the inverse-dose-rate effect were given.

Among non-uranium miners, the association between radon exposure and lung cancer was most extensively studied in Chinese tin miners.[51,52] In 1990, Lubin et al. reported a case control study of miners of the Yunnan Tin Corporation (YTC).[51] This study evaluated the role of radon and smoking in the genesis of the 74 cases of lung cancer, diagnosed within four years of interview and who were alive at the time of study. Controls were chosen from age-matched local residents who were YTC employees and who had not contracted lung cancer. Mean radon exposure was 507 WLM for cases and 247 WLM for controls. This study found that the best model for describing the relationship between radon exposure and smoking was intermediate between additive and multiplicative; in other words, a sub-multiplicative model (although neither the additive nor multiplicative models could be ruled out definitively). They also found an ERR/WLM of 0.017, which is within the range reported by other studies.

Xuan et al.[52] describe the largest series of radon exposed miners, consisting of 17,143 Chinese tin miners in whom 981 lung cancers had occurred at the time of study. Average exposure in the cohort was high at 275 WLM lifetime exposure. Relative risk decreased with increasing exposure rate, consistent with the inverse-dose-rate effect. A sub-multiplicative relationship between risk and smoking was found. The ERR/WLM was 0.006, which is lower than in many other studies, including the case-control study of miners from this same cohort that is reported above;[51] however, this may be consistent with the finding of an inverse-dose-rate effect, because, with this cohort having a higher exposure rate, the inverse-dose-rate effect would give rise to a lower ERR/WLM.

Arsenic, a known lung carcinogen, was a potential confounder of the effect of radon exposure present in the cohort of tin miners.[52] Age-adjusted relative risk reached 8.05 in the highest exposure category (> 800 WLM), but fell to 1.79 (95% CI: 1.0-3.1) when adjusted for arsenic exposure. The corresponding drop in ERR/WLM was 0.062 to 0.0016; however, the authors reported arsenic exposure was highly correlated with radon exposure ($r = 0.6$) and therefore the interpretation of the adjustment for arsenic exposure is problematic.

A number of other studies examined the relationship between radon exposure and risk of lung cancer in base metal miners.[53-55] Although some are methodologically incapable of describing detailed relationships of risk, they are consistent with increased risk of lung cancer with exposure to radon above background levels.

The number, complexity and variability of studies dealing with this issue and the need to control for the important potential confounding factor smoking makes summarization of the literature difficult. Nevertheless, Lubin et al.[46,56] performed a

pooled analysis of the 11 miner cohort studies for which individual exposure data were available. This pooled analysis included miners who had worked in uranium, iron, fluospar and tin mines, including all of the Canadian cohort studies discussed above. From this pooled analysis, which included 65,000 miners and 1.2 million person years of experience, Lubin et al. concluded that (1) the dose-response relationship was linear, despite differing slopes in the different cohorts; (2) excess relative risk (ERR/WLM) decreased with time since first exposure and attained age; (3) an inverse-dose-rate effect was supported, but was not found at exposures below 50-100 WLM; and (4) ERR/WLM was three times as high for never-smokers (ERR/WLM 0.0103) as for ever-smokers (ERR/WLM 0.0034). Although both the additive and multiplicative models of interaction between smoking and radon exposure were consistent with the pooled data, Lubin et al. concluded that a sub-multiplicative model provided the best fit.[46] No clear pattern emerged for the potential confounding effect of arsenic exposure, while silica exposure had little impact on the risk coefficients for radon. The BEIR VI pooled analysis used much the same data and approach.[30]

The available data strongly support the conclusion that lung cancer risk is associated with radon exposures experienced by underground miners in the past. Furthermore, the combined evidence of consistent and strong associations, a biologically plausible mechanism and fully characterized temporal and dose-response relationships support the conclusion that radon exposures can cause lung cancer. While these conclusions relate in particular to high levels of exposure in occupational settings, recent attention has turned to estimation of the risk associated with radon exposures at much lower levels, in particular those found in residential dwellings. The evidence relating to lung cancer risk and residential radon exposure is discussed below.

Residential radon and lung cancer risk

Although the published literature is quite clear with respect to radon posing a risk for lung cancer in the occupational setting of mines with relatively high levels of radon progeny, the risk posed by levels of radon that are commonly encountered in residential settings is less clear. The issue is of critical importance, however, because of the ubiquitous nature of radon and that virtually everyone is exposed to it to some degree. A relatively small excess relative risk that may exist in relation to radon exposures encountered in a residential setting translates into the potential for a far greater number of excess cancers in the general population than does exposure of a relatively small number of miners, although the latter may be exposed to much higher levels of ionizing radiation. Furthermore, the potential risk of radon in the occupational setting resulted in widespread exposure monitoring and extensive efforts at mitigation of risk through use of appropriate ventilation of mining operations. This should result in much lower exposures and corresponding risk. While there has been as yet no widespread organized attempts at monitoring radon levels in homes and mitigation of radon levels where they are found to be excessive, in both the United States and Canada new recommendations have been made to significantly lower the concentration point for radon where mitigation action should be taken. In addition, both have taken steps to inform the public about the risk from radon and are encouraging homeowners to have their homes tested.[57,58]

Evidence relating to the presence or absence of excess risk of lung cancer due to exposure to radon at levels typically found in homes comes from a large number of studies. These fall into two main groups: ecological studies and studies on individuals.

Ecological studies

Canadian studies

Two related publications described an ecological study of the relationship between lung cancer and residential radon exposure in Canada.[59,60] In these studies, indoor radon levels were estimated in 18 Canadian cities and correlated with age-adjusted lung cancer mortality rates for the same cities. A total of 34,380 deaths contributed to the mortality experience. Radon samples were obtained from an average of 778 homes in each of the cities in the summers of 1978 to 1980. No significant correlations were found between average indoor radon levels and lung cancer mortality rates for either males ($r = -0.34$, $p = 0.16$) or females ($r = 0.13$, $p = 0.62$), either before or after adjusting for average rates of smoking.

Stidley and Samet,[61] in reviewing this study, have calculated that there was insufficient power to detect a correlation between lung cancer mortality and residential radon exposure, even had the true correlation been as high as 0.6 (assuming a desired power of 0.8).

Other countries

The review by Stidley and Samet noted above, also looked at 15 ecological studies of lung cancer and indoor radon from a number of countries, including the Canadian study described above. Contained in this review were eight comparison studies and seven ecological regression studies. Stidley and Samet noted that these studies had generated considerable controversy, partly because of the wide between-study variation in results. Seven of the studies had found a positive association between lung cancer and indoor radon, while two had found statistically significant inverse relationships between levels of indoor radon and lung cancer. The remaining six studies had found no association. They also noted that policy makers had placed some reliance on these studies for the purpose of determining appropriate policy direction with respect to indoor radon exposure.

Stidley and Samet concluded the inherent methodological problems associated with ecological studies meant that they should "receive little prominence in describing the public health threat posed by indoor radon, considering their interpretation as evidence of no cancer risk from indoor radon. In fact, further *ecological* studies of indoor radon and lung cancer are to be discouraged."[61] They showed that both modest levels of measurement error and misspecification of the risk model could bias

the results of ecological studies.[62] Other authors reached similar conclusions. Samet et al. reported on the outcome of an international workshop on residential radon epidemiology held in 1989. The workshop concluded that analytical studies should be performed and ecological studies should not, unless warranted by "special situation or unique opportunities." [63]

Analytical studies

Canadian studies

At least two case-control studies of the relationship between residential radon exposure and lung cancer were conducted in Canada. The largest was a study by Létourneau et al.[64] conducted in Winnipeg, the community found (in a previous study by Létourneau) to have the highest average radon levels in residences.[59] Cases were identified through the Manitoba Cancer Treatment and Research Foundation and controls (age and sex matched) were identified at random through the Winnipeg phone directory. Seven hundred thirty-eight case-control pairs were identified between 1983 and 1990. During the initial interview of all subjects (or their proxies), all previous Winnipeg residences occupied by the subjects for periods greater than one year were ascertained. Attempts were made to monitor radon levels in each of the residences that subjects had occupied during their lifetime in the Winnipeg area. This study differed from other case-control studies which monitored only the current residence of the subjects. The authors were successful in monitoring 57 percent of all homes occupied. Measurements were available for nearly 80 percent of the exposures occurring in the window 5 to 15 years before diagnosis of lung cancer. In each of these homes, a radon monitor was placed in the bedroom and basement of the home. Data were collected on potential occupational confounders, education, smoking history and country of birth. These factors were considered predictors in the logistic regression analysis.

The authors did not find a statistically significant relationship between radon exposure and lung cancer. Several issues may have contributed to this finding. First, cases and controls differed significantly in education level and country of birth. Even though the logistic regression models adjusted for these differences between cases and controls (e.g., smoking), some slight residual confounding may have remained. Second, there were several sources of measurement error: The test radon monitors were accurate within +/- 25%; 34% (4448 out of 13,257) of the measurements resulted in complete data; radon levels at the time of measurement may not reflect historic levels (e.g., in homes renovated); and exposure levels could be modified by factors not accounted for, such as sleeping with an open window.[65] Given that such measurement error would likely affect cases and controls equally, it could bias the odds ratio for radon towards the null value.

An earlier case-control study involved lung cancer cases who were diagnosed or died of their cancers between 1969 and 1979. Cases lived for at least seven years in Port Hope, Ontario prior to their diagnosis.[66] The study was undertaken because of concerns that rubble from the demolition of the radium laboratories of the Eldorado Gold Mines Limited facility, used as landfill, was causing high exposures to radon around residences in the community. Cases were identified through the Ontario Cancer Registry. There were 27 cases and 49 controls matched by sex and date of birth. Estimates of radon exposure were obtained from each house occupied by the subjects after 1933.

The authors noted a strong relationship between smoking history and radon exposure. In this instance, when exposure was dichotomized into "lived in a problem home" (i.e., a home with high radon levels) or "did not live in a problem home", all the high exposure cases were smokers and none of the exposed controls were smokers. Despite finding odds ratios greater than 1.0, which approached statistical significance in their conditional logistic regression analysis, the authors concluded the levels of radon exposure in the "problem" homes were not associated with an increased risk to the occupants. The small sample size resulted in limited statistical power and made it impossible to control for the strong confounding effect of smoking.

In summary, the two Canadian case-control studies found no association between residential radon and lung cancer risk. Although the negative findings may be due partly to design limitations that affected statistical power, the Canadian studies are not unique in this regard,[67,68] as described further below.

Other countries

Studies of the relationship between residential radon exposure and lung cancer have been conducted in a number of countries including the United States,[69] Sweden,[70-72] Finland,[73] England,[74] and China.[75] A case-control study of women in New Jersey reported a significant trend in risk with increasing exposure.[69] Risks were comparable to those obtained from miner cohorts. Trends were strongest among light cigarette smokers.[69]

Two residential radon studies have been conducted in Sweden. One involved a total of 586 women and 774 men with lung cancer and 1,380 female and 1,467 male controls[70,71] ; the second, a total of 210 women with lung cancer and 191 hospital and 209 population controls.[72] Both studies reported risk associations between radon exposure and lung cancer risk which were comparable to those obtained from miner studies. Although the Finnish study observed elevated risks, there was no apparent dose-response relationship and the the increase in risk was not statistically significant.[73]

A study in Devon and Cornwall, England was one of the largest case-control studies conducted to date, with 982 lung cancer cases and 3,185 hospital and population controls.[74] Radon exposures over a 30-year period were considered, with measurements obtained in 9,448 out of 13,027 (72.5 percent) of the subjects' homes. When analysis was restricted to the 2,121 subjects for whom complete exposure measurements were available, the ERR per 100 Bq/m^3 was 0.14 (95% CI: 0.01-0.29).

A case-control study was conducted in Shenyang, an industrial city in northeastern China.[75] A total of 308 female lung cancer cases and 356 population controls were studied. No association between radon and lung cancer was observed regardless of cigarette-smoking status.

Meta and pooled analyses

Lagarde and colleagues conducted a pooled analysis of five Swedish case-control studies, restricted to never smokers, resulting in 258 lung cancer cases and 487 controls.[76] They reported odds ratios of 1.08 (95% CI: 0.8-1.5), 1.18 (95% CI: 0.9-1.6) and 1.44 (95% CI: 1.0-2.1) for radon concentrations of 50, 80 and 140 Bq/m^3, repectively, relative to less than 50 Bq/m^3. Overall, they observed an excess relative risk of 1.1 per 100 Bq/m^3.

In response to recommendations made at the 1989 International Workshop on Radon Epidemiology,[63] Lubin undertook a meta-analysis of case-control studies to overcome the small sample size and lack of power of individual studies to detect an elevated risk associated with the low exposure levels that arise in residential settings. Lubin and Boice expected a relative risk of between 1.1 and 1.3 and estimated that the necessary sample size would be from 5,000 to 15,000 lung cancer cases.[77] The meta-analysis included case-control studies with 200 or more case subjects and measurements in one or more residences for all, or nearly all, subjects. Only eight studies in the published literature met these criteria, including the study performed in Winnipeg by Létourneau et al.[64]

The resulting study contained 4,263 lung cancer cases and 6,612 controls. Lubin and Boice concluded the combined data were consistent with extrapolations from the miner data and that the combined relative risk for an increment in exposure of 150 Becquerels (Bq)/m^3 was 1.14. (95% CI: 1.01-1.30). This compares to a model-based RR estimate of 1.13 (95% CI: 1.0-1.2) for miner data where the exposure is less than 50 WLM. In this analysis, it was assumed that a miner exposed to 25 WLM had approximately the same exposure as an individual living 25 years in a house with 231 Bq/m^3 of radon. This meta-analysis provided further evidence in favour of a positive, but weak association between radon levels present in typical residences and lung cancer.

In 2005, two large pooled analyses were published: one of the North American case-control studies[78] and one of the European case-control studies.[79] These two studies provide the most compelling evidence to date that residential radon exposure results in an increased risk of lung cancer. The study by Krewski et al.[78] was based on individual data from the seven North American case-control studies and included 3,662 cases and 4,966 controls. They observed an odds ratio of 1.11 (95% CI: 1.00-1.28) after exposure to radon at a concentration of 100 Bq/m^3 in the exposure time window 5 to 30 years before the index date, which was almost identical to that estimated by extrapolating from the miner data (RR 1.12, 95% CI: 1.02-1.28).

The study by Darby et al.[79] was based on individual data from 13 case control studies from nine European countries. It included 7,148 cases of lung cancer and 14,208 controls. After correcting for the random uncertainties resulting from estimating radon concentrations, the risk of lung cancer was observed to increase by 16 percent per 100 Bq/m^3 (95% CI: 5%-31%). The high degree of agreement between the pooled analyses by Krewski et al.[78] and Darby et al.[79] and the existence of dose-response relationships for both analyses are evidence that residential radon exposure is causally related to lung cancer.

Radon exposure and malignancies other than lung cancer

Although the primary route of exposure of human tissues to radon is by inhalation into the respiratory tract, this is not the only potential route of exposure. It is also possible for radon to be absorbed into the gastrointestinal tract through contaminated drinking water or food, however, this route of exposure is insignificant compared to inhalation since most radon will volatilize at the tap due to radon's high volatility.[80,81] Ionizing radiation has also been linked to leukemia, although the relationship has been mainly with gamma radiation rather than the alpha particle radiation produced by radon progeny. A number of other studies have addressed whether other types of malignancy are related to radon.

Ecological studies have suggested that certain malignancies other than lung cancer may be associated with residential radon exposure. Miller et al.[82] assessed whether residential radon data from 19 cities in Canada were associated with leukemia incidence rates, as a follow-up to a previous report by Henshaw et al.[83] which detected a relationship. Whereas Henshaw et al. had imputed the average provincial residential radon exposures from the data for corresponding cities in those provinces, Miller et al. examined the incidence rates for the cities themselves and found no relationship to the average radon exposures in residences in those cities.

A study by Collman et al.[81] compared childhood cancer rates with average ground water radon concentrations in counties in North Carolina, and found a relative risk of dying from leukemia of 1.33 (95% CI: 1.13-1.57) in the group of counties where radon levels were classified as high. However, data for 25 out of 75 counties had to be imputed because there were no direct measures of radon levels in those counties. A similar study in France[84] found an elevated risk of dying from acute myelogenous leukemia in adults (SMR 1.08, 95% CI: 1.02-1.15), but not acute lymphoblastic leukemia (SMR 0.96, 95% CI: 0.84-1.10). However, data on radon levels was only available for 41 of 95 of the French *départements* (counties) while it was assumed that levels were low in the remaining *départements*. Lack of data for a large percentage of the *départements* was a significant weakness of this study, which was also subject to the usual limitations of ecological studies.

If associations between non-lung cancers and radon exist, they would most likely be detectable in settings where the exposure to radon is greatest. Several of the mining cohort studies examined the potential for such associations. The Ontario study[32] found no significantly elevated risk of any cancer other than lung cancer in the uranium miner cohort. There was also no evidence of an association with non-lung cancers in the Beaverlodge (Saskatchewan) cohort.[40] In the Newfoundland fluorspar miners, there was a borderline statistically significant excess of cancers of the buccal cavity and pharynx (SMR 2.74, 95% CI: 1.00-5.96).[41] The dose-response could not be assessed because of the small number of cases (six observed cases) and also because

other factors may have been confounders (e.g., smoking and alcohol). It was thus not possible to conclude from the Newfoundland study that radon was the factor responsible for this excess cancer risk. In the Chinese tin miner cohort, there was a statistically significant excess of lymphomas (five observed cases, $p = 0.03$). Again, the small number of cases precluded detailed dose-response analysis, but when tertiles of radon exposure were used, the relative risk of lymphoma in the highest tertile group was 7.4 compared to the lowest tertile. In the Colorado Plateau cohort,[44] a statistically significant excess of "Other & unspecified site" tumours (SMR 1.6, 95% CI: 1.2-2.2) and "Benign & unspecified tumours" (SMR 2.4, 95% CI: 1.0-4.6) was found in the white members of the cohort. The meaning of these findings is unclear, but some of these tumours may have been lung cancers that were misclassified (e.g., the primary tumour was not found or could not be distinguished from metastatic disease). Neither of these excess rates was in evidence in the Navajo members of the same cohort.[45] In the West Bohemian uranium miner cohort,[84] there was a statistically significant excess of cancers of the liver (SMR 1.67, 95% CI: 1.16-2.52) and gallbladder and extrahepatic bileducts (SMR 2.26, 95% CI: 1.16-3.94). The liver cancer rate was not correlated with cumulative radon exposure; thus the authors concluded that the excess of liver cancers was likely due to factors other than radon exposure. The biliary tree cancer rates were positively correlated with cumulative radon exposure, but the association was inconsistent with dosimetric evidence from other studies.[85]

In an effort to increase statistical power to detect potential associations between radon and malignancies other than lung cancer, Darby et al.[86] pooled the data from 11 miner cohorts. These 11 cohort studies were the same as those employed by Lubin et al. in their analysis of lung cancer risk.[56] Darby et al. found a significant increase in leukemia deaths (SMR 1.93, 95% CI: 1.19-2.95) in miners who worked for less than ten years. They also found an increase in stomach cancer deaths (SMR 1.33, 95% CI: 1.16-1.52) and liver cancer deaths (SMR 1.73, 95% CI: 1.29-2.28); however, these were not related to cumulative exposure, and the authors concluded that they were not likely due to radon exposure.

Darby et al. also noted statistically significant deficits in deaths related to cancers of the tongue and mouth, pharynx and colon, but there does not appear to be any rationale for considering these deficits to be due to radon exposure. The overall conclusion from this study was that exposure to radon did not pose a serious threat with respect to any cancer other than lung cancer.

Case-control studies also examined the potential for association between leukemia rates and residential radon exposure. Lubin et al.[87] performed a study of childhood acute lymphoblastic leukemia involving cases and controls from nine states in the USA. Cases were eligible if they were less than 15 years old at diagnosis. Radon levels were measured for 97 percent of the exposure period for 505 cases and 443 controls. No association between leukemia rates and even the highest radon exposure levels (> 147 Bq/m^3) was found and the authors concluded that there was no evidence of an association. This study had similar limitations to case-control studies of the association between radon and lung cancer, namely the possibility for mis-specification of the risk model, the potential for errors in the exposure assessment and an insufficiently large sample size.[68]

Health implications for Canadians

There is no convincing evidence that any cancers other than lung cancer are associated with exposure to radon. There is consistent evidence of a substantially elevated risk of lung cancer among Canadians exposed to radon in certain occupational settings, particularly among uranium miners who received radon doses significantly above background doses. The decrease in the number of miners engaged in uranium mining activities and the increasing awareness of the risk (which has resulted in personal exposure monitoring of these workers and government-regulated dose limits, in conjunction with improved ventilation in the mines) should result in a decrease in the risk of lung cancer associated with radon. Given these changes and the relative few employed in the high risk occupations, workplace exposure to radon likely contributes very little to the overall risk to Canadians.

The Environmental Protection Association (EPA) used Lubin and Boice's meta-analysis[77] to estimate that residential radon exposure results in between 7,000 and 30,000 lung cancer deaths per year in the United States. The UNSCEAR 2000 Report[88] also summarized the literature and noted the effect of errors in assessing exposure to indoor radon and concluded that greater statistical precision in estimating risk is required before conclusions are drawn about the magnitude of the health risk.

In the United States, the EPA has recommended that action be taken to reduce residential radon concentrations when they exceed 148 Bq/m^3. The BEIR VI Committee has calculated that the contribution to the attributable risk of radon levels above this action point was 30 percent of lung cancer deaths. If radon mitigation efforts were completely effective at reducing high radon levels to below the recommended action level, then the total reduction in lung cancer mortality would be 3 to 4 percent (i.e., 30 percent of the 12-14 percent of lung cancers attributable to radon) in the United States. In Canada, the recommended action level was reduced from 800 to 200 Bq/m^3 in 2006 and officially adopted in 2007. ICRP-65 recommends a radon action level between 200 and 600 Bq/m^3.[89] Most countries have adopted an action level for new homes of 200 Bq/m^3.[88] Based on a risk model developed by the EPA, radon has been estimated to be responsible for over fifteen hundred cases of lung cancer a year in Canada.[90] Brand has used the BEIR-VI analysis in a Canadian context to estimate the population attributable risk for lung cancer mortality associated with radon at 8% (95% CI: 4%-14%).[91]

In the case of radon, government-mandated remediation below these recommended levels is considered too difficult and costly when there are techniques available to homeowners to reduce radon concentrations. Based on its interpretation of the

available data, the EPA in the United States has begun to inform the US public about the potential risk of lung cancer due to radon in the residential setting. A guide has been produced to inform physicians about the risk of lung cancer from radon. In this guide, the EPA states the following:

> While smoking remains the number one cause of lung cancer, radon presents a significant second risk factor. That is why, in addition to encouraging patients to stop smoking, it is important for physicians to inquire about and encourage patients to test for radon in their homes.

and:

> Enough data exists now, however, to be able to say with certainty that thousands of preventable lung cancer deaths annually in the United States are attributable to indoor residential exposure to radon.[58]

Health Canada has produced a similar guide for homeowners.[57] A number of techniques are available to homeowners to reduce radon concentrations in their homes. These techniques, which are of modest cost, can be effective in reducing radon levels to approximately 75 Bq/m^3.[58] This is half the action level recommended by the EPA, indicating that the EPA recommendations are achievable.

The reduction of the Canadian-recommended action levels, taking into account the most recent evidence regarding the association between lung cancer and radon exposure in the residential setting, appears warranted.

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