HEALTH EFFECTS IN RESIDENTS OF REGIONS WITH HIGH BACKGROUND RADIATION[1]

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For various reasons, health problems created by high natural levels of background radiation are hard to detect. This article reviews the considerable efforts made to detect such problems since the 1950s and reports fragmentary findings indicating that the need for a clear quantitative assessment of the risks is as great as ever.

Introduction

The fact that some areas have high natural radioactivity has been known to scientists and others since soon after the discovery of radioactivity by Henri Becquerel in 1896 *(1)*. Indeed, shortly after that discovery the owners of certain spas promoted the healthful effects of their radioactive drinking water; and in old mines and other areas of high natural radiation, members of the public were encouraged to immerse themselves in the water and breathe the air as a cure for rheumatoid arthritis, endocrine and metabolic disorders, vascular diseases, and geriatric complaints *(2)*.

The health effects of radiation doses in occupationally exposed persons also received attention; but it was not until the 1950s, when the atmospheric atom bomb tests of the United States and the Soviet Union were raising the level of environmental radioactivity, that the long-term effects of exposure to low-level radiation dosages became a matter of public concern around the world. This was the period when the United Nations Scientific Committee on the Effects of Atomic Radition (UNSCEAR) was created, and when the World Health Organization appointed an expert committee to provide advice concerning radiation and human health.

In its first report, entitled *The Effects of Radiation on Human Heredity: Investigations of Areas of High Natural Radiation (3)*, the WHO expert committee identified several areas of high natural radiation where studies of the exposed population might possibly provide information concerning the effects of chronic exposure to low-level radiation. Those areas, selected according to the best information available in 1959, are listed in Table 1.

On the basis of this information, the committee concluded that the Kerala area of India appeared to be the only area known at the time that might profitably be investigated. It was pointed out that there would be difficulties in conducting a study of the size needed to detect the small differences expected between the exposed and control populations. While the committee was fully aware of the desirability of obtaining meaningful information on the effects of chronic low-level radiation doses, it pointedly stated that it was under no illusion regarding the chances that any investigation of high background radiation areas would demonstrate significant genetic changes.

At approximately the same time that A. R. Gopal-Ayengar and K. Sundaram began studying the high natural radiation areas of India, scientists from the Catholic Univeristy of Rio de Janeiro, Brazil (F. X. Roser and T. L. Cullen) and from the Federal University of Rio de Janeiro (C. Chagas and E. Penna Franca) began to study and report on the high natural radiation areas of Brazil (see later sections on India and

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Table 1. Areas of high natural radiation identified by the WHO Expert Committee on Radiation in 1959 as possible locales for research on health effects.

Area	Average natural radiation received in milligrays (mGy) per year (1 mGy = 100 mrads)	Exposed population	Control population	Available health statistics (comments)
Monazite region in India, parts of Kerala and Madras states	13	80,000	Similar ethnic groups in nearby areas	Some information could be obtained easily
Monazite region in Brazil, parts of states of Espiritu Santo and Rio de Janeiro	5	50,000	Unknown	Information would be required
Mineralized volcanic intrusives in Brazil, in states of Minas Gerais and Goiás	16	350	Unknown	Very little information available
Primitive granitic, schistose, and sandstone areas of France	3	7,000,000	Remainder of French population	Information would be required

Source: World Health Organization *(3)*.

Brazil). In addition to resources provided by the Brazilian National Research Council and the Nuclear Energy Commission, much valuable support was provided by Merril Eisenbud and his colleagues at the New York University Institute of Environmental Medicine and by the U.S. Atomic Energy Commission, while the Pan American Health Organization helped to train national scientists and to coordinate these international efforts.

In 1973 PAHO brought together various scientists, including the principal investigators of the studies in Brazil and India, for an international meeting to exchange information, review progress, and discuss further research needs *(4)*. During this meeting it was concluded that although the population groups being studied in Brazil and India were sizable (including about 70,000 people in India and about 6,000 in Brazil), they were not large enough to show subtle biological effects over a wide range of chronic radiation doses. Therefore, it was felt that an effort should be made to identify as many areas as possible in the world where population groups might be receiving doses comparable to the Indian and Brazilian study populations.[3] Accordingly, tentative plans were made for convening an international meeting of investigators in the field of high natural radiation, and a working definition was established for areas of chronic exposure that would qualify as "high natural radiation" areas.

During preparation for the International Symposium on Areas of High Natural Radioactivity that was subsequently held at Poços de Caldas, Brazil, in June 1975 (attended by 93 scientists from 16 countries), the working definition was modified slightly so as to include only those areas that met one or more of the following criteria:

1) The exposure rate from external sources, over extended areas, is greater than 200 milliroentgens (1.74 milligray) per year.

2) The long-lived alpha activity ingested with the local diet (including water) is greater than 50 picocuries (1.85 becquerel—Bq) per day.

3) The radon-222 concentration in potable water is greater than 5,000 picocuries per liter (185 kBq per cubic meter).

4) The radon-220 and radon-222 concentration in the atmosphere is greater than 1 picocurie per liter (37 Bq per cubic meter) *(5)*.

During the progress of the International Symposium, the participants tended to consider areas where natural radiation levels were more than

[3]The dose estimates at this time for the Indian and Brazilian study areas were an annual per capita dose of 400 millirems (400 mrem, equivalent to 4 millisieverts) in India and an annual per capita dose of 700 mrem in Brazil.

three times the worldwide average as "elevated natural background areas," and to consider areas where natural levels were more than 10 times the worldwide average as "high background areas."

Worldwide Background Radiation Levels and Human Exposure to Radionuclides

Worldwide average values for radiation levels and doses are shown in Tables 2a and 2b. These values are based on data from a 1982 UNSCEAR report *(6)*. In general, while there are variations in "normal" radiation levels, a large portion of the world's population does not receive more than two times the worldwide average. For

Table 2a. External sources of radiation, showing the average levels and whole-body doses received in "normal" radiation areas.

Radiation source	Absorbed dose index in air (1 gray = 100 rads)[a]	Annual effective dose in equivalent microsieverts (μSv); 10,000 μSv = 1 rem
Cosmic rays (at sea level)	32 nanograys/hour	280 μSv
Terrestrial radiation		
a) outdoor	50 nanograys/hour	350 μSv (combined outdoor plus indoor)
b) indoor	60 nanograys/hour	

Source. United Nations Scientific Committee on the Effects of Atomic Radiation *(6)*.

[a]The absorbed dose index is the maximum absorbed dose that would occur in a tissue-equivalent sphere 30 cm in diameter that has its center at the point of interest.

Table 2b. Internal sources of radiation, showing the average intakes or concentrations and whole-body doses of residents in "normal" radiation areas.

Radiation source	Intake or concentration in becquerels (Bq), 1 Bq = 27 picocuries	Annual effective dose in equivalent microsieverts (μSv), 10,000 microsieverts = 1 rem
Cosmogenic radionuclides: C^{14}, H^3, Be^7, Na^{22}	–	15 μSv
Primordial radionuclides:		
Potassium-40	60 Bq per kg (concentration in tissue)	180 μSv
Rubidium-87	8 5 Bq per kg (concentration in tissue)	6 μSv
Radium-226	15 Bq per year (intake)	7 μSv
Radium-228	15 Bq per year (intake)	13 μSv
Polonium-210	40 Bq per year (intake)	130 μSv
Radon-222 (outdoor air)	1.8 Bq per cubic meter (average equilibrium equivalent concentration at ground level)	60 μSv
Radon-222 (indoor air, temperate region)	15 Bq per cubic meter (average equilibrium equivalent concentration at ground level)	920 μSv
Radon-222 (global mean outdoor plus indoor air)	–	800 μSv
Radon-222 (thoron) (outdoor air)	0.2 Bq per cubic meter (average equilibrium equivalent concentration at ground level)	20 μSv
Radon-220 (indoor air, temperate region)	0.7 Bq per cubic meter (average equilibrium equivalent concentration at ground level)	200 μSv
Radon-220 (global mean outdoor plus indoor air)	–	170 μSv
Thorium-232	0.01 Bq per year (intake)	3 μSv
Uranium-238	5 Bq per year (intake)	10 μSv
Estimated total external and internal annual effective dose equivalent, rounded to nearest whole number		*2,000 μSv (2mSV)*

Source: United Nations Scientific Committee on the Effects of Atomic Radiation *(6)*.

example, the average dose received from cosmic radiation is 32 nanograys (3.2 microrads) per hour at sea level, and this increases to 41, 62, and 98 nanograys per hour at one, two, and three kilometers above sea level, respectively. Although some large cities are located at high altitudes (e.g., Denver, Mexico City, Nairobi, and Teheran), the average worldwide dose received from cosmic radiation is very near to the dose at sea level. Similarly, in the case of terrestrial radiation about 95% of the world's population lives where the outdoor dose received is between 30 and 70 nanograys (3 to 7 microrads) per hour, and where the indoor dose received is between 20 and 90 nanograys (2 to 9 microrads) per hour.

Areas of human exposure to high natural radiation levels have been identified on the basis of both the external dose received (Table 3) and the concentration of radionuclides found in food or drinking water (Table 4). As the tables show, high external radiation levels have been reported in Austria, Brazil, China, France, India, Iran, Italy, Madagascar, and Nigeria; and areas of high radionuclide intake have been reported in Austria, Brazil, Finland, India, and the United States. The estimated average annual tissue doses and population sizes indicated in the tables suggest that the most promising locales for health effect studies are portions of Brazil and India that have in fact been investigated, and perhaps the Helsinki area of Finland. The findings of various studies that have been reported to date are presented on the pages that follow. Since most of the reports do not provide details concerning the methodology used and the quality control of data collection and processing activities, no judgment concerning the relative merit of the various studies has been attempted.

Austria (2, 7-12)

An investigation of mortality in the Badgastein radioactive spa area, using nonradioactive spa areas with similar geographic and ecologic conditions as controls, showed that cancer mortality was not higher in the Badgastein area and that longevity of the Badgastein population was not lower. A subsequent study of lung cancer risk led the researchers to conclude that any increase in the incidence of lung cancer would be difficult to observe because of the small sample size involved. Further studies showed that the annual lung cancer incidence in Badgastein was not statistically different from the mean observed lung cancer incidence in the entire province of Salzburg. However, it was also found that the people who died of lung cancer had received a higher radiation dose than those who died of other causes.

Chromosome aberrations in peripheral blood lymphocytes of Badgastein population groups were also studied. These groups included inhabitants of the area, spa-house personnel, and doctors and supporting staff members working in the thermal gallery and treatment house. The study included an analysis of 30,770 cells from 122 persons for aneuploid and polyploid cells, morphologically abnormal chromosomes, and chromatid and chromosome aberrations (gaps, breaks, exchanges, fragments, interstitial deletions, and dicentrics). No rings were observed. Since the chromosome aberration frequency was found to be age-dependent, the results were normalized for an age of 50 years.

The dose-response curve from combined alpha and gamma irradiation for all types of aberrations was observed to rise sharply as the dosage increased, up to an annual dose of 2-3 mGy (200-300 mrad). This rise was attributed mainly to a steady increase in background gamma radiation. At doses above 3 mGy (300 mrad) per year, attributed to additional alpha irradiation, the dose-response curve reached a plateau.

The data were further analyzed by dividing the population into people who only received "normal" background irradiation (mainly gamma with a very small alpha component) and people who received a higher alpha dose in addition to the gamma dose. This analysis showed a sharply rising dose-response curve for the group subjected only to "normal" background irradiation. For those subjected to a higher alpha irradiation component, the response was less dose-dependent; and for the group receiving the highest

Table 3. A list of areas found to expose residents to high levels of external radiation, showing the numbers of people and radiation doses involved.

Area	Absorbed dose index in air (1 gray = 100 rads)[a]	Population	Average annual absorbed tissue dose
Austria:			
Badgastein	0.08-0.29 micrograys/hour	6,500	0.7-2.0 milligrays/year
Brazil:			
Monazite area:			
Guarapari	1-2 micrograys/hour in streets (peak of 20 micrograys/hour on beach)	12,000	0.55 milligray/year (range .09 to 2.8)
Meaipe	1.3 microgray/hour (peak of 10)	3,000	–
Cumuruxatiba	0.5 microgray/hour	–	–
Volcanic intrusive area:			
Araxá-Tapira	4 micrograys/hour	1,700	–
China:			
Guangdon Province (Dong-anling and Tongyou)	0.2-0.27 microgray/hour	73,000	2 milligrays/year
France:			
Languedoc-roussillon	0.01-0.3 microgray/hour (peak of 10)	–	–
India:			
Kerala State	0.43 microgray/hour	70,000	4-5 milligrays/year
Iran:			
Ramsar	0.8-55 micrograys/hour	2,000	15 milligrays/year
Italy:			
Lazio and Campania	–	–	–
Madagascar:	–	–	–
Nigeria:	–	–	–

[a]See footnote a, Table 2a.

Table 4. A list of areas in which residents are exposed to high concentrations or intakes of radionuclides.

Area	Radio-nuclide	Daily intake or concentration in becquerels (Bq). 1 Bq = 27 picocuries	Popula-tion	Tissue dosage in sieverts (Sv). 0.01 Sv = 1 rem
Austria:				
Badgastein	Radon-222	air concentration of 30-110 kBq per cubic meter (air concentration)	6,500	.02-3.2 Sv per year (bronchioles)
Brazil:				
Volcanic intrusive area:	Radium-226	0.7-1.5 Bq per day (intake)	200	–
Araxá-Tapira	Radium-228	4.4-8.8 Bq per day (intake)		
Finland:				
Helsinki	Radon-222	630 kBq per cubic meter (average drinking water concentration)	150,000	0.1 Sv per year (lungs)
India:				
Kerala State	Gross alpha	8 Bq per day (intake)	70,000	–
	Radium-228	6 Bq per day (intake)		
United States:				
Illinois, Iowa	Radium-226	110-3,000 Bq per cubic meter (concentration in drinking water)	900,000	–
Maine	Radon-222	370-2,200 kBq per cubic meter (concentration in drinking water)	–	
Texas	Radium-226	370-560 Bq per cubic meter (concentration in drinking water)	1,000	–
Texas	Radon-220	37-300 kBq per cubic meter (concentration in drinking water)	1,000	–

alpha dose, higher than 1 mGy (100 mrad) per month, the response curve reached a peak and even turned downward for two-break events. These results were unexpected. The authors have suggested that their findings could be explained by the activity of repair enzymes regulated by a threshold phenomenon.

Brazil (5)

Owing to the small size of the exposed populations and lack of sufficient medical records, no exposure-related morbidity or mortality studies have been conducted in Brazil. However, a study of somatic chromosome aberrations in peripheral lymphocytes has been conducted among residents of the Guarapari area. (Guarapari is a village in the monazite sands area of Brazil in Espiritu Santo State along the central coastal region about 400 km north of Rio de Janeiro.) The residents studied were exposed to a mean annual external radiation level of 6.4 mGy (640 mrad), the specific levels involved ranging from 1 mGy (100 mrad) per year to 32 mGy (3.2 rad) per year. In all, 13,242 cells from 202 people of this area were analyzed, together with 9,001 cells from 147 people serving as a control group. This control group consisted of residents of a village with a similar socioeconomic level and a normal background radiation level.

The Guarapari residents were not found to have significantly more aneuploid cells or chromatid aberrations than the control group subjects (neither of these defects were considered radiation-induced types of damage). However, a significant increase in the total number of chromosome breaks (a deletion was counted as one break and a dicentric as two) was observed in the Guarapari residents ($P<.05$). This finding, which was attributed to the higher level of natural radiation in the Guarapari area, is thought to be due to inhalation of the decay products of thoron (lead-212 and bismuth-212), rather than to higher external radiation levels. This hypothesis has been supported by a cytogenetic survey of workers exposed to much higher levels of thoron daughters in a nearby monazite ore mill, in whom a positive correlation was found between chromosome aberrations and levels of exposure to airborne lead-212 and bismuth-212.

China (13)

During 1972-1975 a study population of about 73,000 people in the Dong-anling and Tongyou areas of Guangdong Province whose families had been exposed to an elevated radiation level for many generations was compared with a control group of 77,000 persons living in nearby areas with similar geographic, socioeconomic, and ethnic characteristics. In all, 90.6% of the study group families had been living in the high-radiation area for six or more generations. The study group members received an average annual dose of about 2 mGy (200 mrad) to the whole body from external radiation, while the control group members received about 0.7 mGy (70 mrad). The internal whole-body doses received were about 0.35 and 0.24 mGy (35 and 24 mrad), respectively.

A clinical examination of infants and children less than 12 years old (3,504 from the study group and 3,170 controls) for 31 kinds of hereditary diseases and congenital deformities showed no statistically significant differences. Down's syndrome was found to be more common in the study group, with a frequency of 1.71 cases per thousand versus zero in the control group. However, because of the small size of the sample populations, the researchers were concerned about the significance of their findings and realized that further investigation was necessary.

Height, weight, and head circumference measurements of children less than 12 years old (3,239 from the study group and 2,991 controls) did not reveal any significant differences in growth or development. Neither did the rate of spontaneous abortions between 1963 and 1975 (73.9 per 1,000 live births for the study group versus 72.5 for the control group) show any difference between 1,551 study group women with 3,896 pregnancies and 1,716 control group women with 3,062 pregnancies.

Similarly, the frequency of malignancies observed in 1975 through clinical examination of 20,154 study group subjects and 21,235 control group subjects revealed no significant differences. Nor did a retrospective survey of cancer mortality covering the period 1970-1974 show any significant difference between the study group (96,533 person-years) and the control group (122,554 person-years) for malignancies of the breast, cervix, esophagus, intestine, liver, lung, nasopharynx, and other sites.

Likewise, cytogenetic studies of peripheral lymphocytes showed no significant difference between inhabitants of the high background radiation areas and those of the control area with respect to the frequencies of chromatid or chromosome aberrations.

India (5)

A group of scientists from the Bhabha Atomic Research Center carried out a detailed demographic survey of 70,000 people in 13,355 households who were living in the high natural background radiation area of Kerala State. Since the high background area is, essentially, a strip of land about 55 km long and 0.5 km wide that is interrupted by regions with normal background radiation, the control population was selected from residents of these normal areas who had socioeconomic and religious characteristics similar to those of the study area residents. Based upon a sampling of 20% of the households, it was estimated that about 16,600 of the 70,000 persons living in the area were receiving a dose in excess of 5 mGy (0.5 rad) per year, with the average per capita dose being about 4 mGy (0.4 rad) per year. Analysis of the data did not show any statistically significant differences for groups receiving different levels of radiation with regard to their fertility index, the sex ratios of their offspring, infant mortality, pregnancy terminations, multiple births, or gross congenital abnormalities. The researchers concluded that the variables that were studied were not susceptible enough to modification by radiation to show any statistically significant differences. They did observe, however, that a group exposed to more than 20 times the normal background radiation did have the lowest fertility index and the highest infant mortality of any study group.

Another group of researchers from the All India Institute of Medical Sciences obtained some interesting results while studying enlargement of the thyroid gland. This group found no difference in the histological characteristics of goiter in a population living in the high natural radiation area and a control group living in an area of normal background radiation, but it did observe a higher frequency of Down's syndrome. Specifically, 12 cases of Down's syndrome were observed in the study population of about 12,000 people, as compared to no cases of Down's syndrome in the control population of about 6,000 people. Although this frequency of Down's syndrome (1:1,000) is among the highest observed worldwide, it was mentioned during the discussion of these findings that a frequency of about 1:800 had been observed in a New Delhi population exposed to normal radiation levels. Additional observations by this group of researchers included a higher frequency of severe mental abnormality of genetic origin (23 cases in the study population versus four cases in the control group) and a higher frequency of limb malformations (three cases in the study population versus none in the control group). A factor complicating this study is the circumstance that no dosimetric data on radiation exposure were presented; and since it has been shown that radiation exposure is highly variable in the monazite areas, the fact that an individual lived near the monazite sands does not necessarily mean that a high radiation dose was received.

Further cytogenetic studies of chromosome aberrations in cultured whole blood were performed by the group from the All India Institute of Medical Sciences. This work yielded the results shown in Table 5. The number of chromosome aberrations found among the four study groups differed significantly from that found in the control group ($P<0.001$). The most common types of chromosome aberrations were deletions and acentric fragments (the average number being 2.5 per 100 cells, with a range of 1.4-3.2). The number of dicentrics and rings was low (the average number per 100 cells being 0.6, with a

Table 5. Results of cytogenetic studies of people from the high background radiation area of Kerala State and control subjects.

Population group	No. of persons studied	Chromosome aberrations per 100 cells
Control subjects (Purrakade-Punnapura)	39	0.2
Residents of the high radiation area	46	1.9
Workers in the monazite industry (Manavalakurichi)	17	3.1
Patients with Down's syndrome	–	3.5
Parents of patients with Down's syndrome	–	3.6

Source: Academia Brasileira de Ciências *(5)*.

range of 0.4-1.2). As a result of these findings, the researchers suggested that the chronic low-level radiation was causing genetic damage to the population.

United States

The Midwest Environmental Health Study (5, 14). In 1962 a retrospective study of approximately 900,000 residents of the states of Illinois and Iowa was initiated. This population was living in communities with a relatively high radium-226 concentration in drinking water—the weighted mean being 174 Bq per cubic meter (4.7 picocuries per liter)—and with roughly equal levels of radium-224 and radium-228. The object of the study was to determine whether this population experienced a higher rate of health effects than did a control population living in similar communities where the water supplies contained a concentration of radium-226 below 37 Bq per cubic meter (1 picocurie per liter).

The study found that the overall age-adjusted and sex-adjusted mortality due to malignant neoplasms involving bone was greater in the communities with high radium-226 levels than in the control communities (P = 0.08). More precisely, when age-specific mortality from malignant neoplasms involving bone were calculated for two specific age groups (20-29 years and 60-69 years), the observed mortality was greater in the exposed population than in the control population. These differences were found to be statistically significant, with P values of 0.01 and 0.07, respectively. In four of the remaining seven age groups the observed mortality was higher in the exposed population than in the control population; however, the differences involved were not found to be statistically significant.

At the time of the study, some concern was expressed about the validity of the findings for the following reasons:

1) Two neighboring states (Wisconsin and Missouri), portions of which have water with high radium-226 levels (but apparently not in public drinking water supplies) exhibited mortality from malignant neoplasms involving bone that was higher than that of the control population but lower than that of the exposed population.

2) Chicago, Illinois, obtains its drinking water from Lake Michigan; this water has a radium-226 content of only 1 Bq per cubic meter (0.03 picocuries per liter). Nevertheless, mortality from malignant neoplasms involving bone in the city of Chicago was found to be higher than that observed in the exposed population.

3) Crude mortality (deaths per 100,000 inhabitants per year) from malignant neoplasms involving bone appeared to decline during the study period, falling from 1.6 in 1950 to about 0.95 in 1962. This decline was accounted for entirely by reduced mortality among those over 29 years old.

4) Some workers *(5)* felt at one point that if the study had used the key words "sarcoma" or "Ewing's tumor" in reviewing death certificates, rather than the broader concept of malignant neoplasms involving bone, a clearer indication of which neoplasms were induced by radiation might have been obtained. However, when the analysis was made on this basis, no significant difference was observed in mortality among the exposed and control populations.

Despite these various considerations, the researchers concluded at the time that "the adjusted mortality rates based on deaths coded to malignant neoplasms involving bone were consistently and sometimes significantly higher in the exposed population than in the control."

Additional complicating factors, which have led other scientists to conclude that no health effects due to high radium-226 levels in drinking water had been observed, are as follows:

1) Since water softening units remove radium, some households in the exposed area may have consumed little radium.

2) Since the study population was mobile, it is very difficult to know how long any kind of water may have been consumed.

3) Since bottled sources of drinking liquid were used by much of the population, it is difficult to know the exact origin of the water that was consumed.

Drinking water and cancer incidence in Iowa (15, 16). Using state-wide Iowa cancer incidence data for the years 1969-1971 and 1973-1978, age-adjusted and sex-specific disease rates for six cancer sites (bladder, breast, colon, lung, prostate, and rectum) were calculated for three groups of municipalities. For purposes of selection, it was decided that each municipality included in the study should have between 1,000 and 10,000 inhabitants, a public water supply derived solely from wells more than 152 meters deep, and an unsoftened public water supply. The 28 municipalities that qualified for inclusion in the study were then placed in three groups according to the radium-226 content of their water (0-2, 2-5, or over 5 picocuries per liter).

This study found that the rate of lung cancer among males increased with radium-226 levels, and that the relative risk for those in the highest radium-226 group was 1.68 times that of those in the lowest group. The test of the hypothesis that the rate of male lung cancer was the same for all the groups of municipalities showed that the observed differences were statistically significant ($P<.002$). Differences observed between rates of female breast cancer in the three municipalities appeared to be less significant ($P=0.07$).

When the municipalities were divided into two groups (one with water containing less than three picocuries of radium-226 per liter and one with water containing more than that amount), it was found that age-specific lung cancer rates for males of all age groupings were higher in the group of municipalities with over three picocuries of radium-226 per liter.

When smoking habits were investigated, no parallel was observed between geographic differences in smoking and differences in the radium levels of water supplies, and it was accepted that smoking patterns in the different groups of communities were similar. Other potential explanatory variables examined by multiple regression analysis included median income, occupation (agricultural versus industrial), and water fluoride levels. After these variables were considered, a significant relationship still remained between the radium-226 level and male lung cancer ($P=0.028$). The authors noted that geographic mobility during the onset of disease and the use of home water softeners (which are installed in about 42% of all Iowa homes) would both tend to reduce the population at risk. It was also suggested that radium-226 could be a surrogate for radon-222 and other radioactive elements, and that while definitive relationships could not be established, more detailed studies should be considered.

Results to Date

In all, the data from studies of human exposure to higher than normal levels of natural background radiation can be summarized as follows:

1) Chromosome aberrations have been observed.

2) Down's syndrome has been observed and may be related to radiation exposure.

3) Malignant neoplasms related to bone are apparently promoted by high concentrations of radium-226 in drinking water. There is concern about the validity of this conclusion. However, the same complicating factors that are cited as causing concern about the findings (e.g., water softening, population mobility, and the drinking of liquids from outside the study area) could very well be operating to reduce the number of malignant neoplasms that might otherwise have

been observed. In addition, when the Iowa study population was divided into just two age groups (above and below 30 years of age), the population below age 30 using water with a high radium-226 content was found to have a higher mortality than the control population in this age range (P = .10). This finding agrees with theoretical concepts postulated by E. E. Pochin concerning the optimum age at which populations should be studied for evidence of fatal malignancies due to radiation *(17)*.

4) Various researchers have looked for other effects including the following: heightened mortality from various cancers, gross congenital abnormalities, changes in the fertility index, effects on growth and development, an increase in hereditary diseases, heightened infant mortality, reduced longevity, increased multiple births, changes in the sex ratio, and increased rates of spontaneous abortion. Aside from the already noted increase in malignant neoplasms involving bone and the possible increase in Down's syndrome, these efforts have not demonstrated significant effects.

The fact that such effects have not been demonstrated may be due to any of several factors. For one thing, the normal frequency of a given effect in the study population may be so high that the excess produced through exposure to a higher radiation level cannot be determined—given the limited size of the study population. For another, sufficiently strict discipline may not have been maintained during the experimental observations, and errors may have been made in obtaining data. Finally, the effects involved may not occur at the levels of radiation to which the study populations have been exposed; that is, there may be a level of radiation below which the effect is not induced, or else is induced but can be counteracted.

Regarding cancer risks, the issue of statistically valid conclusions has been discussed by Land, who has given the following example based on the assumption that excess risk is proportional to radiation dose *(18)*. If a population of 1,000 were needed to determine the effect of 1 gray (100 rads), then for lower doses the following numbers would be required:

0.1 gray (10 rads)	100,000 people
0.01 gray (1 rad)	10,000,000 people

One of Land's contentions is that in view of the lack of resources for adequate studies of populations exposed to low levels of radiation, considerable risk is involved in trying to do the studies anyway, since misleading results could be obtained that would command undue credibility simply because of the effort expended on them.

A sample of the statistics dictating the population size required for cohort studies of radiation effects is provided in Table 6. The data in that table, based upon calculations by Dr. Roy E. Shore of the New York University Medical Center's Institute of Environmental Medicine, were derived using a formula presented by Schlesselman *(19)*. To give an example from the table, if the normal incidence of a disease in a control group were 12 cases per 100,000 group members per year, while the incidence in the exposed population (during the study period) were twice that of the controls (24 cases per 100,000), both the control group and the exposed population would need to be observed for 200,000 person-years in order to be 90% sure of finding a statistically significant difference while limiting the chance that the observed difference did not really exist to 5%.

Relevant comments on this subject have been included by Dreyer et al. *(20)* in a report on a feasibility study performed for the U. S. Nuclear Regulatory Commission. That study, mandated by the U.S. Congress, sought to determine if more epidemiologic research should be carried out for the purpose of resolving some of the controversy about the effects of low doses of radiation. The authors concluded that in view of the uncertainties involved, "no single population can securely provide enough information to distinguish the absence of effects from small effects at low doses" *(20)*. To overcome this difficulty, the pooling of data from studies of different groups was suggested. For purposes of their study, Dreyer et al. defined a "low" dose as a single dose of 5 rems (50 millisieverts) or less to the whole body, or a chronic dose that

Table 6. A table of multipliers showing how much the study group incidence must exceed the control group incidence, and how many person-years of observation would be needed, in order to be 90% sure of finding an apparently significant difference with 95% confidence that the difference found actually exists.

Person-years of observation per group	Multipliers showing how much the study group incidence per 100,000 inhabitants must exceed the control group incidence, given the control group incidences shown at the top of each column (cases per 100,000 population)[a]											
	0.5 cases	1 case	2 cases	4 cases	8 cases	12 cases	16 cases	24 cases	32 cases	48 cases	64 cases	100 cases
100	>1,000	>1,000	>1,000	>1,000	>1,000	675	507	339	255	171	129	84
250	>1,000	>1,000	>1,000	839	421	282	212	142	107	73	55	36
500	>1,000	>1,000	849	426	215	144	109	73	56	38	29	20
1,000	>1,000	854	429	216	109	74	56	38	29	21	16	11
2,000	860	430	216	110	56	38	30	21	16	12	9.3	6.8
4,000	432	217	110	56	30	21	16	12	9.3	6.9	5.7	4.4
6,000	289	146	74	39	21	15	12	8.5	7.0	5.3	4.5	3.5
8,000	218	110	56	30	16	12	9.3	7.0	5.7	4.5	3.8	3.1
10,000	175	89	46	24	13	9.8	7.9	6.0	5.0	4.0	3.4	2.8
15,000	118	60	31	17	9.8	7.3	6.0	4.7	4.0	3.2	2.9	2.4
20,000	89	46	24	13	7.9	6.0	5.0	4.0	3.4	2.9	2.5	2.2
30,000	60	31	17	9.8	6.0	4.7	4.0	3.2	2.9	2.4	2.2	1.91
40,000	46	24	13	7.9	5.0	4.0	3.4	2.9	2.5	2.2	2.0	1.77
50,000	37	20	11	6.8	4.4	3.5	3.1	2.6	2.3	2.0	1.9	1.68
70,000	27	15	8.7	5.4	3.7	3.0	2.7	2.3	2.1	1.85	1.72	1.56
100,000	20	11	6.8	4.4	3.1	2.6	2.3	2.0	1.88	1.69	1.59	1.46
200,000	11	6.8	4.4	3.1	2.3	2.0	1.88	1.69	1.59	1.47	1.40	1.32
500,000	5.9	3.9	2.8	2.2	1.77	1.61	1.52	1.42	1.36	1.29	1.23	1.19
750,000	4.6	3.2	2.4	1.91	1.61	1.49	1.42	1.33	1.29	1.23	1.20	1.16
1,000,000	3.9	2.8	2.2	1.77	1.52	1.42	1.36	1.29	1.25	1.20	1.17	1.14
5,000,000	2.0	1.68	1.46	1.31	1.22	1.18	1.15	1.12	1.10	1.08	1.07	1.06
10,000,000	1.68	1.46	1.32	1.22	1.15	1.12	1.11	1.09	1.07	1.06	1.05	1.04

[a]For example, if the control group had an annual incidence of 12 cases per 100,000 and the exposed population had an annual incidence 2.0 times that (24 cases per 100,000), then both the control group and the exposed population would need to be observed for 200,000 person-years.

was accumulated at the rate of 5 rems (50 millisieverts) or less per year. This classification was applied to both populations subjected to unusual levels of environmental radiation and populations that were occupationally exposed.

In addition, a 1981 report from the U.S. Government Accounting Office to the U.S. Congress concluded that "There is as yet no way to determine precisely the cancer risks of low-level ionizing radiation exposure, and it is unlikely that this question will be resolved soon" *(21)*.

Overall, as these comments suggest, the prognosis for a fruitful epidemiologic study of populations exposed to high natural radiation levels is not good. However, it is also difficult to extrapolate effects observed at high doses and high-dose rates, or in animal studies, to chronic low-level doses received by humans. At the same time, the need for information about the effects of human exposure to unusually high natural radiation levels is self-evident. Taking all of these points into consideration, the 1975 International Symposium on Areas of High Natural Radioactivity *(5)* made the following recommendations:

1) The World Health Organization (WHO), International Atomic Energy Agency (IAEA), and Food and Agriculture Organization (FAO), should encourage documentation of radioactivity anomalies and the extent of exposure of indigenous human populations. These agencies of the United Nations should also assist in establishing a worldwide system for comparing measurement and analytical techniques. This is particularly necessary for analytical procedures involving the heavy radionuclides, but it is also desirable for external radiation measurements.

2) The data on human exposure to thoron and radon in buildings are inadequate, and systematic measurements should be encouraged.

3) There is a need for long-term measurements of the dose to the lung from radon daughters. The dose should be expressed as rem (sievert) to the basal cells of the bronchial epithelium.

4) WHO, in collaboration with the IAEA, should offer assistance to developing nations that wish to assess the extent of the exposure of their populations to natural radioactivity.

5) All public water supplies derived from aquifers in sandstone or fractured granitic rock, or from aquifers in contact with black shales, should be sampled for radium-226. If the concentration is greater than 1 picocurie per liter (37 Bq per cubic meter), additional measurements should be made for radium-228, lead-210, and polonium-210.

6) The epidemiologic work in India's Kerala State and in Brazil should be continued. A firm negative finding would be useful, and there is the possibility that with development of new techniques some new unanticipated effects will be observed.

7) WHO/FAO should communicate with departments of agriculture in member states requesting that they provide information on the extent of farmland known to be fertilized naturally with uraniferous phosphates.

8) WHO/FAO should request that member states identify locations of public water supplies known to be derived from aquifers in contact with sandstone, fractured granite, or black shale.

9) The question of whether radiation resistance has developed among indigenous flora and fauna in areas near radioactive anomalies should be investigated.

Taking into account the scarcity of resources, it is understandable that some of these recommendations were not feasible, or were not of sufficient priority to warrant action. However, in view of current knowledge it appears that several of these recommendations (notably numbers two and three, and also number six with respect to Kerala State) merit further consideration.

With regard to recommendations two and three, it is noteworthy that a nationwide sampling of Canadian homes, carried out in the summer months of 1977 and 1978, found about 36% of the homes to have radon concentrations greater than 37 Bq per cubic meter (1 picocurie per liter) *(22)*. These concentrations were measured from samples taken in basements, when the homes studied had basements, and from samples taken at ground level in homes that had no basements. (Ventilation tends to be poor in basements, and radon tends to accumulate there.) In all, this work has come to include over 14,000 homes in 18 Canadian cities with a total population of 11 million inhabitants.

Using the resulting data, investigators have examined the relationship between lung cancer mortality and radon daughter concentrations while controlling for smoking habits *(23)*. The results have shown no association between radon daughter concentrations and lung cancer mortality, with or without the adjustment for smoking habits. This suggests that any effect of radon daughter exposure on lung cancer mortality must be small in comparison to the effect of smoking.

Other surveys carried out in Canada, Sweden, and the United States have indicated that sizable population groups may be exposed to average radon concentrations in the range of 2-10 picocuries per liter (74-370 Bq per cubic meter), and that in some locations (Sweden and eastern Pennsylvania) more than 10% of the study population may be exposed to concentrations greater than 20 picocuries per liter (740 Bq per cubic meter) *(24)*. Building materials, underlying soil and rocks, and well water have all been identified as sources of radon in homes with high concentrations *(25)*. Moreover, efforts to conserve energy by sealing houses tightly, and thus reducing ventilation, have resulted in higher radon levels.

The accumulated findings concerning exposure to radon in the home have created a dilemma for U.S. and other policymakers, because the exposures involved commonly exceed the maximum permitted exposure to man-made radiation sources. Therefore, if a U.S. policy similar to that for man-made radiation sources were pursued, limiting the permitted radiation dose to a small fraction (e.g., a tenth to a thirtieth) of the occupational dose limit, then a very large number of dwellings would have to be altered *(26)*. And even if this dose limit for population groups were raised to a quarter of the occupational limit, it would still require the alteration of about 4% of the houses in the United States, a circumstance creating considerable psychological and financial stress for their owners. In terms of lung cancer deaths, estimated on the basis of occupational exposure, the situation is as shown in Table 7.

Table 7. Estimated annual risk of death from lung cancer from various levels of radon daughter exposure, expressed in terms of the occupational exposure limit.

Fraction of occupational exposure limit (4 working level months per year)	Estimated risk of death after age 40 from lung cancer (deaths per year per million people exposed)
1/20[a]	40
1/10	80
1/8	100
1/4	200
1/2	400
1	800

[a]Estimated average natural background exposure in the United States.

According to calculations made by J. Harley *(26)*, if the population exposure were limited to the following indicated fractions of the occupational limit, the corresponding yearly reductions in lung cancer incidence would be as shown:

1/2 occupational limit = 600 lung cancer cases eliminated
1/4 occupational limit = 1,500 lung cancer cases eliminated
1/8 occupational limit = 3,000 lung cancer cases eliminated

However, the home alterations that might be required could be very costly, and a balance between risk-reduction and cost would be needed.

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Thus, looking at the development of studies conducted in high background radiation regions from the 1950s to the 1980s, it appears that the need for a clear quantitative assessment of the risk of low-level exposure to radiation, based upon epidemiologic observations in human populations, is as great as ever. Nearly 30 years ago, early Brazilian proponents of epidemiologic studies in high natural radiation areas were reputed to have said "Nature has been performing experiments for us for centuries. We need only the intelligence to ask her the right questions" *(5)*. That comment is as valid today as it was then.

SUMMARY

Possible health problems created by high natural levels of background radiation are hard to detect, partly because the health problems involved would exist to some degree irrespective of radiation exposure, partly because other factors affect the incidence of such problems, and partly because the differences between normal background radiation levels and radiation levels found in most high-radiation areas are not extreme. Nevertheless, the need to know about such health effects is evident, and so various studies conducted over the past 30 years have sought to determine whether those effects exist and what they are.

In Austria, investigation of mortality in the area of the Badgastein radioactive spa area detected no clear-cut relationship between residence in the area and lung cancer or reduced longevity. However, the observed frequency of chromosome aberrations in peripheral blood lymphocytes was found to increase as study population exposure to gamma radiation rose.

In Brazil, another study of peripheral lymphocyte chromosome aberrations found residents of an area with high natural background radiation to show a significant increase in the frequency of chromosome breaks. The finding was attributed to inhalation of thoron decay products (lead-212 and bismuth-212) rather than to high external radiation levels.

In China, long-term residents of an area with higher than normal background radiation were not found to have a significantly higher incidence of chromosome aberrations, malignancies, cancer mortality, spontaneous abortions, or childhood growth and development problems. Down's syndrome was found to be more common in the study population than in a control population, but the significance of that finding is uncertain because of the small number of cases involved.

In India, one research group found no significant health effects attributable to high background radiation except for a relatively low fertility index and high infant mortality in a group exposed to over 20 times the normal level of background radiation. However, another group detected an unusually high incidence of Down's syndrome and an unusually high level of chromosome aberrations among people living in an area with high natural background radiation.

In the United States, a retrospective study of 900,000 people living in communities with high levels of radium-226 in the drinking water found an abnormally high rate of death in certain age groups from malignant neoplasms involving bone. Another study found an association between levels of radium-226 in drinking water and rates of male lung cancer among exposed populations.

Also, surveys in Canada, Sweden, and the United States have indicated that sizable population groups may be exposed to high radon concentrations in the home. While the consequences of such exposure are uncertain, it has made policymakers consider what level of home exposure to radon should be allowed before building modification is required.

Overall, however, the fragmentary and uncertain nature of many of these findings makes it hard to draw firm conclusions about the health risks involved or the desirability of countermeasures. So despite considerable efforts and some progress over the past three decades, the need for a clear quantitative assessment of the consequences is as great as ever.

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