REVIEW ARTICLE

Radon in Indoor Spaces

An Underestimated Risk Factor for Lung Cancer in Environmental Medicine

Klaus Schmid, Torsten Kuwert, Hans Drexler

SUMMARY

Background: Occupational medicine has long recognized radon to be a cause of lung cancer, especially among miners working under ground. Until recently, however, little scientific evidence was available about the risk to the general population caused by indoor radon.

Methods: The authors analyzed literature that they found by a selective search in the light of the recently published S1 guideline of the German Society of Occupational and Environmental Medicine (*Deutsche Gesellschaft für Arbeitsmedizin und Umweltmedizin*) and a recent publication of the German Commission on Radiological Protection (*Strahlenschutzkommission*).

Results: Exposure to indoor radon and its decay products is a major contributor to the radiation exposure of the general population. In Germany, the mean radiation exposure due to radon in living rooms and bedrooms is about 49 Bq/m³. It is well documented in the scientific literature that indoor radon significantly increases the risk of lung cancer, probably in a linear dose-response relationship with no threshold. Every 100 Bq/m³ increase in the radon concentration is estimated to increase the relative risk for lung cancer by 8% to 16%. After cigarette smoking, radon is the second main cause of lung cancer in the general population without occupational exposure.

Conclusions: From the point of view of preventive environmental medicine, it is important to identify buildings with high radon concentrations, initiate appropriate measures, and minimize radon exposure, particularly in new buildings.

Lung cancer is the third most common kind of cancer in Germany in both men and women. According to the most recent available figures of the German Cancer Society (*Deutsche Krebsgesellschaft*), lung cancer was newly diagnosed in approximately 46 040 persons in Germany—32 850 men and 13 190 women—in the year 2004 (1). Although most patients with lung cancer are still men, the percentage of women has been rising steadily in recent years. This fact is usually attributed to changes in smoking behavior (2). An estimated 80% to 90% of all new cases of lung cancer are due to active cigarette smoking (2).

There is no longer any scientific doubt that passive smoking also damages health. The German Cancer Research Center (*Deutsches Krebsforschungszentrum*) estimates that more than 260 persons in Germany die each year of lung cancer due to passive smoking (3). It should be pointed out that lung cancer is only one aspect of the negative health effects of active and passive smoking. Many other effects, e.g., on the cardiovascular system, have been scientifically documented (3).

Aside from cigarette smoke, a wide variety of toxic substances have been identified as potential causes of lung cancer in human beings, among them asbestos, polycyclic aromatic carbohydrates, arsenic, hexavalent chromium compounds, and many others. The patient's occupation usually plays the most important role in these exposures (4). We will merely mention here the physician's obligation to report the suspicion of an occupational disease in such cases (5). In Germany at present, the public discussion of topics in environmental medicine chiefly concerns the potential of various toxic substances to cause lung cancer in the general population—not just the toxins that are ingested during active and passive smoking, but also others, such as asbestos and diesel motor emissions. The purpose of this article is to take a closer look at another risk factor for lung cancer that has been largely ignored in the public discussion to date, namely, radon in indoor spaces.

Methods

For this paper, the authors evaluated published studies on the risk of lung cancer due to radon in indoor spaces, which were retrieved by a selective search in PubMed, the literature database of Medline. The recently published S1 guideline of the German Society for Occupational and Environmental Medicine (*Deutsche*

Cite this as: *Dtsch Arztebl Int* 2010; 107(11): 181–6
DOI: 10.3238/arztebl.2010.0181

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FIGURE 1

Gesellschaft für Arbeitsmedizin und Umweltmedizin) (6) and a current publication on this subject by the German Commission on Radiological Protection (*Strahlenschutzkommission*) (7) were also taken into account.

What is radon?

Radon is a naturally occurring, radioactive noble gas with the atomic number 86. It is odorless, tasteless, colorless, and chemically nearly inert. It is found in the radioactive decay series of uranium and thorium, in which it is formed from its mother nuclide, radium. The very long-lived parent nuclei and their breakdown products are natural components of rock and soil. A number of isotopes of radon are known, of which radon-222 is the most stable: it decays to polonium-218 with a half-life of 3.8 days (7). This article follows common usage by using the term “radon” to include all radon isotopes and their short-lived decay products.

This map of the geogenic radon potential in Germany, scale 1 : 2 million, is the result of a nationwide mapping of the radon activity concentration in subsurface air at a depth of 1 m that was carried out by the Bonn Radon Working Group (Geology Department, University of Bonn, and the Kemski & Partner company). Although the map can be used as a rough guide, it does not provide any valid prognostic information on a regional scale. Reprinted with the kind permission of Kemski & Partner, Bonn

Sources of exposure

Radon enters the environment by decay of the uranium and thorium found in rock and soil. The highest radon concentrations are observed in uranium mines (8), but high levels of radon exposure can arise in other types of mines as well. Exposures of these kinds, and exposures due to work in some types of water-storage facilities, are occupational in nature and thus do not belong to the topic of this article.

In radon balneology, the low level of alpha radiation that arises from the radon present in certain medicinal springs is purported to have a health-promoting effect. Treatments are delivered in the form of “radon baths” or “radon emanations,” e.g., by having the patient spend time in a “radon healing gallery.” Such very brief exposures for therapeutic purposes should be subjected to a rigorous risk-benefit analysis; this matter, however, is likewise beyond the scope of the present article.

One factor influencing the concentration of radon activity at the earth’s surface is the variable uranium and radium content in rock and soil substrata. High values are found, for example, in the Ore Mountains (*Erzgebirge*), an extensively mined mountain range in Germany and the Czech Republic, as well as in other regions. Further factors include processes influencing the transport and release of radon within rock and soil, as well as climatic and meteorological conditions in the atmosphere (6, 7). Kemski et al. created a field mapping of the geogenic radon potential in Germany (*Figure 1*), based on standardized subsurface air measurements; high variability was observed, sometimes also within small areas (9). Air near the ground may contain radon in high concentrations, while the concentration of radon activity declines with increasing height above the ground. Human interventions in nature, particularly mining for ore, may result in locally higher radon concentrations.

Depending on the local geological and hydrogeological situation, drinking water may contain concentrations of natural radionuclide activity that deliver a non-negligible degree of radiation exposure to the population (10). The radon content of drinking water in Germany, however, generally poses no danger to the

consumer, and the same holds for the radon content of natural gas (7).

Radon can be formed in construction materials and then partially released in the houses that are built from them. In Germany, however, the radiation exposure from construction materials is only slight (7).

Most of the radon in indoor spaces is derived from the entry of radon-containing subsurface air into buildings from the soil around them (e1). Radon enters houses through leakage sites in the foundation plate and in underground portions of the walls, and then accumulates indoors (Figure 2).

The indoor radon concentration depends mainly on the following factors:

- the nature of the soil on which the building stands,
- the nature of the construction materials,
- climatic conditions and pressure relationships (in particular, the pressure gradient between the subsurface air and the interior of the building),
- the season (e2) (with higher values usually prevailing in the colder half of the year),
- air exchange and the degree of leakiness of windows and doors (6).

Radon concentrations are not constant within a building. The concentration is usually highest in the basement and declines with increasing elevation above the ground.

The available data have been used to generate representative figures for the distribution of radon concentrations in building interiors in Germany (7, 11). Although the concentrations that actually arise in houses and individual rooms can be estimated statistically (e3), they must be directly measured in each individual case for preventive purposes.

Radiometric parameters and units

The activity of a radionuclide is defined as the number of decays or nuclear transformations per unit time. The unit of activity is the becquerel (Bq). One Bq equals one decay per second. The activity concentrations of radon and its decay products are expressed as a ratio of activity to volume, i.e., in Bq/m^3 . The working level (WL) is an alternative unit of activity concentration that is used primarily in mining. Cumulative exposure can thus be expressed in either of two units: $\text{Bq/m}^3 \text{ hr}$ or working level months (WLM) (10). One WLM corresponds to a month's exposure to an activity concentration of one WL; it is defined as 1 WL multiplied by 170 hours (the working time in one month).

Measurement of exposure

Radon concentrations can be measured inexpensively by means of a passive measuring device or an electronic apparatus with an immediate readout. Either way, the most important consideration is that the measurement should be carried out in the proper expert manner, with quality assurance (12, e4, e5). Because the values fluctuate considerably over time, short-term measurements provide little useful information. On its website, the German Federal Office for Radiation

FIGURE 2

Radon in the environment: The radon activity concentrations in rock, soil, and bodies of water, and in indoor and outdoor spaces, cover a wide range, from a few Bq/m^3 to millions of Bq/m^3 . Modified from: Kemski J, Klingel R, Siehl A: Das geogene Radon-Potential. In: Siehl A (ed.): Umweltradioaktivität. Berlin: Ernst & Sohn Verlag 1996; 193 (e29). Reprinted with the kind permission of Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

Protection (*Bundesamt für Strahlenschutz*) publishes lists of measuring facilities that meet the mandatory quality assurance criteria.

Radon activity concentrations

In Germany, the concentration of radon activity outdoors ranges from 1 to 15 Bq/m^3 , with an average value of about 9 Bq/m^3 (7). In interior spaces, exposure varies widely, from 10 to $10\,000 \text{ Bq/m}^3$. Measurements in the living rooms and bedrooms of 27 000 dwellings yielded an arithmetic mean value of 49 Bq/m^3 and a geometric mean value of 37 Bq/m^3 (7). Indoor values in Germany are above 100 Bq/m^3 in 36% of cases, and above 200 Bq/m^3 in about 18% of cases (9). Extremely high indoor exposures to radon are mainly found in residential housing near old mining districts (7).

Indoor radon exposure is present, not just in Germany, but around the world, mainly as a function of the geological substratum and the materials used in building construction.

Biological effects in man

It has been known for more than 100 years that miners in the Ore Mountains suffer from an increased incidence of pulmonary disease, particularly lung cancer. Historically, lung cancer among miners was called “Schneeberg disease,” after the mining town of Schneeberg in the German state of Saxony (13). Radon was identified as its cause in the early 20th century. The inhalation of radon exposes the bronchial mucous membranes to a high level of alpha radiation, which

interacts with bronchial epithelial cells, damaging their DNA and inducing neoplasia.

Radon-induced lung cancer has long been recognized, and reimbursed, as an occupational disease. Occupational exposure in uranium mining is also considered a possible cause of other forms of cancer, particularly the leukemias (except chronic lymphatic leukaemia), bone cancer, and liver cancer (14); these diseases, however, might be caused by other aspects of exposure that are specific to uranium mining and that do not pertain to indoor radon exposure.

In general, it is not clear to what extent scientific knowledge from the field of occupational medicine can be extrapolated to environmental medicine. The problem of risk estimation in low dose ranges arises for many types of exposure, e.g., asbestos exposure. Environmental medicine usually deals with much lower levels of exposure than are present in high-exposure occupations, but often over a longer period of time. Thus, the exposure of particularly susceptible individuals, e.g., children, the elderly, or persons with pre-existing conditions, requires special consideration (e6, e7).

The fundamental question arises whether epidemiological knowledge obtained from populations with high exposure can be extrapolated to the realm of low exposures, and, if so, how this can be done. Epidemiological research faces the major challenge of measuring small risks in a statistically valid manner—e.g., through well-planned and well-conducted studies in environmental medicine, with adequate study populations—and thereby arriving at independent estimates of risk that are not based on extrapolation.

In environmental medicine, the role of indoor radon exposure in the causation of lung cancer was at first a matter of controversy (15). A current publication of the Commission on Radiological Protection (7) provides an overview of the individual studies that appeared up to the year 2005, while further research findings continue to be published (e8–e10). When studies of this matter are planned and conducted, attention must be paid not just to the accurate determination of the individual long-term radon exposure in dwellings (e5, e6), but also to the subjects' smoking behavior. For this reason, many small-scale studies have failed to detect risks in the low-dose range with statistical validity.

It was only the performance of larger studies with improved epidemiological methods that made it possible to gain new knowledge in this area. The connection between indoor radon exposure and lung cancer has now been conclusively demonstrated by the concordant findings of multiple epidemiological studies from Europe, the USA, and China. In Germany, large-scale case-control studies have been carried out in the eastern and western study areas by Wichmann et al. (16), Kreienbrock et al. (17), and Kreuzer et al. (18). These three studies together documented a total of 2963 newly diagnosed cases of lung cancer and involved 4232 control subjects randomly drawn from the general population. The German studies were a component of a pooled evaluation performed for Europe as a whole.

On the European level, the pooled evaluation of 13 studies from 9 countries was based on a total of 7148 cases and 14 208 controls (19). The main findings of this analysis were as follows:

- Even after smoking behavior is taken into account, there is a clear association between radon concentrations in indoor spaces and the occurrence of lung cancer.
- A dose-response relationship was seen even in the realm of low doses ($<200 \text{ Bq/m}^3$), and no evidence for a threshold value was found.
- Radon in indoor spaces is estimated to be the cause of about 9% of all deaths from lung cancer and 2% of all deaths from cancer in Europe (19).

These European findings are in accordance with those of a pooled evaluation of 7 American case-control studies involving a total of 4081 cases and 5281 controls (e11, 20, 21), as well as a pooled evaluation of two Chinese case-control studies involving 1050 cases and 1996 controls (22).

These findings, obtained from the pooled evaluation of case-control studies, are also consistent with data from animal experiments and *in vitro* studies, as well as with extrapolations from data obtained from miners (e12, e13).

In summary, scientific studies have clearly demonstrated that radon exposure increases the risk of lung cancer. This knowledge has been incorporated in the classification issued by national and international bodies concerned with the subject (e14–e24).

Current scientific knowledge suggests a linear dose-response curve without a threshold (e25). There is now a worldwide consensus that indoor radon exposure can cause lung cancer, and that action is necessary in the form of suitable programs for radon measurement and rational interventions to limit radon exposure (23).

The level of risk

The pooled European study on the risk of lung cancer due to radon has shown that each 100 Bq/m^3 of measured long-term radon exposure raises the relative risk by 8.4% (95% confidence interval [CI], 3.0%–15.8%) without correction, and by 16% (95% CI, 5%–31%) after correction for uncertainties in the estimation of exposure (19). An estimate is available for the number of cases of lung cancer in Germany caused by indoor radon exposure (e26): If one assumes that 5% of all deaths from lung cancer are caused by indoor radon exposure, one arrives at a figure of 1896 cases per year (e26). This number far exceeds the estimated number of deaths per year from lung cancer due to passive smoking (ca. 260 cases) (3) and makes clear that radon, after cigarette smoking, is the second most important cause of lung cancer in the general population that is not occupationally exposed. The relevance of other environmental risk factors, such as asbestos or polycyclic aromatic carbohydrates, to health is considered to be markedly lower (7). It has been estimated that a reduction of the maximum value of radon activity concentration in dwellings to 100 Bq/m^3 would prevent

about 300 deaths from lung cancer in Germany each year (7).

Necessary measures

It is both rational and necessary to keep radon concentrations as low as possible in indoor spaces where people are present for more than merely transient periods of time. The German program entitled "Environment and Health" (*Umwelt und Gesundheit*) recommends, for example, that values below 100 Bq/m³ should be considered mandatory for newly constructed buildings, and desirable for older buildings (e27). When older buildings are renovated, interventions to prevent radon entry can be considered, e.g., by eliminating leakage sites in parts of the building that are in contact with the surrounding soil, by utilizing natural or artificial methods of ventilation and gas removal, and by regulating pressure relationships by means up to and including pumping air out from under the foundations. The results of such interventions should be checked with control measurements. The Federal Office for Radiation Protection lists interventions that have been demonstrated to be effective in its Radon Manual for Germany (*Radon-Handbuch Deutschland*) (24).

It is very important for new buildings to be made "radon-proof" from the beginning. Aside from the ethical obligation to minimize the presence of a demonstrated risk factor for cancer, methods of limiting exposure have also been studied from the cost-benefit point of view (25, e28). Although the avoidance and prevention of indoor radiation exposure is currently a component of the German "Environment and Health" program (e27), no radon protection law has yet been passed in Germany.

Conflict of interest statement

The authors declare that they have no conflict of interest as defined by the guidelines of the International Committee of Medical Journal Editors.

Manuscript submitted on 27 May 2009; revised version accepted on 14 August 2009.

Translated from the original German by Ethan Taub, MD.

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KEY MESSAGES

- In occupational medicine, radon exposure has long been recognized as a risk factor for lung cancer, particularly among uranium miners.
- For the general population, the radon concentration in indoor spaces accounts for a major component of the natural radiation exposure.
- The fact that indoor radon exposure appreciably elevates the risk of lung cancer has been well documented by scientific research. It is estimated that indoor radon exposure causes 1896 deaths from lung cancer in Germany each year.
- If the risk of lung cancer from indoor radon exposure is to be minimized, buildings with high radon concentrations must be identified, and appropriate interventions must then be initiated. New buildings should be constructed to be "radon-proof."
- The problem of indoor radon exposure merits greater attention in the current public discussion of environmental policy in Germany.

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