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An Advisory Committee of the Atomic Energy Control Board of Canada — Secretariat: Ottawa, Canada K1P 5S9
Comité consultatif de la Commission de contrôle de l'énergie atomique du Canada — Secrétariat: Ottawa, Canada K1P 5S9

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ACRP Advisory Committee on Radiological Protection

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RISK ESTIMATES FOR EXPOSURE TO ALPHA EMITTERS

by the

Advisory Committee on Radiological Protection

A report to the
Atomic Energy Control Board
Ottawa, Ontario

July 1982

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RISK ESTIMATES FOR EXPOSURE TO ALPHA EMITTERS.

A report submitted to the Atomic Energy Control Board by the Advisory Committee on Radiological Protection.

ABSTRACT

The primary scope of this report is to evaluate the risk of lung cancer from occupational exposure to short-lived daughters of radon and thoron. The Subcommittee on Risk Estimates (SCRE) considers that inhalation of radon and thoron daughters is the major radiation hazard from alpha radiation in uranium mining.

The secondary scope of this report is the consideration of the applicability of the risk estimates derived from miners to the general public.

The risk to members of the public from radium-226 in drinking water is also condidered.

Some research requirements are suggested.

SOMMAIRE

Le présent rapport vise d'abord à évaluer le risque de cancer du poumon résultant de l'exposition aux produits de filiation du radon et du thoron à courte période radioactive.

Le deuxième but est de considérer la possibilité d'appliquer au public en général les mêmes calculs estimatifs que ceux dérivés des études usr certains mineurs.

Le rapport aborde également la question du risque pour le public résultant de l'ingestion de radium 226 contenu dans l'eau potable.

On suggère enfin quelques recommandations importantes en matière de recherche.

Preface

Since the 1950's the Atomic Energy Control Board has made use of advisory committees of independent experts to assist it in its decision-making process. In 1979 the Board restructured the organization of these consultative groups resulting in the creation of two senior level scientific committees charged with providing the Board with independent advice on principles, standards and general practices related to radiation protection and the safety of nuclear facilities. The two committees are the Advisory Committee on Radiological Protection (ACRP), which held its first meeting in May, 1979, and the Advisory Committee on Nuclear Safety (ACNS), which was established a year later.

The records of meetings are filed in the AECB Library, and reports are catalogued and published as part of the Board's public document collection. Reports carry both a committee-designated reference number, e.g. ACRP-1, or ACNS-1, and an AECB reference number in the "INFO"-series.

Acknowledgements

The following report was prepared by the Standing Subcommittee on Risk Estimates (SCRE) of the Advisory Committee on Radiological Protection (ACRP) and endorsed by the ACRP at its May 1982 meeting.

The members of the Subcommittee on Risk Estimates at the time of preparation of this report were:

Dr. J. Muller, Chairman
Dr. T.W. Anderson
Dr. G.W. Gibbs
Dr. D.K. Myers
Dr. H.B. Newcombe

Dr. V. Elaguppillai, Secretary

The Subcommittee made use of the report on, "Risk Estimates for the Health Effects of Alpha Radiation", prepared by D.C. Thomas and K.G. McNeill under a contract with the Atomic Energy Control Board, (available as AECB report INFO-0081) and of other relevant publications in the scientific literature which are referenced in that report.

RISK ESTIMATES FOR EXPOSURE TO ALPHA EMITTERS

EXECUTIVE SUMMARY

Based on the consideration of practical needs to protect workers and the public from undue exposure to alpha radiation, the Subcommittee on Risk Estimates decided to give the evaluation of the health effects of inhalation of radon-222 and its short lived daughters the highest priority. The effect of radon-220 (thoron) and its short lived daughters was also considered because of the presence of these nuclides in some Canadian uranium mines. The Subcommittee also considered the health effects of ingestion of two naturally-occurring radium isotopes, radium 226 and radium 228.

The Subcommittee reviewed current research and considered future research requirements in Canada that might help to improve risk estimates for exposure to alpha emitters.

Type of data considered:

The effects of exposure to alpha radiation can be studied using simple biological models, experimental animals, observations on human populations, and microdosimetric techniques.

The Subcommittee found that each of the above approaches has its advantages and shortcomings. However, for the purpose of deriving quantitative risks estimates, it is most desirable to use human observations whenever possible, and resort to other approaches, mostly microdosimetry, whenever no useful human data are available.

Risk estimates for miners derived from epidemiological data:

A number of epidemiological studies, including studies of uranium miners in the U.S.A., Czechoslovakia and Ontario, fluorspar miners in Newfoundland and metal miners in Sweden, were reviewed by the Subcommittee.

The studies on uranium miners in the U.S.A. and Czechoslovakia were considered best suited for the purpose of risk evaluation.

Having examined the available data and their limitations, the Subcommittee concluded that the exact shape of the exposure-response relationship cannot be established with certainty. However, the best estimates of lifetime risk, as based on a linear relationship are not substantially different from the corresponding estimates obtained from a supralinear (convex) relationship. Differences between these estimates are of no practical significance.

The Subcommittee noted limitations in the various epidemiological studies on which risk estimates for miners exposed to radon daughters are based. In all cases, assumptions have to be made to extrapolate from observed risks over a limited period of observation to lifetime risk. The use of the relative risk model for extrapolation beyond the period of observation yields higher risk estimates, in terms of predicted life time excess cancer cases per unit exposure, than does the absolute risk model. The predicated loss of life expectancy calculated by the two approaches is not greatly different.

In risk estimates given by various agencies, different weights were assigned to various epidemiological studies. None of the agencies, however, had the benefit of the use of raw data for analysis. Since all agencies considered the same published data, it is not surprising that they arrived at similar ranges of risk estimates; minor differences are mainly due to the various weights given to the different studies and to the various models used to extrapolate to lifetime risk.

A summary of the various risk estimates for exposure to radon daughters are given in the following table:

Authors	Lifetime risk per WLM	
UNSCEAR 1977	$2 - 4.5 \times 10^{-4}$	(1)
UNSCEAR 1977	0.7×10^{-4}	(2)
BEIR 1980	$2 - 6 \times 10^{-4}$	(3)
ICRP 1981	$1.5 - 4.5 \times 10^{-4}$	(4)
Thomas & McNeill 1982	$0.5 - 12 \times 10^{-4}$	
SCRE 1982	$1 - 6 \times 10^{-4}$	(5)

The Subcommittee considers that the risk estimates by national and international agencies, as given above, are compatible with published epidemiological information, and that the lifetime risk of lung cancer incidence *for miners is probably in the range of* 1 *to* 6×10^{-4} *per* WLM.

Risk estimates for members of the public

The risk estimates based on miners' data should not be applied dirctly to the general population. No reliable epidemiological data are available at present that would allow risk estimates to be made directly for the general population. Since the absolute risk for the general population is likely to be lower than that for miners, the Subcommittee recommends that, based on the present evidence, for practical purposes, a risk estimate in the region of 1×10^{-4} per WLM may be applied to the general population.

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1) based on Czechoslovakian and Swedish data
2) based on Colorado data only
3) derived indirectly from the data given in BEIR 1980 report
4) obtained from ICRP publication 32
5) recommended by the Subcommittee on Risk Estimates of ACRP.

<u>Risk estimates for thoron daughters:</u>

The Subcommittee notes that there are no epidemiological data available to estimate the risk from exposure to thoron and its daughters. Hence it concludes, based on microdosimetric comparison, that the the risk of cancer induction by 1 WLM of thoron daughters is about one-third of that for 1 WLM of radon daughters.

<u>Radium in drinking water:</u>

The Subcommittee concludes that a reasonable estimate of the potential lifetime risk of radium-induced cancers would be about 3×10^{-4} for continuous lifetime ingestion of fluids containing 1 Bq (27 pCi) radium-226 per litre. Th risk per Bq radium-228 ingested is thought to be similar to that for radium-226.

<u>Research requirements:</u>

The Subcommittee reviewed current research and considered future research requirements. The most important requirements for future research in Canada that might improve risk estimates for alpha emitters appear to be related to epidemiological studies of miners in Canada. A number of specific suggestions are noted in the report.

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I. INTRODUCTION

The principal effects of exposure to low levels of ionising radiation are induction of cancer among some of the exposed individuals and of genetic effects among some of the descendants. The probability of these effects increases with increasing exposure. The relationship between exposure to radon and thoron daughters and the probability of health effects may be studied by the use of a) simple biological models, b) animal experiments, c) epidemiological techniques, and d) microdosimetric comparisons.

These approaches are not independent alternatives and are used together wherever possible. The strengths and limitations of the kinds of evidence contributed by each approach contributes are discussed briefly in the following sections.

a) Simple biological models

The relationship between exposure to alpha radiation and the corresponding biological effects could be studied in simple biological systems such as cell cultures. Although it is relatively easy to conduct experiments on simple systems, the effects observed on such systems cannot be easily extrapolated to complex systems, such as the human body, where additional mechanisms come into play. However, the data obtained from the study of simple biological systems may facilitate the better understanding of the mechanism of cancer induction in a complex system.

b) Animal experiments

Animal experiments are useful for the understanding of the exposure-response relationship in a complex system. While it is possible to design and to carry out such animal experiments under strictly controlled conditions, extrapolation of animal data to humans should only be carried out with great caution. Biological effects in different species may be qualitatively similar but are often quantitatively different. In view of these uncertainties it is not credible to make a direct extrapolation of risk estimates obtained from animal data to humans.

c) Epidemiological techniques

In epidemiological studies, human populations exposed to ionising radiation are followed for certain periods, and morbidity and mortality information is analysed.

The follow-up periods of health effects, such as cancers, do not normally extend up to the extinction of the exposed populations, and extrapolations over the remaining life span of the populations are therefore necessary. In addition, the accuracy of risk estimates is affected by a number of confounding factors that limit the direct applicability of risk estimates derived from one population to another. The risk estimates based on human studies are therefore not always directly applicable to other human populations.

d) Microdosimetric comparison

The microdosimetric comparison of radon and thoron daughters is based on the calculation of the mean effective dose equivalents resulting from the exposure to the respective radionuclides. The dose calculation requires the assumption of suitable kinetic models and of several variables such as the size of inhaled particles, fractions of attached and unattached daughter products, and their desorption rates from the attached dust particles. Several of these assumptions are subject to uncertainties, and therefore so also are the results of calculations based on these assumptions.

Microdosimetric comparisons are useful for estimating the risk resulting from the inhalation of radionuclides, such as thoron daughters, for which no epidemiological data are available. The risk estimates for thoron daughters may be based on the known effects of radon daughters, when allowance is made for the difference in the effective dose equivalents.

Microdosimetric calculations also play a valuable role in extrapolating from known health effects of certain radium isotopes to predicted effects of other bone-seeking radionuclides.

> *The Subcommittee on Risk Estimates concludes that each of the above four approaches has its uses and limitations. Whenever human data are available they should be fully utilized for risk estimates. These data are available for radon daughters. But no epidemiological data are available for measuring the health effects of thoron daughters on human populations. Hence risk estimates for thoron daughters could only be deduced from microdosimetric comparison with the effect of radon daughters.*

2. MAJOR EPIDEMIOLOGICAL STUDIES

Important sources of data used in the risk estimates for lung cancer come from the studies of uranium miners in the Colorado plateau and Czechoslovakia. Although data from other studies, such as the Ontario uranium miners and St. Lawrence fluorspar miners studies, are available in the literature, they suffer from serious methodological limitations. The two major studies as well as the Ontario uranium and Newfoundland fluorspar miners studies are discussed briefly in the following sections.

2.1 Colorado plateau uranium miners study

This is a cohort study of 3366 white and 780 non-white mine and mill workers who had worked one or more months underground in uranium mines in the Colorado plateau, before the end of 1963, and followed through September 1974.

It is a large study in which miners exposed to relatively high concentrations of radon daughters were well followed up. The study used a modified life-table technique, where miners were divided into various exposure categories depending on their cumulative exposure at different times during the individual's mining experience. With the accumulation of exposure, a miner may move from a lower to a higher exposure category, and the person-years accumulated while he was in the lower exposure category will be assigned to the lower exposure category. In this way a miner often contributed person-years at risk to more than one exposure category.

Exposures received by the miners were estimated on the basis of work histories and on nearly 43,000 radon daughter measurements in some 2,500 mines, measured during the period from 1951 to 1968. However, a large proportion of the estimated exposures in the study group is not based on actual measurements. In addition, the average exposure in each category was arbitrarily assumed to be the mean of the lower and upper limits of that category.

The observed cancer deaths in each exposure category were compared with expected deaths among the male population in the four states (Arizona, Colorado, New Mexico and Utah) in the Colorado plateau.

The data obtained from this study are in a form permitting the calculation of both absolute and relative risks of lung cancer.

2.2 Czechoslovakian uranium miners study

This is also a cohort study of a group of miners who started mining between 1948 and 1952, in the uranium mines in Czechoslovakia, and were followed through 1975. The exact size of the study group is not given but can be estimated at about 2300 persons. The exposure levels in this group were moderate as compared to the Colorado study. Individual smoking histories are not available. Instead, a random group of 700 miners was sampled to estimate the amount of smoking in the mining population as a whole. Apparently no difference was found in the smoking habits of the sampled mining group as compared with the general population.

Initial analyses of the Czechoslovakian data were based on life-table comparisons with national cancer death rates among males. In these analyses, the miners were divided into various categories based on their final exposures. The person-years at risk accumulated by a miner throughout his occupation were assigned completely to his final exposure category. In this approach, a miner contributed person-years at risk completely to the one category pertaining to his final exposure.

A subsequent re-analysis of the Czechoslovakian data used a modified life-table technique similar to that used in the U.S. study.

Radon daughter exposure data were estimated from work histories of the miners, and from a set of nearly 120,000 measurements of radon gas. Observed cancer death rates in each exposure category were compared with the national cancer death rates among the male population.

The data obtained from this study are in a form permitting the calculation of both relative and absolute risks of lung cancer.

2.3. Ontario uranium miners study

This is a combined cohort and case control study of about 15,000 miners who had worked one or more months in underground uranium mines in Ontario, between 1955 and 1974, and who were followed to the end of 1974.

The cohort study does not give data suitable for risk estimates, and the main limitations of the case control study are failure to adjust for age and person-years at risk.

2.4. <u>Newfoundland fluorspar miners study</u>

This is a cohort study of nearly 2,400 miners who had worked one or more months underground in the fluorspar mines in St. Lawrence, Newfoundland, between 1933 and 1971, and who were followed through 1971.

The main limitation of this study is unsatisfactory exposure estimates. The study is being re-evaluated by Health and Welfare Canada and the Atomic Energy Control Board.

> *The Subcommittee concludes that the U.S. and Czechoslovakian epidemiological data are the best available information for risk estimates. However, even these data have limitations and therefore the risk estimates based on these data are, at best, approximate.*

3. ABSOLUTE AND RELATIVE RISK MODELS

Lung cancer does not usually appear in excess until several years after the exposure to radon and thoron daughters. The excess is likely to continue well beyond 30 years and, until now, the follow-up in the various studies has not been for a sufficiently long period. Because of this difficulty, the cancer incidence beyond the follow-up period can only be projected using a suitable risk model.

There are two types of risk models, absolute and relative, commonly used in risk estimates. The absolute risk model assumes that the excess cancer rate begins a certain number of years after the exposure, and continues for a definite period, or to death. The absolute risk of cancer per unit exposure is defined as the ratio:

$$\frac{\text{(Observed number of cases)} - \text{(Expected number of cases)}}{\text{(Person years at risk)} \times \text{(Average exposure)}}$$

The relative risk model assumes that the excess cancer is expressed as a percentage of the natural, age-specific, cancer risk of the exposed population. Since the expected natural cancer rates increase sharply with age, the number of radiation-induced cancers may also increase sharply with the age of the exposed individuals. The relative risk of cancer per unit exposure is defined as the ratio:

$$\frac{\text{Observed number of cases}}{\text{(Expected number of cases)} \times \text{(Average exposure)}}$$

During the period of observation, both models give the same number of excess cancers per unit exposure. But they give different results when extrapolated beyond the period of observation. The lung cancer rate is highly dependent on age and the amount of cigarettes smoked. Extrapolation beyond the actual period of observation of study populations, yields a higher lifetime risk using the relative risk model than an absolute risk model which assumes a constant annual risk per unit of exposure independent of age. In spite of this fact, the predicted loss of life expectancy calculated by the two models is not greatly different. It is not yet clear which model is more appropriate for risk estimates in the case of radon and thoron daughter exposure.

The Subcommittee recommends that, in view of the above uncertainty, wherever possible, both absolute and relative risk models should be used to evaluate the risks of lung cancer due to exposure to radon daughters. However, for regulatory purpose, the final risk estimates should be expressed in terms of lifetime risk of excess cancers per unit exposure.

4. CONFOUNDING FACTORS AFFECTING THE RISK ESTIMATES

The risk estimates for lung cancer from exposure to radon and its daughters, given in this report, are based primarily on the epidemiological studies of U.S. and Czechoslovakian miners. Other relevant data have also been considered. The Subcommittee on Risk Estimates is aware of the many limitations in these studies. Nevertheless, these studies provide the best available data for deriving risk estimates for lung cancer in persons occupationally exposed to radon daughters. The various limitations in the major epidemiological studies are discussed briefly in the following sections.

4.1 Accuracy and precision of exposure estimates

Estimates of the radon daughter concentrations that existed in the uranium mines concerned are subject to uncertainties. Prior to 1951, only radon gas was measured. In the U.S.A., the pre-1951 measurements were made only in a few mines, while many mines were never investigated at all. Radon daughter concentrations in the uranium mines for the pre-1951 period were estimated on the basis of a few radon gas measurements, the history of the mining operations, and on the basis of radon daughter measurements in the post-1951 period. Although there are some reports of potential biases in the early measurements, the available data are not adequate to confirm such reports.

In Czechoslovakian mines radon gas measurements were made only during the years when the exposures were the highest. Assumptions of possible equilibrium conditions between radon and its daughters were made later, based on sporadic measurements of radon daughter concentrations carried out at a time when the ventilation had been improved. These facts lead to some doubt about the accuracy of exposure estimates.

4.2 Interaction between smoking and radiation exposure

Smoking is harmful to miners, as it is to other men, but, in addition, it appears to be more so in combination with exposure radon daughters. The interaction between smoking and radiation exposure may be either additive, multiplicative or a combination of both. Since most lung cancers in the general population are caused by cigarette smoking , differences in smoking habits between uranium miners and their control population may substantially alter the risk estimates.

Although more information is available about the smoking history of U.S. miners than others, the data are not adequate to identify clearly any specific mode of interaction between smoking and radon daughter exposure. However, the U.S. data seem to favour a mode of interaction which is intermediate between the additive and multiplicative processes. Smoking data on other uranium miners, including Czechoslovakian miners, are of poorer quality and no firm conclusion can yet be drawn about the mode of interaction between smoking and radon daughter exposure.

4.3 Other carcinogenic factors in the mining environment

Miners are likely to be exposed to other agents, such as dust, diesel fumes and trace metals which may be either carcinogenic or modify the carcinogenic effect of exposure to radon daughters. No human data are available to describe the effects of such agents in combination with exposure to radon daughters. On the other hand, some animal experiments have shown enhanced carcinogenic effects of exposure to radon daughters with co-exposure to haematite dust and some constituents of diesel fumes.

4.4 Other exposure prior to and after uranium mining

Uranium miners might have been exposed to radiation and other carcinogens in other mines (both hard rock and non-hard rock mines) or in other occupations, prior to or after their exposures in uranium mines. None of the available epidemiological studies have adequately allowed for all these possible contributing factors.

4.5 Time in relation to latency and age

The interval between the initiation of a cancer by exposure to radiation and the observed end point is the latent period. The end point may be the diagnosis of cancer or death due to cancer. If the exposure is received over a relatively short period, the latent period is the interval between the exposure and the chosen end point. In uranium mines, the exposures are usually received over several years and the interval between the initiation of cancer and the end point cannot be measured with confidence because of the uncertainty about the instant of initiation of cancer. Therefore, in such chronic exposure conditions, for practical purposes, the interval between the initial exposure and the chosen end point, usually cancer death, is frequently taken as the latent period.

Epidemiological studies indicate that excess lung cancer among uranium miners exposed to high concentrations of radon daughters in the past begins to appear about 10 years after the initial exposure, reaching peak levels in about 15 to 20 years, with excess cancer still observable 30 years later. Because of the uncertainty in the estimates of the time-course of lung cancer risk, estimates based on the available epidemiological data should be treated with caution.

The Subcommittee concludes that all confounding factors discussed in the above sections have not been adequately accounted for in available epidemiological studies, thus affecting both accuracy and precision of risk estimates.

5. EXPOSURE - RESPONSE RELATIONSHIP

The relationship between exposure and the corresponding health effects is frequently described by three patterns: linear, sublinear and supralinear. In the linear relationship, the risk per unit exposure is the same at all exposure levels. In the sublinear relationship, the risk per unit exposure increases with increasing exposure. On the other hand, the supralinear relationship suggests that the risk per unit exposure increases with decreasing exposure. The supralinear relationship is usually ascribed to a cell-killing effect at high exposure levels although other factors might possibly be involved. Although the cell-killing effect is established in radiation biology, it is not clear whether the same effect is apparent at concentrations of radon daughters that were, in the past, inhaled by uranium miners.

Thomas and McNeill* examined the nature of the exposure-response relationship for lung cancer among miners by using a general equation,

$$R = (A + bD^{c}) \qquad \text{Equation 1}$$

where R is the ratio of observed to expected cancers at exposure D, b and c are constants, and A is the ratio of observed to expected cancers at zero exposure.

If the constant $c = 1$, the exposure-response relationship is linear, implying that the risk per unit exposure is constant at all exposure levels.

If $c > 1$, the relationship is sublinear, implying that the risk per unit exposure increases with increasing exposure.

If $c < 1$, the relationship is supralinear, implying that the risk per unit exposure increases with decreasing exposure. This relationship is sometime called a power function of convex type.

Thomas and McNeill, in one of their analyses, assumed that observed and expected cancers are equal at zero exposure, implying $A = 1$, and fitted all available epidemiological data (including those of the Colorado plateau, Czechoslovakia, Newfoundland, Swedish and Ontario miners) and obtained a value of $c = 0.92$. This corresponds to a slightly convex (supralinear) relationship.

It should be pointed out, however, that the assumptions that miners with no exposure to radon daughter products above normal levels have the same lung cancer risk as the general male population chosen as controls and that their relative lung cancer risk at zero exposure is equal to one, are not necessarily valid. Differences in socio-economic status and in lifestyle might well cause the relative risk at "zero exposure" to be greater than one. Thus there is no justification for using a value of $A = 1$, in equation 1, when calculating risks. As a consequence there is no evidence from the epidemiological data for a supralinear exposure-response relationship at low exposures.

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* Thomas, D.C. and McNeill, K.G. Risk Estimates for the Health Effects of Alpha Radiation. INFO-0081, (1982), Atomic Energy Control Board, Ottawa, Canada.

An analysis of the risk estimates obtained from linear and supralinear models indicates (Table 1) that, for practical exposure levels, the estimates are not significantly different from one another. Other analyses carried out by Thomas and McNeill do not alter this conclusion.

Table 1

Excess relative risks estimated by linear (c = 1) and supralinear models (c = 0.92) at three different exposure levels

MODEL	Excess relative risk of cancers per WLM at 1, 10 and 100 WLM			Doubling dose in WLM
	1 WLM	10 WLM	100 WLM	
Supralinear (c = 0.92)	$3x10^{-2}$	$2.6x10^{-2}$	$2.1x10^{-2}$	44
Linear (c = 1)	$2.3x10^{-2}$	$2.3x10^{-2}$	$2.3x10^{-2}$	44

The Subcommittee concludes that, in view of the uncertainties in the various epidemiological data, the exact shape of the exposure-response relationship cannot be established with certainty. Best estimates of the excess relative risks based on a linear relationship are not substantially different from the corresponding estimates based on a supralinear (convex) relationship. Differences between these estimates are of no practical significance.

6. RISK ESTIMATES BY NATIONAL AND INTERNATIONAL ORGANISATIONS

The risk of lung cancer among miners exposed to radon and its daughters has been estimated in UNSCEAR[1] (1977), BEIR[2] (1980) and ICRP[3] (1981) reports.

UNSCEAR has examined the epidemiological data for uranium miners in Czechoslovakia, the Colorado plateau and Ontario, for fluorspar miners in St. Lawrence, Newfoundland and for metal miners in Sweden, and reported that most of the data are consistent with the linear exposure-response relationship. The most probable value for the lifetime risk of lung cancer for miners exposed to radon and its daughters is concluded to be in the range of 2.0 to $4.5x10^{-4}$ per WLM; this range is based mainly on the Czechoslovakian data. The risk estimate based on the Colorado data is about $0.7x\ 10^{-4}$ per WLM.

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1. United Nations Scientific Committee on the Effects of Atomic Radiation. U.N, New York (1977).
2. Advisory Committee on Biological Effects of Ionizing Radiations, U.S. National Academy of Sciences, Washington, D.C. (1980).
3. International Commission on Radiological Protection Pergamon Press, New York (1981). ICRP 32.

The BEIR 1980 Committee also analysed the major epidemiological data and favoured a linear exposure-response relationship, but did not give a value for lifetime risk of lung cancer for miners exposed to radon daughters. However, the Subcommittee on Risk Estimates made the assumption of a constant rate of exposure from age 20 to 64 and calculated the minimum lifetime risk, using a life-table technique and a constant risk factor independent of age at the time of appearance of cancer, and the risk of lung cancer starting 10 to 15 years after initial exposure. The maximum risk was calculated similarly, but the risk factor was assumed to increase with increasing age as indicated in the BEIR 1980 report. Based on these assumptions the numbers given in the BEIR 1980 report report are transformed into lifetime risks in the range of 2 to 6 x 10^{-4} per WLM. This estimate is primarily based on Czechoslovakian and Newfoundland data. The Colorado data gave a three-fold lower estimate. It should be noted that the BEIR Committee estimates imply that the risk of lung cancer is strongly dependent on the age at exposure, with a higher risk for older age groups.

The ICRP 1981 report suggests a lifetime risk of 1.5 to 4.5 x 10^{-4} per WLM based on epidemiological data. After consideration of microdosimetric as well as epidemiological data, the ICRP selected 1.65 x 10^{-4} per WLM as the best single value for the lifetime risk of cancer incidence resulting from inhalation of radon daughters by workers.

The report of Thomas and McNeill recommended an excess relative risk of 2.3 % per WLM. These authors have considered a variety of models for the prediction of lifetime risk of lung cancer among miners, assuming a constant rate of exposure from age 15 to 64 years. Their predicted lifetime risks for lung cancer from exposure to radon daughters cover a range from 0.5 to 12 x 10^{-4} per WLM*, with a best estimate of about 6.5 x 10^{-4} per WLM.

The Subcommittee has noted shortcomings in the various epidemiological studies on which risk estimates for miners exposed to radon daughters are based. In all cases, assumptions have to be made to extrapolate from observed risk over limited periods of observation to lifetime risk. The use of the relative risk model for extrapolation beyond the period of observation yields higher risk estimates than does the absolute risk model, in terms of predicted lifetime excess cancer cases per unit exposure. This however is not paralleled by a comparable predicted loss of life expectancy.

In risk estimates given by various agencies, different degrees of confidence were expressed concerning the various epidemiological studies. None of these agencies, however, had the benefit of the use of the raw data for analysis.

Since all agencies considered the same published data, it is not surprising that they arrived at similar ranges of risk estimates; minor differences are mainly due to the various weights given to the different studies and to the various models used to extrapolate to lifetime risk.

A summary of the various risk estimates for exposure to radon daughters are given in Table 2.

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* See Tables 8.2 and 8.3 on pages 125-6 of the Thomas-McNeill report.

Table 2

Summary of the various risk estimates for exposure to radon daughters

Authors	Lifetime risk per WLM*	
UNSCEAR 1977	$2 - 4.5 \times 10^{-4}$	(1)
UNSCEAR 1977	0.7×10^{-4}	(2)
BEIR 1980	$2 - 6 \times 10^{-4}$	(3)
ICRP 1981	$1.5 - 4.5 \times 10^{-4}$	(4)
Thomas & McNeill 1982	$0.5 - 12 \times 10^{-4}$	
SCRE 1982	$1 - 6 \times 10^{-4}$	(5)

The Subcommittee considers that the risk estimates by national and international agencies as given above are compatible with published epidemiological information, and that the lifetime risk of lung cancer incidence for miners is probably in the range of 1 to 6 x 10^{-4} per WLM.

7. APPLICABILITY OF MINERS DATA TO THE GENERAL POPULATION

The composition of a mining population is significantly different from that of the general population. An average member of the general population is not normally exposed to the same levels (and types) of dust, cigarette smoke, diesel fumes and other air contaminants that a miner is. This is particularly true for females in the general population. Breathing rates are also likely to be different because of differences in age and physical activity. Hence the risk estimates obtained from the miners data cannot be applied directly to the general population.

High risk estimates for the general public, approaching 10×10^{-4} per WLM have been suggested by some investigators, on the basis of the relative risk model. However, an analysis by Evans and others** gave a maximum risk estimate of 1×10^{-4} per WLM for the general public.

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* 1) based on Czechoslovakian and Swedish data
2) based on Colorado data only
3) derived indirectly from the data given in BEIR 1980 report
4) obtained from ICRP publication 32
5) recommended by the Subcommittee on Risk Estimates of Advisory Committee on Radiological Protection (ACRP).

** Evans, R.D., Harley, J.H., Jacobi, W., McLaren, A.S., Mills, W.A. and Stewart, C.G. Estimate of risk from environmental exposure to radon-222 and its decay products. Nature, Volume-290, 12 March 1981, pp. 98-100.

The Subcommittee concludes that the risk estimates based on miners data should not be applied directly to the general public. No reliable epidemiological data are available at present that would allow risk estimates to be made directly for the general public. The absolute risk for the general public is likely to be lower than that for miners. For practical purposes, the Subcommittee recommends that, based on present evidence, a risk estimate in the region of 1 x 10^{-4} per WLM be applied to the general population. The WLM is in this case defined simply as exposure to one WL for 170 hours without any corrections for variations in breathing rates.

8. RISK ESTIMATE FOR EXPOSURE TO THORON DAUGHTERS

The observed excess cancers among miners who worked in Elliot Lake uranium mines can be ascribed to the combined exposure to radon and thoron daughters; but there are no epidemiological data from which the hazards of thoron daughters alone can be assessed. Therefore risk estimates for exposure to thoron daughters can best be obtained by microdosimetric comparisons that permit extrapolations from the known effects of exposure to radon daughters.

The main contribution to the WLM from thoron daughters is derived from the long-lived ^{212}Pb (ThB, $t_{\frac{1}{2}}$=10.6 hours). Its half-life is sufficiently long to allow for significant translocation from the lungs into other parts of the body. Thus, many of the alpha particles are emitted in tissues other than the lungs. By contrast the daughters of radon-222 all have half-lives much shorter than lead-212 and emit most of their alpha particles in the lungs. Therefore, exposure to 1 WLM of radon daughters gives a threefold greater dose equivalent to the lungs, and a threefold greater cancer risk, than exposure to 1 WLM of thoron daughters.

The Subcommittee on Risk Estimates concludes that, based on microdosimetric comparison, the risk of cancer induction by 1 WLM of thoron daughters is about one-third that for 1 WLM of radon daughters.

9. HEALTH EFFECTS FROM RADIUM IN DRINKING WATER

Data on health effects of radium come primarily from studies on about 900 patients injected for therapeutic reasons with radium - 224 in Germany, and about 2000 dial painters and other persons in the U.S.A. who ingested appreciable quantities of radium - 226 (plus radium-228). Excess bone cancers appeared in both groups; in the individuals with significant uptake of radium - 226, excess head carcinomas also appeared.

The BEIR 1980 and UNSCEAR 1977 reports derived risk estimates from the above epidemiological data. The lifetime risk estimates for radium - 224 were about 2 x 10^{-4} per rad of average bone dose, corresponding to a risk of 0.25 x 10^{-4} per rad of dose to endosteal cells (bone lining cells). Thomas and McNeill arrived at a similar estimate of risk (Table 3).

Table 3

Estimates of life time risk of bone cancer after exposure to radium - 224

Source of estimate	Risk per rad average bone dose per 10^4 persons
UNSCEAR (1977)	1.7 - 2.2
BEIR III (1980)	2
Thomas-McNeill - (1982)	1 - 2

The same dose-equivalent to the endosteal cells should have the same effect independent of whether it was produced by radium - 224 or radium - 226. Epidemiological data are compatible with this assumption.

Radium-226, which is formed in the uranium-238 decay series, is present in minute amounts in most drinking water and foodstuffs. The concentrations of radium-226 in drinking water in Canadian cities and towns do not normally exceed 0.01 Bq (0.3 pCi) per litre. Under these conditions, much of the normal ingestion of radium-226 (0.03-0.06 Bq/day) results from the ingestion of foodstuffs. Radium-228 (and its daughter radium-224), which is formed in the thorium-232 decay series, has received less attention; according to UNSCEAR 1977, the amount of radium-228 in the human body is usually about one-third that of radium-226.

The Guidelines for Canadian Drinking Water Quality (1978)* set for radium-226, a target concentration of 0.1 Bq per litre and a maximum acceptable concentration of 1 Bq per litre. Using a linear dose response relationship, Thomas and McNeill estimated that continuous ingestion throughout life of water containing 1 Bq of radium-226 per litre would result in a lifetime risk of about 4 radiation-induced cancers per 10^4 persons. Approximately half of these cancers would be bone sarcomas and half would be head carcinomas. This calculated lifetime risk depends on certain assumptions concerning retention of ingested radium in children which are believed to be overly simplified.

The ICRP 1979 metabolic and microdosimetric models indicate that ingestion of 1 Bq of radium-226 by adults would result in an accumulated dose over the next 50 years of 3.4×10^{-5} rad to the bone surfaces. Assuming a lifetime risk of 0.25×10^{-4} bone cancers per rad to the bone surfaces, continuous ingestion of 2 litres per day of water containing 1 Bq radium-226 per litre for 50 years would result in a maximum lifetime risk of about 0.3 bone cancers per 10^4 persons.

Taking into account the doses to other organs and tissues, the risk factor per Bq of radium-226 ingested is about four times higher. Extending the exposure over the whole lifetime increases the risk still further.

On the basis of microdosimetric comparisons, the risk per Bq from ingestion of radium-228 is thought to be similar to that for radium-226.

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* Health and Welfare Canada. Ottawa, Canada (1978).

The Subcommittee concludes that a reasonable estimate of the potential lifetime risk of radium-induced cancers would be about 3×10^{-4} for continuous lifetime ingestion of fluids containing 1 Bq (27 pCi) of radium-226 per litre. The risk per Bq of radium-228 ingested is thought to be similar to that for radium-226.

10. RESEARCH REQUIREMENTS

Various experimental approaches to improvement of risk estimates for exposure to alpha emitters have been considered. Improvements to the metabolic models used in microdosimetric comparisons are currently under active development in Canada, the U.K., the U.S.A., West Germany and other countries; it is recommended that these improvements in microdosimetry should be kept under active review. Animal experiments on cancer induction by radon daughters and other alpha emitters have been carried out and are continuing in France, the U.S.A. and other countries; some animal experiments on carcinogenic interactions between radiation and cigarette smoke condensate have also been carried out in Canada. The results of these animal experiments should also be kept under active review.

Epidemiological studies on miners in Canada are directly concerned with a practical situation where deleterious health effects of alpha emitters have been demonstrated in human populations. Points noted by the Subcommittee are listed below.

(a) The Newfoundland fluorspar miners, Ontario miners and Eldorado miners who were in the past exposed to high concentrations of radon daughters are already under study. The Subcommittee strongly encourages continuation of these studies.

(b) Information on other groups of uranium miners in Canada may be most readily available in future through the National Dose Registry of Health and Welfare Canada. The Subcommittee recommends that the National Dose Registry ensure that uranium miners can be readily identified in their files by place and duration of work, as well as by name and the other usual identifiers. This additional identification by place and duration of work is important so that follow-up studies will be possible in the future even where no other agency is able to supply lists of names of miners to the National Dose Registry.

(c) Continuing efforts are encouraged to collect smoking histories of miners as an aid to statistical interpretation of group data.

(d) Efforts are strongly encouraged to improve methods to facilitate and reduce the costs of follow-up of miners using the records in the Canadian Mortality Data Base and the National Cancer Incidence Reporting System.

(e) Reports on the results of epidemiological studies of past miners should be combined with estimates of the range of uncertainly of past exposures to radon daughters, thoron daughters and external radiation.

(f) Current efforts to measure individual exposures of miners to radon daughters, thoron daughters and external radiation will greatly facilitate future epidemiological studies.

(g) The possibility should be explored whether or not radiological findings or other health indicators provide useful predictions of mortality outcome.

As a result of further considerations, the Subcommittee cautions against large scale studies of populations with very small differences in levels of exposure to radon daughters or other alpha emitters, particularly when these studies are costly and the expected differences in health effects are so small that they would not be detectable against a fluctuating background of cancer incidence in which the effects of other carcinogenic agents are overwhelming. Studies of this kind will not lead to any improvement in risk estimates for alpha emitters. Past radium workers from the Eldorado refinery in Port Hope are already under study, as are past employees of Atomic Energy of Canada Limited, some of whom may have been occupationally exposed to low levels of alpha emitters; it is however not anticipated that either of these studies will provide information that will improve current risk estimates for alpha emitters. Members of the Subcommittee did not know of any other identifiable population group in Canada, other than those considered above, which should be investigated in order to improve risk estimates for alpha emitters. Two potential Canadian groups that have not been identified are patients exposed in the past to Thorotrast and past radium dial painters; methods by which persons in these groups could be identified and their exposures could be determined should be considered.

The Subcommittee reviewed current research and considered future research requirements. The most important requirements for future research in Canada that might improve risk estimates for alpha emitters appear to be related to epidemiological studies of miners in Canada.