— **Minireview** —

Radon Exposure and its Health Effects

Yuji Yamada*

Radon Research Group, Research Center for Radiation Safety, National Institute of Radiological Sciences, 4–9–1, Anagawa, Inage-ku, Chiba 263–8555, Japan

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About half the natural radiation dose to humans is due to radon and its decay products. It is well known that exposure to high levels of radon causes lung cancer, but as yet, there is still little data on the effect of long-term exposure to low levels of environmental radon. The studies by our radon research group at the NIRS are directed toward determining the health effects of low level exposure to environmental radon. In this paper, our current studies on radon are reviewed.

Key words —— environmental radon/thoron, health effects, α exposure

INTRODUCTION

Radon is an odorless and colorless radioactive noble gas. It emanates from soil and water, and produces decay products in the air. When radon gas and its decay products are inhaled they are considered to have a negative effect on our health. In fact, the high concentration of radon gas as found uranium mines is recognized to cause lung cancer. There is a much historical data on the radon problem in mines. According to the paper by W. Jacobi titled "Schneeberger Lung Disease,"[1] the average radon concentration in most of the mines at Schneeberg, called "the death mine," was within a range of 70–120 kBq/m^3. Recent epidemiological investigations of miners were reviewed in the Biological Effects of Ionizing Radiation (BEIR) VI report.[2] The report indicated that the lung-cancer risk in miners is roughly linearly related to the exposure level.

According to the United Nations Scientific Committee on the Effects of Atomic Radiations (UNSCEAR) 2000 report,[3] the arithmetic mean concentration of indoor radon among the countries studied in the report is 46 Bq/m^3. The highest level was found in Czech, where a concentration of 140 Bq/m^3 was observed. The average concentration for Japan was very low and reported to be 16 Bq/m^3. Overall, the average concentration is not so high in the report. In general, most of the concentration distributions are known to be approximately lognormal. Therefore the number of dwellings with levels over 10 times the average is not so small. The indoor concentrations in some dwellings in Sweden have been observed to be over 10 kBq/m^3, which is as high as found in mines where excess lung cancers observed.[4] But the magnitude of the health effects due to residential radon exposure is not still clear. The health effects from residential radon exposure have represented an important study topic for the last three decades.

This subject is also very important when considering the main principle of radiation protection 'the linear non-threshold hypothesis (LNT),' which assumes that cancer risk is linearly proportional to dose. Further studies are necessary to remove any potential public health threat. We are now focusing on radon-220 (thoron), which is one of the isotopes of radon. Thoron also affects radon measurements, so that misunderstanding may be leaded in the risk evaluation of radon exposure.

Based on the above considerations, our radon research group has conducted a research program titled "Environmental Radon and its Biological Effects." The research activities are directed towards the following three subjects,

Characterization of environmental radon/thoron and their related aerosols,

*To whom correspondence should be addressed: Radon Research Group, Research Center for Radiation Safety, National Institute of Radiological Sciences, 4–9–1, Anagawa, Inage-ku, Chiba 263–8555, Japan. Tel.: +81-43-206-3097; Fax: +81-43-206-4097; E-mail: yj_yamad@nirs.go.jp

Basic research & development and modeling environmental radon using a radon/aerosol chamber,
Determining the biological effects, dosimetry and risk analysis on radon/thoron exposure.

The current status and further details of each subject are described in this paper.

CHRACTERIZATION OF ENVIRONMENTAL RADON/THORON AND THEIR RELATED AEROSOLS

Radon is an ubiquitous indoor air pollutant that is found worldwide. Its sources are soil, building materials, groundwater, *etc*. Wood-based building materials contain little natural radioactive substances such as radium. Radon is produced by the radioactive decay of radium. Radon has many isotopes, but the nuclides radon-222 and radon-220 (thoron) is our concern because of their presence in our human environment and the possibility of their health effects on the public. Uranium-238 and Thorium-232 are the original nuclides of the above two radon isotopes. Their decay series are illustrated Figs. 1(a) and 1(b), respectively. The contribution of each nuclide to radiation exposure is quite different when half-life, radiation type and physical form (solid or gaseous) are considered. Radon-222's half-life of 3.8 days is long enough for it to enter into indoor and cause an increase in the indoor concentration, but is relatively too long to enter into the respiratory tracts and to irradiate the cells. In the uranium decay series, decay products called "radon progeny or daughters" contribute to radiation exposure. In the thorium decay series, the half-life of thoron is only 56 sec and thus the transferred range is limited to the neighborhood of the source. Generally speaking the presence of thoron is often low. Thus, the exposure to thoron is not considered to be a serious problem and not much attention to it has been paid in most radon surveys. But recently thoron it being considered very important for its role risk evaluation for the following two reasons. The first concerns the equipment used for taking radon measurements. Some radon monitors are sensitive to thoron and thus the measured concentration of radon may possibly be affected by the presence of thoron. The second is that in a recent survey[5] areas with high levels of thoron (over 200 Bq/m^3) were found.

In one our other projects, a new radon/thoron discriminative passive monitor was developed[6] (see the next section). Also we have used thoron progeny passive monitors to estimate the equilibrium equivalent thoron concentration (EETC) for dose evaluation. Radon surveys were conducted at the Chinese loess plateau. Typical cave dwellings are shown in Fig. 2. Inhabitants of these dwellings number over three million. This area is good for epidemiological studies because of the high indoor radon concentrations, the large population and the low residential mobility. Recently, a large-scale case-control study was conducted in the area by a joint China-U.S. team.[7] Their results found that increased lung cancer risks for indoor radon exposures may equal or exceed the extrapolations based on the data for miners. In our radon survey, two hundred indoor measurements were made in two provinces of Shaanxi and Shanxi for a long-term exposure period of six months. The average radon concentrations were 76 and 52 Bq/m^3, respectively. These

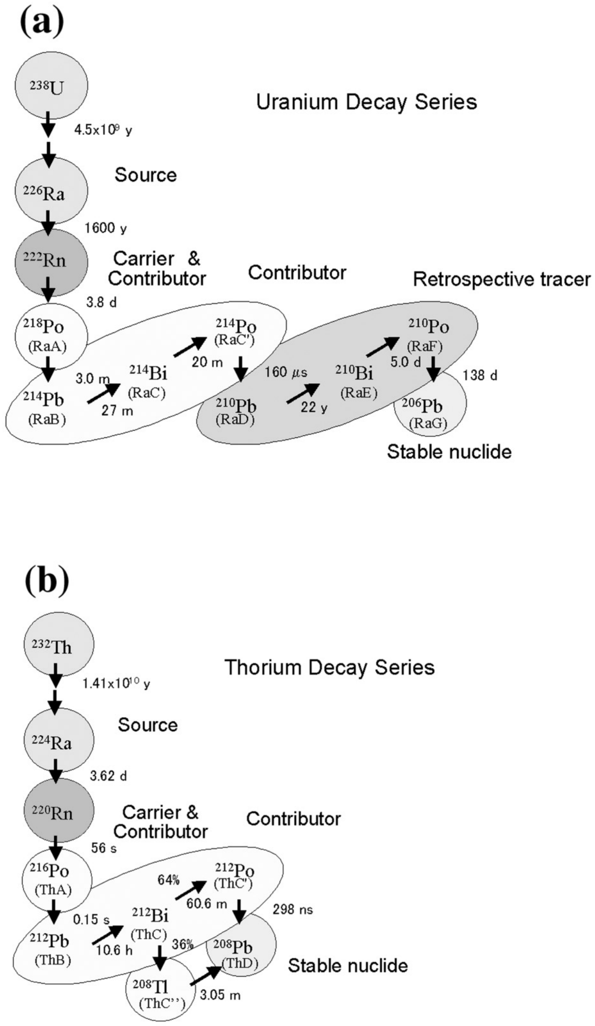

Fig. 1. Radon/Thoron Related Nuclides and their Role in Exposure to Humans

Fig. 2. Typical Cave Dwellings in the Chinese Loess Plateau

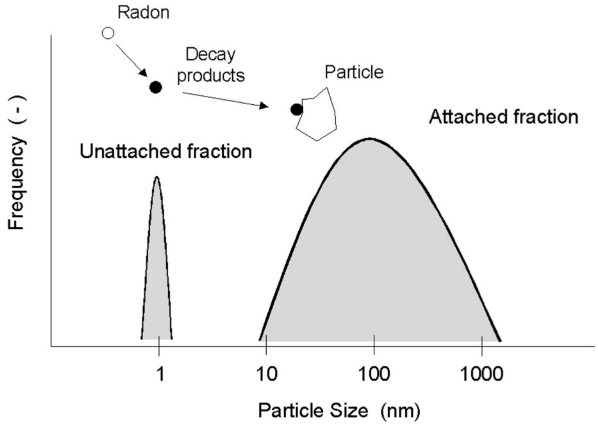

Fig. 3. Schematic Illustration of the Size Distribution of Radon Decay Products

concentrations are not low but commonly found in the region. On the other hand, at the same time, high concentrations of 255 and 182 Bq/m^3 were observed for indoor thoron.[8] If non-discriminative monitors were used in such circumstances of high thoron concentration, the measured radon concentration might be significantly affected. According to our estimation, the radon concentration would be overestimated by a factor of two or three. The accuracy is dependent on the sensitivity of the monitor to thoron. As for the EETC, values of 2.2 and 1.4 Bq/m^3 were obtained. These figures were much lower than expected from the conservative assumption that the equilibrium factor is 0.1. These new findings for high thoron concentration with a low equilibrium factor are very important for dose estimation. It is well known that some radon monitors are affected by thoron. Under circumstances such as those at the Chinese loess plateau, any oversight concerning the existence of thoron will lead serious misunderstandings in the overall results.

In addition to the Chinese loess plateau area, radon surveys have been conducted in the southern part of China, the so-called "HBRA," where the level of background radiation is high. With respect to the exposure-dose relationship, the area is considered to be good for conducting research. A similar survey using radon/thoron discriminative monitors was also conducted in Korea. In Japan, a large-scale survey is scheduled for the 2003 fiscal year. A new radon/thoron discriminative monitor based on a NIRS design will be used in the survey.

BASIC RESEARCH & DEVELOPMENT AND MODELING ENVIRONMENTAL RADON USING A RADON/AEROSOL CHAMBER

Radon is an inert gas and its half-life of 3.8 days is long enough for the gas to enter into the human environment. Radon is ubiquitous and relatively stable. But radon decay product is solid and behaves as an airborne particle. The behavior is easily influenced by circumstances. Initially, decay products are free atoms in the air and "unattached" to other aerosol particles. But these decay products are so small that they easily attach to aerosol particles. The fraction that attach depends strongly on the size and concentration of carrier aerosol particles. A typical size distribution of the decay products is bi-modal as illustrated in Fig. 3. The smaller mode, ranging from 0.5 to 3 nm, is commonly referred to as the "unattached" fraction of the decay products, while the larger mode, from 50 to 300 nm, consists of decay products attached to aerosol particles. Many types of instruments for determining radon concentration are commercially available but accurate size measurement techniques and analysis of radon decay products have not yet been developed. Two collection techniques using the principles of inertial impaction and Brownian diffusion are being tested in our group. A Graded Screen Array (GSA), which is one of the diffusion methods, looks very promising, especially for sizing of the "unattached" fraction in a nanometer range.

In order to simulate a natural radon atmosphere, a large 25 m^3 walk-in chamber was built at our radon research laboratory. The chamber is designed

Fig. 4. Radon Measurement Intercomparison Experiment at NIRS

so that radon and hygro-thermal conditions can be controlled with special emphasis on carrier aerosol simulation. By using this radon/aerosol chamber, basic radon behavior and methodological studies are being conducted. With this new walk-in chamber it is easy to determine the influences the conditions in the chamber on the behavior of radon and the response of radon monitors. This was demonstrated when the facility was used for an intercomparison experiment for radon measurements as shown in Fig. 4. Participants in two experiments held at NIRS in 2002 included over 10 universities and laboratories from around Japan. Some variation in the accuracy of measurements was found. Since the variation among the same instruments was relatively small, the main reason for the discrepancy may have been because of differences in the calibration method. The primary problem is there is no standard source of radon. To reduce such variations, periodic international intercomparison experiments are absolutely necessary.

As radon is a potential public health threat, a radon control study is also being conducted by our group. The possible removal mechanism pathways are: radioactive decay, ventilation to outdoors and adsorption. With radon's half-life of 3.8 days, waiting for its decay is not reasonable. Ventilation is a very effective method but a stopgap technique. Using activated charcoal traps is a very common method and their performance under certain circumstances is confirmed. But they have some disadvantages including lack of stability over the long-term, and a low removal efficiency per unit volume, *etc*. In order to solve this fundamental problem, a completely new method was developed in collaboration with a private company. Radon is inert, but under certain circumstances it forms a solid compound by chemical reaction. This is the principle of the new radon trap we are developing. The prototype device is desktop size and its capacity as a radon trap is still limited. A more efficient version for practical use is being developed. Also new coating materials that form a radon barrier are being looked into. Some types of urethane resin are effective in reducing radon penetration, but truly radon limiting materials have not yet been developed. Since indoor radon comes mainly from building materials, coating materials might be applicable as a "removal" technique.

DETERMINING THE BIOLOGICAL EFFECTS, DOSIMETRY AND RISK ANALYSIS ON RADON/THORON EXPOSURE

There are two epidemiologic and dosimetric approaches for evaluating public health risks from radon exposure. In the epidemiologic approach, lung cancer data on miners exposed to high radon concentrations are extrapolated to an environment with a much lower concentration. The basis of the dosimetric approach is the Japanese Atomic-bomb Survivor Cohort Study. The dosimetric approach uses a physical model to estimate a bronchial epithelial dose per unit exposure and converts the lung dose with radiation and tissue weighting factors to an effective dose. Unfortunately there is a significant difference in the radon risk determined by the above two approaches. According to the BEIR VI report,[9)] the risk estimated dosimetrically by Birchall and James[10)] was found to be larger than that estimated from the miner data by a factor of 4–5. One of the major uncertainties in the dosimetric approach is assuming an α-particle Relative Biological Effectiveness (RBE) of 20. Also the difference between the two approaches for determining the Dose Conversion Factor (DCF) from radon concentration to effective dose is still not solved. This is especially so for thoron exposure, and the problem is rather serious as there is little biological data on thoron.

It is still very difficult to be definite as to whether residential radon causes cancer in humans. The main reasons are the many confounding factors such as smoking, air pollution, ionizing radiation, *etc*. With this in mind, *in vivo* studies using experimental animals and *in vitro* studies would be very effective.

There is some debate over how respiratory cells are affected by radiation induced lung cancer, but and initial NIRS study on radon exposure to trachea epithelial cells has been conducted to identify cytological and genetic biomarkers. The penetrating power of α-particles emitted from radon and its decay products is weak, thus that the deposited α-energy to the target is limited to only a very thin layer, less than 100 μm from the surface. This means that the surface conditions under *in vitro* studies are very important. In order to simulate actual conditions, Air-Liquid Interface (ALI) cultures were introduced to our exposure study. The biological response of the cells in ALI cultures was confirmed to be close to the *in vivo* response found in the previous study.[11] The exposure study is in progress and the results will be summarized in near future.

Bio-kinetic data in live humans is essential for dose calculation and risk estimation. The intake routes of radon and its decay products are mainly inhalation and ingestion. The dose contribution of inhaled radon is not so high because radon is a gas and it is readily exhausted with exhaled air. On the other hand, its decay products are solid and behave as aerosol particles, so they deposit in the respiratory tract and deliver their α-energy to the respiratory cells. The depositon region and the deposition efficiency are affected by physical and biological factors such as particle size, breathing pattern, *etc*. The dose of α-energy delivered to the respiratory tract cannot be directly measured, but the deposited activity can be measured by using external monitoring techniques. Deposition and retention data of radon decay products have been accumulated by our group. On the contrary, there are limited data on ingested radon. The bio-kinetics of radon ingested from drinking water is interesting, and a retention curve with fast and slow components has been observed in *in vivo* measurements.[12] The result was beyond the expectations of the generalized model for nuclides. A bio-kinetic model is useful for simulating the complex event sequence after the intake of radon and its decay products. In addition to bio-kinetic data, new survey data on environmental radon such as radon/thoron discriminative data should be taken account into for dose evaluation. Also particle size data for the decay products must be considered as the DCF is strongly dependent on particle size. As shown in Fig. 5, when particle size is taken into consideration there is a difference in dose of over 20 times.[13] If attention is paid to not only the biological effects but also dose evaluation, differences in the DCF between the dosimetric and the epidemiologic approaches might be reduced.

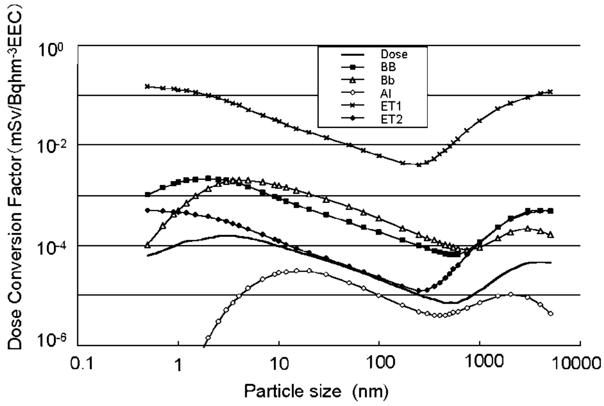

Fig. 5. Particle Size Dependency of Dose Conversion Factor

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