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LONG-TERM INVESTIGATIONS IN AUSTRIA OF ENVIRONMENTAL NATURAL SOURCES OF IONIZING RADIATION AND THEIR IMPACT ON MAN*

By F. STEINHÄUSLER

From the Institute for General Biology, Biochemistry and Biophysics, Division of Biophysics, University of Salzburg

(Div.-Director: Univ.-Prof. Dr. E. Pohl)

Summary

The exposure of man to the natural radiation environment (NRE) represents the largest contribution to the radiation burden from all sources of ionizing radiation. The dose due to this exposure results in an increased risk for predominantely somatic effects, e. g. cancer induction. In many national and international radiation protection guidelines the exposure from the NRE is recommended as a reference baseline. However, the practical application of this recommendations is difficult: a) NRE-levels show large temporal and local variations; b) individual doses resulting from this exposure are very different in a given population due to the large range of living- and working conditions and age- and sex-dependence of dose assessments. Furthermore the characterization of the radiation burden of population groups using the whole body dose-concept is unsuitable because the absorbed dose differs largely for different organs and tissues.

In an investigation over several years the NRE was studied for three population groups in Austria: citizens in a "normal" environment; non-uranium miners with elevated occupational exposure only; inhabitants and employees of radon spas with generally increased NRE-levels. Main emphasis was on the determination of individual doses for different radiation sensitive tissues and organs. Applying a methodology based on demoscopical methods frequency distributions of the external gamma dose rate ($>$ 3100 measurements) and atmospheric radon and decay products ($>$ 8800 measurements) were

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determined for a city, and in modified version also for mines and spas. In addition dietary uptake was determined by radionuclide analysis of food and drinking water. In Salzburg city 90 % of the exposure rate is less than 60 mR/yr. However, despite this low external irradiation almost 20 % of the rooms show an annual mean radon concentration between 1 and 5 pCi/l. This exceeds by far the maximum permissible concentration (MPC) of 0.33 pCi/l as defined in Austria for non-occupational continuous exposure from man-made sources. In the case of non-uranium underground miners more than 10 % of the work sites show radon concentration values in excess of the Austrian MPC-value for occupational exposure, i. e. 30 pCi/l, whilst the occupational gamma ray exposure is neglegible. In the spa area of the Gastein valley the terrestrial gamma dose rate is significantly higher than in Salzburg city, mainly due to the elevated radionuclide content of both subsoil and construction material. This causes in about 15 % of the cases the gamma dose rate indoors to range from 120—200 mR/yr and the radon concentration from 3—9 pCi/l, although neither of these buildings is used in connection with therapeutic radon treatment. In 10 % of the buildings, where radon mineral water is used for treatment, indoor radon values range from 18—80 pCi/l and in over 5 % 150 pCi/l can be reached.

With the radioactivity data of the urban environment and age-dependent life-style patterns individual organ-specific dose histograms were calculated for 729 test subjects. The highest dose is absorbed in the basal cell of the bronchial epithelium, where about 5 % of the citizens are exposed to levels beween 5000 and 11000 mrem/yr, although Salzburg city is considered an area with "normal" radioactivity. In the case of miners and spa inhabitants, resp. workers dose calculations were carried out for different population groups, based on the central range of radioactivity data for the characterisation of the specific NRE. Under disadvantageous working conditions in underground mines the occupational dose to the basal cells — in addition to the dose from the NRE during spare time — can reach almost 4000 mrem/yr. This value is even exceeded by employers in radon treatment facilities, who are exposed to a bronchial epithelial dose up to 22000 mrem/yr. Since inhaled radon and decay products are considered to induce lung cancer, the risk for lung cancer induction due to exposure to the NRE was calculated using data on spontaneous lung cancer rates and data from epidemiological studies. Applying conservative risk assumptions derived from epidemiological studies amongst uranium-miners up to 100 % of all non smoking related spontaneous lung cancer cases in a "normal" urban environment may be attributed to inhaled radon decay products. For some employees in the investigated radon spa hotels and treatment centers the risk for lung cancer induction is up to ten times higher than for a citizen of Salzburg. The risk from NRE-exposure can exceed man-made radiation and other non-radiation risks (including traffic accidents) of man's environment.

Zusammenfassung

Die Strahlenexposition des Menschen durch die natürlich radioaktive Umwelt (NRU) liefert den größten Beitrag zur Strahlenbelastung durch alle Quellen ionisierender Strahlung. Die aus dieser Exposition resultierende Dosis bedingt ein erhöhtes Risiko für vorwiegend somatische Effekte, z. B. Krebsinduktion. In vielen nationalen und internationalen Strahlenschutz-Richtlinien wird die Strahlenbelastung durch die NRU als Referenzwert empfohlen. Jedoch ist die praktische Anwendung dieser Empfehlung aus folgenden Gründen schwierig: a) NRU-Werte zeigen ausgeprägte zeitliche und örtliche Schwankungen; b) Individualdosen aus dieser Exposition sind stark unterschiedlich für eine gegebene Bevölkerung aufgrund der großen Unterschiede in den Lebens- und Arbeitsbedingungen sowie der Alters- und Geschlechtsabhängigkeit der Dosisberechnungen. Weiters ist die Charakterisierung der Strahlenbelastung von Bevölkerungsgruppen unter Verwendung des Begriffs der „Ganzkörperdosis" ungeeignet, da die absorbierte Dosis für verschiedene Organe und Gewebe stark unterschiedlich ist.

In einem mehrjährigen Forschungsprogramm wurde die NRU für drei Bevölkerungsgruppen Österreichs studiert: Stadtbewohner in einer „normalen" Umwelt; Bergarbeiter (ausgenommen Uranbergbau) mit lediglich beruflich bedingter erhöhter Strahlenbelastung; Bewohner und Beschäftigte in Radonkurorten mit generell erhöhten NRU-Werten. Schwergewicht der Untersuchung lag bei der Bestimmung von individuellen Dosen für Gewebe und Organe mit unterschiedlicher Strahlenempfindlichkeit. Unter Anwendung einer demoskopischen Untersuchungsmethode wurden Häufigkeitsverteilungen der externen Gammadosisleistung (> 3100 Messungen) und des atmosphärischen Gehaltes an Radon und seinen Zerfallsprodukten (> 8800 Messungen) für eine Großstadt bestimmt; in einer modifizierten Form ebenfalls für Bergwerke und Kurorte. Zusätzlich wurde die Aufnahme durch die Nahrung mittels Radionuklidanalyse von Lebensmitteln und Trinkwasserproben erfaßt.

In Salzburg-Stadt beträgt die Strahlenexposition in Räumen in 90 % der Fälle weniger als 60 mR/Jahr. Trotz dieser niedrigen externen Strahlenbelastung weisen annähernd 20 % der Räume eine jährliche mittlere Radonkonzentration zwischen 1 und 5 pCi/l auf. Dies übertrifft bei weitem die maximal zulässige Konzentration (MZK) von 0,33 pCi/l, wie sie in Österreich für nichtberuflich bedingte kontinuierliche Strahlenbelastung durch künstliche Strahlenquellen gültig ist. Im Fall von Bergarbeitern in Untertagbaubetrieben liegt in über 10 % der Fälle die Radonkonzentration am Arbeitsplatz über dem in Österreich zulässigen MZK-Wert für beruflich bedingte Strahlenexposition (30 pCi/l); hingegen ist die beruflich bedingte Belastung durch Gammastrahlung vernachlässigbar. Im Gebiet der Radon-Kurorte des Gasteiner Tales ist die terrestrische Gammadosisleistung beträchtlich höher als in Salzburg-Stadt, vorwiegend aufgrund des erhöhten Radionuklidgehaltes

von Boden und Baumaterial. Dadurch bedingt reicht in 15 % der Fälle die Gammadosis in Räumen von 120 bis 200 mR/Jahr und die Radonkonzentration von 3 bis 9 pCi/l, obwohl keines dieser Gebäude für Zwecke der Radontherapie verwendet wird. In 10 % jener Gebäude, in denen radonhaltiges Thermalwasser zu therapeutischen Zwecken Verwendung findet, reichen die Radon-Raumluftwerte von 18 bis 80 pCi/l; in über 5 % der Fälle können 150 pCi/l erreicht werden.

Mit den Radioaktivitätsdaten über die urbane Umwelt und altersabhängige Lebensgewohnheiten wurden individuelle organ-spezifische Dosishistogramme für 729 Testpersonen berechnet. Die höchste Dosis erhalten die Basalzellen des Bronchialepithels, wobei ca. 5 % der Stadtbewohner eine Belastung zwischen 5000 und 11 000 mrem/Jahr erhalten, obwohl Salzburg-Stadt als Gebiet mit „normaler“ Umweltradioaktivität betrachtet wird. Im Fall von Bergarbeitern und Bewohnern bzw. Arbeitern in Radonkurorten wurden Dosisberechnungen für verschiedene Bevölkerungsgruppen durchgeführt, wobei die spezifische NRU durch die zentrale 90-%-Masse der Daten charakterisiert ist. Bei ungünstigen Arbeitsbedingungen im Untertagbergbau kann die beruflich bedingte Dosis der Basalzellen — zusätzlich zur Dosis durch die NRU während der Freizeit — annähernd 4000 mrem/Jahr erreichen. Dieser Wert wird sogar noch übertroffen von Arbeitern in Radontherapiestationen, die eine Bronchialepitheldosis bis zu 22 000 mrem/Jahr erhalten. Da Inhalation von Radon und Zerfallsprodukten als Ursache für die Induktion von Lungenkrebs anzusehen ist, wurde das Risiko für die Entstehung von Lungenkrebs aufgrund der NRU-Exposition berechnet. Diesen Berechnungen lagen Angaben über die spontane Lungenkrebshäufigkeit und von epidemologischen Untersuchungen an Uranbergarbeitern zugrunde. Sogar bei Verwendung von konservativen Annahmen über das Risiko können möglicherweise bis zu 100 % aller spontanen Lungenkrebsfälle unter Nichtrauchern in einer „normalen“ Umwelt auf die Inhalation von Radonzerfallsprodukten zurückgeführt werden. Für einige Arbeiter in den Hotels und Therapiezentren der untersuchten Radonkurorte ist das Risiko einer Lungenkrebsinduktion bis um einen Faktor 10 erhöht gegenüber dem eines Bewohners der Stadt Salzburg. Das Risiko durch NRU-Exposition kann größer sein als das Risiko durch künstliche Radioaktivität oder auch andere Risiken (inklusive Straßenverkehr) in der Umwelt des Menschen.

1. Introduction

In the past the radiological impact resulting from man’s exposure to the natural radiation environment (NRE) has been underestimated. This is in contrast to the widespread concern about environmental contamination and associated risks due to the intended large scale use of nuclear technologies, e. g. for power production. In order to assess any risk from a certain action, such as the introduction of a new technological process, it is necessary to relate this risk to a defined baseline. Already in 1960 it was suggested to use for this purpose the "natural background radiation" [1]. At present the use of this concept is proposed again in the mathematical treatment of risks from low-level radiation exposure and appropriate setting of standards for the general population. It is suggested that a level of man-made radiation is acceptable if this level is "small" compared to the natural background; "small" should be taken as the standard deviation of the population weighted natural background [2, 3]. Also international radiation protection recommendations and regulations of national committees define the NRE as the point of reference for all legislative definitions of the maximum permissible radiation burden from man-made sources [4, 5]. This concept has the following inherent advantages:

a) mankind has always been exposed to the NRE during all stages of evolution, resulting in a steady-state exposure to a temporally constant level of risk;
b) the level of this risk can only be partially influenced by technical means, e. g. choice of building material and ventilation conditions in the building.

The situation is complicated by the fact that even the presently valid recommendations by the International Commission on Radiological Protection (ICRP) states that its dose limits are not intended to apply to "normal" levels of natural radiation. At the same time ICRP admits that there is no sharp dividing line between levels of natural radiation than can be regarded as "normal" and those that are more elevated owing to human activities or choice of environment [6].

Therefore, the practical application of the concept is associated with great difficulties because of the rather ambiguous definition of the terms "natural"- and "background radiation" Man ceased living in a "natural" radiation environment during all of his evolution. Since then his various activities resulted finally in such a modification of his NRE that today man is increasingly exposed to technologically enhanced natural radioactivity (TENR). This leads to the request for jurisdiction over the use and occurrence of naturally occurring radioactive material and the formation of special national and international committees, e. g. US-Task Force on Natural Radioactivity Contamination Problems [7] or OECD/NEA Group of Experts on Radon Dosimetry and Monitoring [8]. Furthermore, the quantitative determination of the radiation burden resulting from the NRE is a complex task because it results from the superposition of many components, some of which show pronounced local and/or temporal variations. Significant differences of the NRE can be found within every country, even within a small region such as a town. Numerous investigations have been carried out on one or the other component of the NRE [4]. However, in all cases only mean values for population groups have been reported. This information has only limited use, since the knowledge of the mean dose value does not permit the assessment of the number of people in high risk groups, who receive a dose e. g. ten times higher than average. Even if it is possible to group the population of a region according to the radioactive environment in which it is living, the radiation burden is very different for various tissues and organs. Therefore organ- and tissue-specific dose frequency distributions have to be determined for the given population.

This paper describes the demoscopical methodology developed and its application in the assessment of the total radiation burden to different organs and tissues from the NRE. Three population groups, living, resp. working in very different radiation environments were studied:

a) an urban population in a typical European city, representative for the "normal" NRE;
b) miners in non-uranium mines, working only in an elevated NRE;
c) inhabitants and workers in a radon spa area, living and working at elevated levels of natural radioactivity.

The potential risk for radiation induced somatic damages, resulting from the exposure to the specific NRE is determined and compared to risks from other man-made sources.

2. Sources of the natural radiation environment

Man is irradiated externally by cosmic rays and by natural radioactive nuclides in the geological subsoil, construction material and atmosphere; the latter representing the terrestrial gamma radiation component. Due to incorporated natural radionuclides the human organism receives also internal irradiation via the main pathways inhalation and ingestion (Fig. 1).

2.1 Cosmic rays

Cosmic rays in the lower layers of the atmosphere consist of an ionizing and a neutron component. Although the ionizing component has been studied extensively for the last fifty years, data in the literature differ up to 40 % [9, 10, 11]. At present the most probable value for the dose outdoors due to the ionization component is 28 mrad/yr at sea level [4]. Indoors shielding occurs due to attenuation of the incident electrons. This results in a reduction of the absorbed dose, e. g. in the case of a concrete layer within a thickness of 200 mm about 15 % as compared to outdoors [12].

As large uncertainties are associated with data on the neutron component, neutron flux densities have been reported which vary by almost a factor 3 [13]. For estimates of the annual absorbed dose at sea level and latitudes above 40° 0.4 mrad is the most likely value.

2.2 Terrestrial gamma radiation

Outdoors about 98 % of the external exposure results from the members of the ^{238}U-series. ^{232}Th-series and ^{40}K contained in the ground; the gamma flux from radon daughters in the air accounts for the rest under normal atmospheric conditions. About 65 % of the total exposure rate from naturally occurring sources in the ground results from photons with an energy between 0.5 and 2 MeV and a mean of about 1 MeV [14].

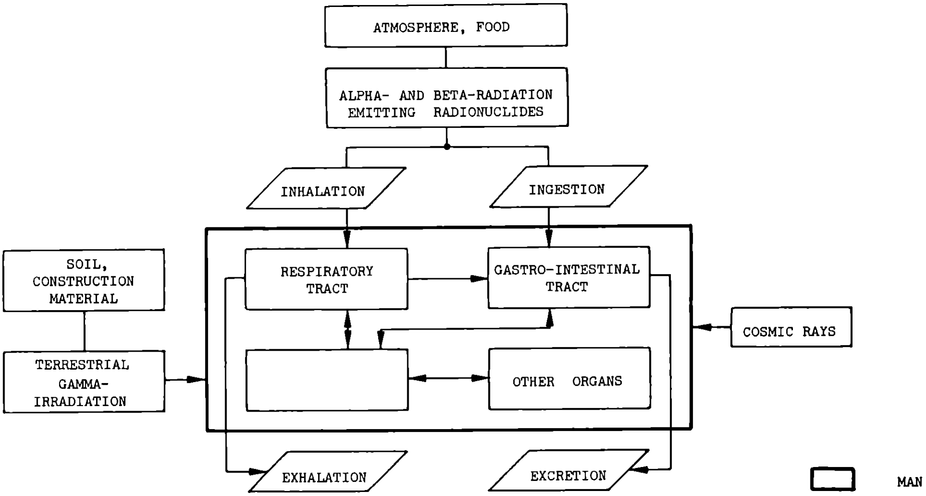

Fig. 1: Compartmental description of external and internal sources of the natural radioactive environment (NRE) and their impact on man

Indoors the gamma dose level is mainly determined by the content of ^{226}Ra, ^{232}Th and ^{40}K in the construction material used. The material can act both as an additional source of radiation and in most cases also as shielding material against the gamma radiation from sources outdoors. Only in the case of thin wall-construction ($< 10\ \mathrm{gcm}^{-2}$) and using materials of low density, e. g. prefabricated wooden buildings, gamma radiation originating outdoors will also contribute significantly to the exposure indoors.

2.3 ^{222}Rn, ^{220}Rn and their decay products

Radon is exhaled from the soil, rocks and construction material and is always present in the atmosphere outdoors as well as indoors. Radon and its decay products, incorporated via inhalation, cause in parts of the respiratory tract the highest radiation dose from all natural sources.

Outdoors and indoors radon concentration changes temporally because of the influence of meteorological parameters, resp. ventilation conditions. The influence of the former was studied indoors in closed rooms in dependence of 24 meteorological variables [15]. The results of the multiple regression analysis showed that the statistically significant variables can be grouped into two categories, signifying the influence of exhalation on the radioactivity in room air and the dependence on the atmospheric stability conditions in the lower layers of the atmosphere (Tab. 1).

Table 1

Statistically significant meteorological variables showing influence on different radionuclides (A_i) contained in room air and the time delay (Δt) before their influence becomes effective indoors (15)

Meteorological variable	Effective period Δt (hours)	Radionuclide effected A_i
Influence on exhalation:		
Dropping barometric pressure	24	^{220}Rn, ^{222}Rn, ^{212}Pb, ^{214}Pb
Rising soil temperature	24	^{222}Rn, ^{212}Pb, ^{214}Pb
Rising mean temperature outdoors	24	^{222}Rn, ^{212}Pb
Stability effect:		
Change of daily mean wind speed	24	^{220}Rn, ^{222}Rn, ^{212}Pb, ^{214}Pb
Temperature gradient of surface layer atmosphere	0	^{222}Rn*
Change of relative humidity outdoors	7	^{220}Rn, ^{222}Rn, ^{212}Pb, ^{214}Pb
Change of temperature and its daily range outdoors	24	^{222}Rn, ^{212}Pb, ^{214}Pb

Other nuclides not investigated.

Indoors radon is exhaled from the construction material and deemanated into the air from domestic use of drinking water and natural gas. The contribution to the radiation burden of the general public from the latter source is significant [16]. Domestic water causes a contribution to the indoor radon level typically in the order of about 10^{-4} of the radon concentration in the water [17]. This means that water with a radon concentration exceeding 10 nCi/l, e. g. in areas with elevated radium content of the subsoil or the use of radon-rich water indoors in spas, represents a source that can contribute significantly to the atmospheric indoor radon level.

The most important source for human exposure to atmospheric radon decay products results from radon released indoors from the building material of surrounding walls, ceiling and floor. The exhalation rate is dependent on the material content on ^{226}Ra and ^{232}Th as well as characteristics of the emanating surfaces, such as porosity and surface coating. Building materials generally have an exhalation of about 0.1—2 atoms/kg . s; however, some natural materials (e. g. light-weight concrete in Nordic countries) can have exhalation of up to a factor 100 higher [18]. Also due to technological processes certain industrial waste products, recycled as construction material (e. g. phosphorgypsum from fertilizer production), can contain elevated levels of ^{226}Ra [19]. This causes a significantly increased radiation burden for the inhabitants [20].

Indoor radon concentration is also largely influenced by the ventilation conditions, which are dependent on both the living patterns of the inhabitants and meteorological conditions outdoors. Due to the influence of the ventilation rate and the plate-out of free and aerosol-attached radon decay products on different surfaces, radioactive equilibrium between radon and decay products is hardly ever reached in inhabited rooms.

2.4 Dietary intake of natural radionuclides

Natural radionuclides are incorporated through the uptake of food and drinking water. After resorption from the gastro-intestinal tract into the bloodstream they are deposited in all organs.

Major sources of incorporated radionuclides, such as ^{40}K and ^{14}C, take part at the normal metabolism and reach a constant level in the different tissues, which is independent of the dietary nuclide content. Other ingested natural radionuclides of significance for the human exposure, e. g. the bone-seeking long-lived nuclides of the ^{238}U- and ^{232}Th-series, are accumulated continuously. Normally the dose contribution from natural radionuclides incorporated with the diet is low as compared to the other sources of the NRE, except for ^{40}K (see 5.3).

3. Methodology of measurement

Fig. 2 shows the information required for the assessment of the individual organ-specific dose, i. e. characteristics of the individual life-style and physiology, annual mean values for the atmospheric concentration of radon and decay products, radionuclide content in food stuffs as well as the mean external irradiation by cosmic rays and terrestrial gamma radiation. The large amount of data needed for each individual necessitates the development of a suitable methodology [21].

3.1 Preoperational planning

a) Urban population

In many countries of the industrialized parts of the world the majority of the people live in an urban environment. Therefore the dose assessment of urban dwellers is representative for the largest part of the population.

Representative for the urban population a typical European city, Salzburg (Austria), was selected. About 130 000 inhabitants live at 425 m above sea-level at the exit of the Salzach valley on the slope of the Northern Calcerous Alps. The geological subsoil consists mainly of lime stone and gravel with a generally low content of natural radionuclides. Therefore Salzburg has the lowest mean gamma dose rate outdoors of all major Austrian cities [22]. The climatic KÖPPEN-classification is Cbf, i. e. moderately warm rain climate with a mean temperature of the warmest month below 22° C, at least four months with mean temperatures of 10° C higher and precipitation during all months [23]. Architectural styles of buildings inhabited comprise of modern prefabricated concrete/glass/steel-constructions as well as medieval buildings made of natural stone.

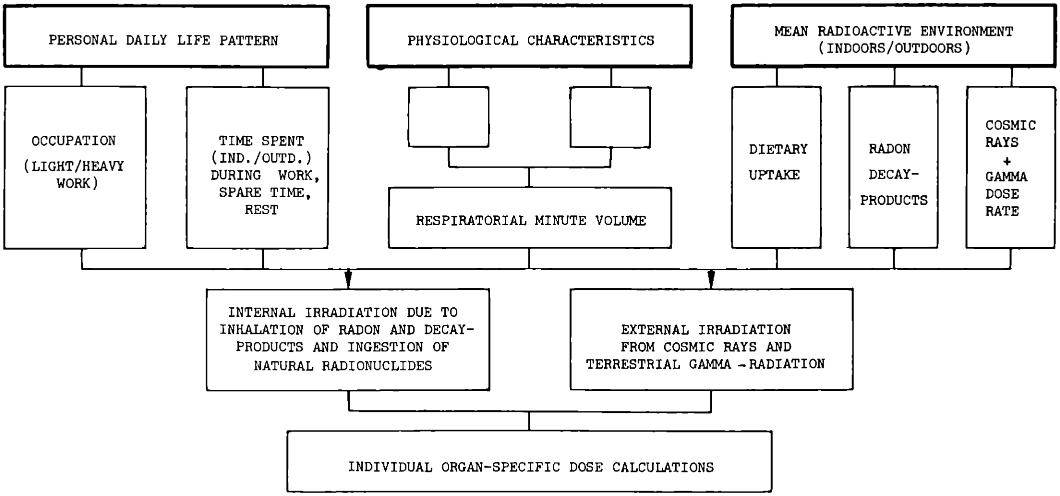

Fig. 2: Personal, physiological and radiological input data for calculation of the dose to different organs from exposure to the NRE

Based on statistical information from the municipal department of statistics the number of measurements in each urban district was determined according to the specific population density. Information on professions, sex and age of the inhabitants permit the assessment of the amount of time spent indoors and outdoors during various activities. Since in our civilization, particularly in the Northern hemisphere, man spends up to 90 % of his time indoors, main emphasis has been put on indoor measurements, such as private homes, offices, schools and production sites. Altogether 729 test-persons of different ages and professions from various districts of the city were selected for this study. None of them were professionally exposed to ionizing radiation.

b) Non-uranium miners

It is well known that the somatic risk for the induction of lung cancer is increased for uranium miners by a factor 4—5 as compared to the general public due to the exposure to elevated levels of radon and decay products. However, this increased risk is not limited to uranium miners only. Also miners of other minerals as well as workers employed in large tunnel projects (road works, hydroelectric power plants) can receive an increased radiation burden from the NRE due to their professional activities, although initially they are not considered as radiation workers at all. Therefore it is very important for radiation protection purposes to assess the dose to non-uranium miners.

In Salzburg and Upper Austria 14 underground- and open pit mines and two tunnels for a hydroelectric power plant in Salzburg with altogether about 2000 workers were selected for this project. The majority of measurements were carried out at the actual work sites. In the mines measurements were performed repeatedly at different seasons to account for the varying ventilations. Furthermore, office- and storage-rooms were also included in the program.

c) Inhabitants and workers in a radon spa area

Water, containing high concentration of radon 222 naturally, is used in many countries for therapeutical treatment of different diseases. No recommendations from international organizations deal with the potential risk from the exposure to increased levels of radon and decay products for the patient; only a few countries apply radiation protection measures for the employees. There are no results available from epidemiological studies on population groups living in areas with increased exposure to radon and decay products[1].

In Badgastein, Austria, the geological subsoil is formed by gneiss and micaschist and shows generally elevated radioactivity. However, the largest contribution to the radioactive environment results from the 19 thermal springs with a daily supply of about 5 10^6 liters of water (temperature up to 48^0 C) and a mean ^{222}Rn concentration of 40 nCi/l.

From this water about 1 million liter (mean radon concentration: 41 nCi/l) is supplied to the radon spa Bad Hofgastein, situated about 8 km south of Badgastein. In both spas the thermal water is not only delivered to treatment centers, but also to a large number of spa hotels (about 120 in Badgastein

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[1] An exception is the comprehensive investigation on chromosome aberrations in the lymphocytes of the peripheral blood of inhabitants and workers in the radon spa area of Gastein [58].

and 55 in Bad Hofgastein). These hotels have their own bathrooms and treatment facilities. Nearly all of the radon transported by the thermal springs (73 Ci/yr) is deemanated into the atmosphere of both spas. A large proportion of the radon is expelled into the open atmosphere during collection of the thermal water at the spring heads located in the center of Badgastein and in the reservoirs of both spas. The amount of radon remaining in the water (mean radon concentration in the bath water is 10—13 nCi/l for Badgastein and 15—20 nCi/l for Bad Hofgastein) is deemanated almost completely indoors during the therapeutical use, mainly by the taking of baths. From the bath rooms radon enters the atmosphere of other rooms, including living- and sleeping rooms of spa hotels because in most cases suitable ventilation systems are missing. The main difference between the two radon spas is the fact that Badgastein receives about 80 % (58 Ci/yr), but Bad Hofgastein only 20 % (15 Ci/yr) of the total amount of radon delivered by the springs [24].

In this study the inhabitants of the village Böckstein were included. This village is situated 5 km south of Badgastein and it has no thermal springs, spa hotels or radon treatment centers. However, the geological subsoil of Böckstein shows even higher levels of natural radioactivity than in Badgastein. This is partially reflected in the radionuclide content of the construction material used, e. g. stones for wall constructions.

Near Böckstein a special form of radon treatment is offered, the socalled "Thermal"- or "Health Gallery" In this former mine the mean atmospheric radon concentration is 3000 pCi/l with a temperature up to 41° C. It has been used for therapeutical treatment (radon inhalation) since 1949. Employees entering the gallery up to 292 hours/yr receive very high doses. Since their number is very small and the conditions for this treatment procedure are unique in the world, the results from the investigation of this specific NRE as well as the dose/risk assessment are not included in this study and have been published elsewhere [59].

Dose and associated risk have been assessed for the following population groups: inhabitants of Badgastein, Bad Hofgastein and Böckstein, living and working in building without treatment facilities; inhabitants of Badgastein and Bad Hofgastein, working and, in the most cases, also living in spa hotels (with radon treatment facilities) or special treatment centers. The latter groups include employees in radon treatment facilities, e. g. bath attendants, nurses and laboratory personnel as well as hotel staff. Also in many cases hotel owners or managers live with their families in the spa hotels.

3.2 Measurements of components of external radiation sources

Cosmic rays can be measured only with special dosimeters, which show a linear response up to very high energies. However, in most cases it is sufficient to calculate the dose contribution from data in the literature, e. g. UNSCEAR-reports [4, 13]. For a given site elevation above sea-level and geomagnetic latitude have to be taken into consideration.

For the measurement of external gamma radiation a specially developed low-level scintillation dosimeter with a variable time-constant was used [25]. This instrument has an isotropic and energy-independent response from 30 keV to 2.5 MeV, which corresponds almost to the range of gamma ray energies from the NRE. All measurements were corrected for the simultaneously measured, altitude dependent contribution from the cosmic ray component. Therefore the data represent the terrestrial gamma radiation without cosmic rays. In underground mines this correction was unnecessary because the cosmic ray component was mostly absorbed by rock- and soil layers above.

In the urban and spa environment more than 600, resp. 2000 measurements were taken outdoors in front of the selected site and indoors at different floors, e. g. basement, staircase, living- and working-rooms. In mines over 500 readings were performed at actual work sites as well as in buildings and outdoors (tailings, etc.) in the mining area. In the mines investigated the following minerals were mined: gypsum, coal, salt, quartz, koalin and copper.

In order to quantify the contribution of NRE-source terms samples of soil, rock and construction material were analysed for their content on the natural radionuclides ^{238}U, ^{226}Ra, ^{232}Th, ^{228}Th and ^{40}K. Since the different nuclides can be discriminated most accurately by the gamma radiation emitted, specific nuclide concentration was determined with low-level gamma specrometry. The experimental set-up of the gamma spectrometer consists of a Ge(Li)-detector with lead shielding, a multichannel analyzer (MCA) and computerized data-storage and -evaluation [26]. The Ge(Li)-detector has an efficiency of 27 % relative to a 3″ × 3″ NaI(Tl)-crystal and a resolution of 2.5 keV (^{60}Co). The gamma spectra stored in the 4096 channel-MCA are analyzed on-line with a PDP-8/F computer for the nuclide concentration. Homogenized samples were dried and stored in air-tight polyethylen containers for 3—4 weeks. This prevents the escape of the gaseous ^{222}Rn and permits the measurement of the ^{226}Ra concentration by using the gamma rays emitted by the short-lived radon decay products.

3.3 Measurement of components of internal radiation sources

The most important contribution to the dose from internal irradiation results from inhaled radon and decay products. Due to the large temporal and local variations of these nuclide concentrations a sampling method was developed which improves the assessment of mean values based on grab-sampling.

For the project "urban environment" five "control-stations" with defined ventilation conditions were installed, representing different materials and architectural styles. At these stations double-filter devices were used to carry out two or more daily measurements of ^{222}Rn, ^{214}Pb and ^{212}Pb [27]. Thus long-time mean values were obtained for the control-stations. At several hundred sites (living-, sleeping- and working-rooms), related to the test-persons selected (see 3.1), in about 250 additional private and public buildings and outdoors radon grab-samples were taken at different seasons. For this purpose specially developed air-bags were used [28]. These grab samples were measured for radon with an ionization chamber in connection with a high-input resistance FET-electrometer [29]. The deviation of the ^{222}Rn-concentration at the control stations from the long-term mean values was used as a factor for correcting the grab sample-radon values against diurnal fluctuations. All values were corrected in this manner and therefore temporal mean values could be calculated for the respective sites. Altogether over 5000 measurements of radon and decay products were carried out in the urban environment.

In the mines, associated buildings and outdoors more than 600 radon grab-samples were taken at different season and ventilation conditions in the manner described. In general the atmospheric nuclide concentration increases with the age of the air used for ventilation of the mine. In order to assess the upper possible value for given working conditions the concentration of short-lived radon decay products was determined in the mine exhaust air (60 measurements) at selected sites, using single-filter devices and associated nuclear electronics as published [21].

In the spa region of Gastein temporally integrating sampling procedures were used in addition to radon grab-sampling. For this purpose the sample container is filled slowly during many hours with an electric pump of low flow-rate (typically: 2 l/hour). Thereby the sample is representative for the mean radon concentration during the collection period, e. g. a working day. A total of over 2000 grab- and integral-samples was collected in the two spas Bad Hofgastein and Badgastein, as well as in the neighbouring village Böckstein.

For the determination of the dietary uptake of natural radionuclides random samples of basic food were taken from local stores and analyzed with the gammaspectrometric method described (see 3.2). Drinking water was sampled from local water supply systems, both at the well-heads and reservoirs as well as at the consumer endpoint at different seasons. Temporal fluctuations of the ^{226}Ra- and ^{222}Rn-concentration in the water and their dependence on environmental (meteorological, hydrological) parameters was studied, using extensive statistical correlation analysis. The radionuclide concentration of about 2000 water samples was determined with ionization chambers [29].

4. Results of measurements

4.1 Terrestrial gamma radiation

a) Citizen in an urban environment

Fig. 3 shows the frequency distribution of outdoor and indoor annual terrestrial gamma dose rate D_γ' (without cosmic ray contribution) in the urban environment of Salzburg. Both histograms are asymmetrical and have positive skewness with a coefficient of variation $c_v > 33\,\%$. Therefore the data were transformed logarithmically and the goodness-of-fit of a Gaussian distribution with the transformed values was checked with the Chi-Square- and Kolmogorov-Smirnov-test [30]. The population of Salzburg receives a low exposure by indoor terrestrial gamma radiation: 90 % receive an exposure rate of $D_\gamma' \leqq 60$ mR/yr; only for about 1 % is $100 \leqq D_\gamma' \leqq 139$ mR/yr. With the transformed data characteristic measures of central tendency (median, μ) and dispersion (central range of data [crd]) were calculated (Tab. 2). The latter represents the dispersion of the median value [30][1]. Also

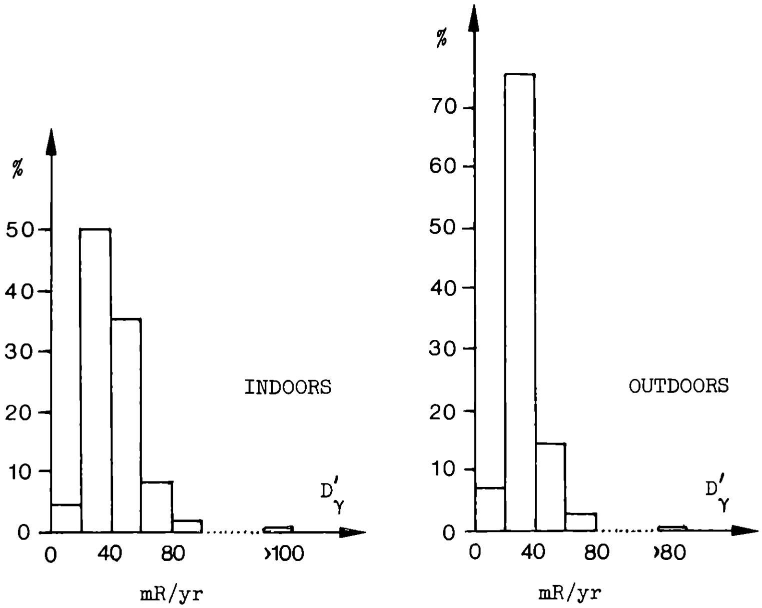

Fig. 3: Frequency distribution of the terrestrial gamma dose rate (D_γ') in the urban environment of Salzburg city

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[1] The dispersion around the median value (crd), i. e. (median) (factor of dispersion)$^{\pm 1}$ is characteristic for a given lognormal distribution.

contained are the extreme values (min, max). It can be seen that the median indoor exposure is about 30 % higher than outdoors. This exceeds the estimated global average ratio of indoor to outdoor exposure of 18 % considerably because of the very infrequent use of wood as building material in Salzburg, whereas UNSCEAR assumes 20 % of all buildings worldwide to be made of wood [4].

b) Occupational contribution for non-uranium miners

The histogram of the data on the terrestrial gamma dose rate (D_γ') of non-uranium miners is shown in Fig. 4; all data, except for underground mining, were corrected for cosmic ray contribution. Due to similar characteristics for the frequency distribution to the data for Salzburg city ($c_v > 50\,\%$), logarithmic transformations were used and median and central range of data determined. For 80 % of the open-pit miners the gamma dose rate during working hours amounts to less or equal to 15 mR/yr; the same percentage of underground miners are exposed to about twice this dose rate. In both cases, however, the contribution from D_γ' received by the miner during working hours is insignificant[1] as compared to levels he is exposed to during non-

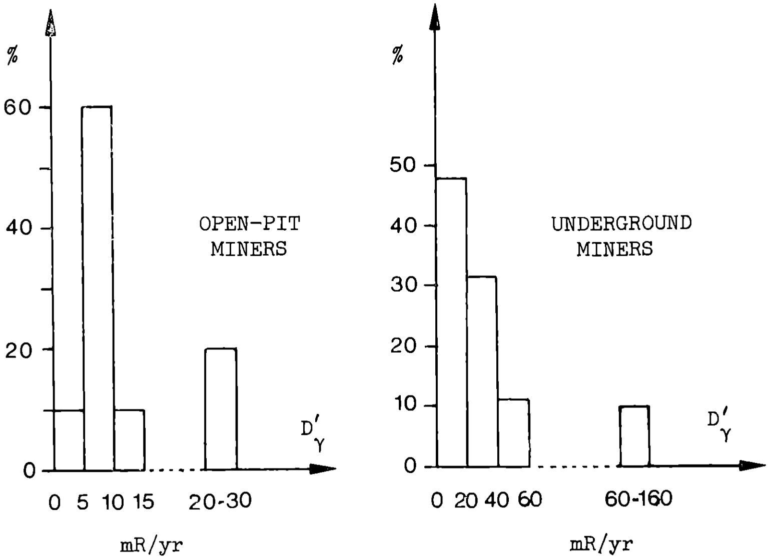

Fig. 4: Frequency distribution of the occupational terrestrial gamma dose rate (D_γ') for non-uranium miners (1920 working hours per year)

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[1] The term "significant" is used, if the compared values proved to be significant after application of the two-sided U-test at a level of significance $\alpha \leqq 0.1$ [30].

occupational activities, e. g. indoor exposure in residential dwellings. Although about 5 % of the underground miners are exposed to a dose rate of $70 \leqq D_\gamma' \leqq 160$ mR/yr, the crd-values cover about the same range as for the indoor exposure of citizens in an urban environment (see Tab. 2, 3). The median occupational exposure of underground miners corresponds with the median outdoor exposure in Salzburg city, which also indicates that the profession of non-uranium miners contributes little to the overall gamma exposure from the NRE.

Table 2

Median (μ), extreme values and central range of data (crd) of the terrestrial gamma dose rate D_γ' (Salzburg city)

Type of exposure	D_γ' (mR/yr)			
	μ	min	max	crd
Indoors	39	14	139	30—62
Outdoors	30	7	121	22—43

Table 3

Median (μ), extreme values and central range of data (crd) of the terrestrial gamma dose rate D_γ' (non-uranium miners, 1920 working hours per year)

Type of exposure	D_γ' (mR/yr)			
	μ	min	max	crd
Open-pit mining	9	4	24	6—15
Underground mining	24	1	156	10—60
In the mining area:				
a) Outdoors	7	6	29	5—10
b) Indoors (offices, workshops, changing rooms, etc.)	14	4	41	9—22

c) *Inhabitants and workers in radon spas*

After the necessary logarithmic data transformation ($c_v > 33$ %) median (μ) and central range of data (crd) were calculated (Tab. 4) for the radon spas Badgastein (Bg) and Bad Hofgastein (Bh), as well as for Böckstein (Bö).

The exposure of inhabitants and workers to terrestrial gamma radiation is significantly elevated in the Gastein area as compared to D_γ'-levels for citizens of Salzburg due to the elevated radionuclide content of subsoil and building materials as discussed in section 3.1/c. The results from measurements in the spa hotels and treatment centers show that — compared to other indoor measurements — the contribution from atmospheric radon decay products to the gamma exposure rate is very small.

Table 4

Median (μ), extreme values and central range of date (crd) of the terrestrial gamma dose rate (Gastein area)

Type of exposure	D_γ' (mR/yr) μ	min	max	crd
a) *Badgastein (Bg)*				
Outdoors	67	20	180	40—102
Spa hotels and treatment centers	110	40	160	84—145
Other buildings – Center	93	26	200	49—154
Periphery	102	29	180	75—137
b) *Bad Hofgastein (Bh)*				
Outdoors	40	5	145	23— 58
Spa hotels and treatment centers	67	23	128	40—102
Other buildings	67	6	163	40—102
c) *Böckstein (Bö)*				
Outdoors	102	23	198	67—137
Indoors	137	43	286	93—189

In all three areas investigated the median indoor exposure D_γ' is elevated between 35 % and 45 % compared to outdoor. This is an agreement with the result obtained in Salzburg city and confirm that the use of bricks and stone predominantly as construction material increases the terrestrial gamma dose rate indoors.

d) Soil and building material

In Salzburg city and the Gastein area soil samples were analyzed with gammaspectrometric methods for their concentration of ^{238}U, ^{226}Ra, ^{232}Th, ^{228}Th and ^{40}K (Tab. 5). ^{226}Ra and thorium are significantly elevated in Badgastein compared to Salzburg and Bad Hofgastein. This is in agreement with the elevated terrestrial gamma dose rate D_γ' for Badgastein.

The results of the building material samples in Salzburg city generally showed very low nuclide concentrations; also the standard deviation for samples of the same group of materials was small. One exception was an orange-coloured ceramic tile with high U/Ra-content, which resulted in a gamma dose rate at the surface of almost 300 mR/yr. In the meantime this product has been taken off the market because of concern about radiation protection.

4.2 Atmospheric concentration of radon and decay products

Since all radon frequency distributions were more or less asymmetrical with positive skewness ($c_v > 33$ %), all data were transformed as described (see 4.1).

Table 5

Natural radioactive nuclides in soil and building materials

Sample	Nuclide concentration (pCi/g)				
	^{238}U	^{226}Ra	^{232}Th	^{228}Th	^{40}K
Soil:					
Salzburg	2.1 ± 1.1	0.9 ± 0.3	0.6 ± 0.1	0.6 ± 0.1	7 ± 0.4
Hofgastein	0.4 ± 0.3	0.6 ± 0.1	0.6 ± 0.1	0.7 ± 0.1	8 ± 0.3
Badgastein — Center	1.5 ± 0.8	1.9 ± 0.2	1.5 ± 0.2	1.5 ± 0.2	14 ± 1.0
Periphery	0.8 ± 0.7	1.4 ± 0.2	1.0 ± 0.2	1.1 ± 0.2	11 ± 1.0
Building material from Salzburg city:					
Sand	< 0,5	0,3 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	2 ± 0.1
Gravel	0,4 ± 0.4	0.3 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	2 ± 0.1
Clay brick	1.6 ± 1.3	1.2 ± 0.1	0.2 ± 0.1	1.5 ± 0.1	27 ± 1.0
Ceramic tile (light coloured)	1.4 ± 1.3	1.4 ± 0.1	1.0 ± 0.1	1.1 ± 0.1	6 ± 0.3
Ceramic tile (orange)	473 ± 14	124 ± 30	1.2 ± 0.3	1.6 ± 0.1	6 ± 0.3

a) Urban environment

The histograms of annual mean radon 222 concentration values indoors and outdoors in Salzburg city are shown in Fig. 5. The outdoor radon values reflect the generally low levels of the NRE in this area: almost 50 % of the cases are below or equal to 0.2 pCi/l, compared to an average surface air concentration worldwide of 0.1 pCi/l [31]. Indoors about 70 % of the rooms have annual mean radon levels or equal to 0.6 pCi/l, which is also low in comparison to the global average radon concentration indoors of 1 pCi/l [4]. However, despite this low radon concentration in most cases, in about 15 % of the rooms the annual mean radon concentration ranges from 1—5 pCi/l.

Similar to the ratio indoors/outdoors for the terrestrial gamma radiation also the median radon concentration is elevated by about 40 % inside buildings compared to the atmosphere outdoors (Tab. 6).

Table 6

Median (μ), extreme values and central range of data (crd) of atmospheric radon 222 (Salzburg city)

Type of exposure	^{222}Rn-concentration (pCi/l)			
	μ	min	max	crd
Indoors	0.4	<0.1	5.2	0.3—0.7
Outdoors	0.3	<0.1	1.3	0.1—0.5

From the results of the indoor filter measurements the mean ratio ^{214}Pb ^{222}Rn was determined as 0.6 ± 0.1. This is slightly higher than the average equilibrium factor $F=0.5$ found in buildings of Europe, U.S.S.R. and U.S.A. [4]. However, neither of the buildings investigated in Salzburg city had air-conditioning or forced air-heating systems, which are in wide-spread use in U.S.A. and cause a reduction of this ratio due to increased air movement and -filtration.

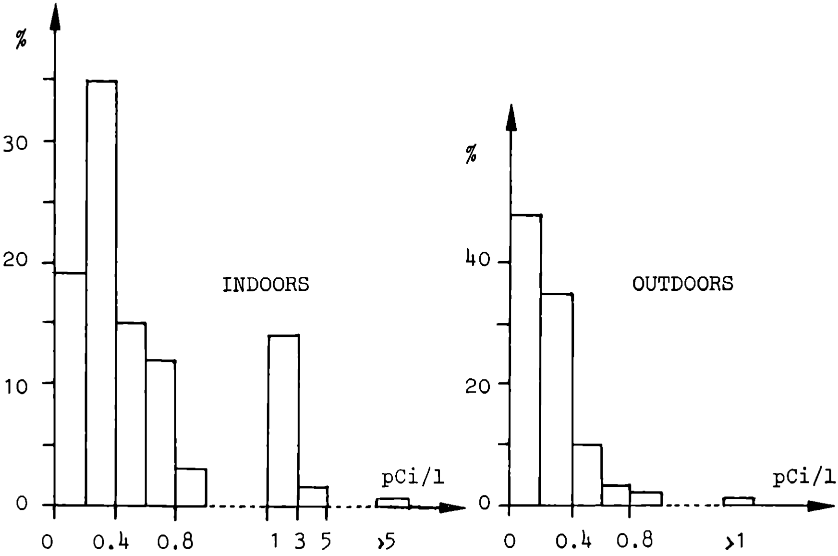

Fig. 5: Frequency distribution of the atmospheric radon 222-concentration in the urban environment of Salzburg city

At the control stations the long-lived ^{222}Rn-decay product ^{210}Pb and the ^{220}Rn-decay product ^{212}Pb were measured as well, the latter contributing significantly to the dose of the respiratory tract [49]. The mean values at the different stations ranged from 0.04—0.2 fCi/l for ^{210}Pb, resp. 10—60 fCi/l for ^{212}Pb.

b) Non-uranium mines

The radon levels in the open-pit mines investigated correspond with the outdoor radon concentration in the urban environment. Both, median radon concentration and frequency distribution show that mining in open-pits does not increase the atmospheric radon levels (Fig. 6, Tab. 7). This is in contrast to underground mines, where radon levels are significantly elevated as compared to the urban environment. Whilst in 30 % of the cases radon levels are below 3 pCi/l, about 1/3 of the work sites has radon values between 6 and

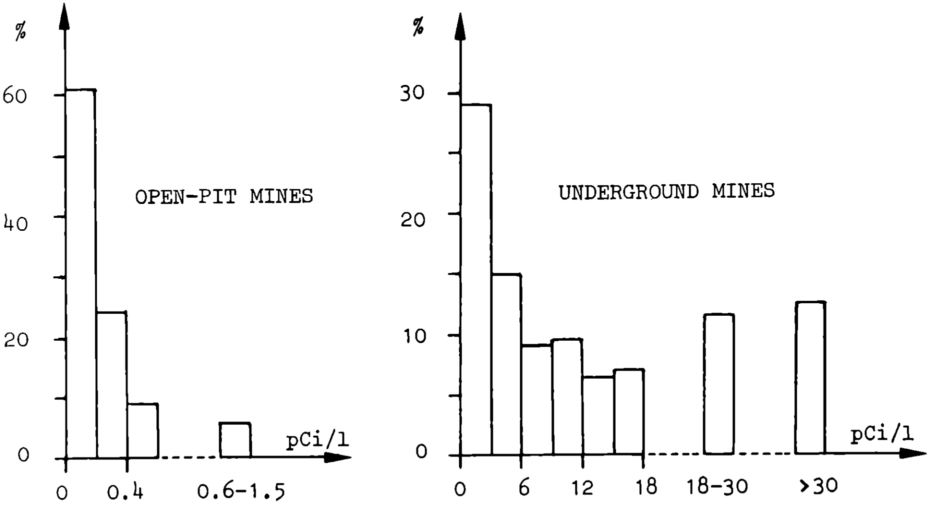

Fig. 6: Frequency distribution of the radon 222-concentration in the air of non-uranium mines

Table 7

Median (μ), extreme values and central range of data (crd) of atmospheric radon 222 (non-uranium mines)

Type of exposure	^{222}Rn-Concentration (pCi/l) μ	min	max	crd
Open-pit mining	0.2	<0.1	1.5	0.1— 0.3
Underground mining	6.2	<0.1	104	3 —12
In the mining area:				
a) Outdoors	0.1	<0.1	0.9	<0.1— 0.1
b) Indoors (Offices, workshops, changing rooms, etc.)	0.4	<0.1	7.3	0.3— 0.6

18 pCi/l; over 10 % range from 18—30 pCi/l, resp. even exceed 30 pCi/l.

Neither open-it, nor underground mining activities show any influence on the median radon concentration outdoors or inside structures in the mining area, e. g. offices or maintainance building (Tab. 7). Median concentration and central range of data show no significant difference to corresponding indoor values of Salzburg city.

In underground mines measurements of the atmospheric concentration of radon decay products were carried during natural ventilation conditions as well as during additional mechanical forced ventilation. The results show that for natural ventilation the mean ratio ^{214}Pb ^{222}Rn during working hours is 0.5 ± 0.2. Additional forced ventilation reduces this ratio to 0.4.

c) Radon spas

Fig. 7 (B, D, E) contains the histograms of the atmospheric radon concentration outdoors, indoors and in the radon spa hotels and treatment centers in Badgastein (Bg) and Bad Hofgastein (Bh); for comparison, the corresponding data are presented for Böckstein (Bö) in Fig. 7 (A, C). Median (μ), extreme values and central range of data (crd) are given in Tab. 8.

Table 8

Median (μ), extreme values and central range of data (crd) of atmospheric radon 222 (Gastein area)

Type of exposure	^{222}Rn-Concentration (pCi/l)			
	μ	min	max	crd
a) *Badgastein (Bg)*				
Outdoors	0.7	< 0.1	9.6	0.1— 3.0
Spa hotels and treatment centers	6.4	0.2	150	1.5—27
Other buildings — Center	1.8	< 0.1	17	0.6— 5.0
Periphery	1.1	< 0.1	6.1	0.3— 3.5
b) *Bad Hofgastein (Bh)*				
Outdoors	0.3	< 0.1	1.5	0.1— 0.8
Spa hotels and treatment centers	1.9	0.2	17	0.3—10
Other buildings	0.5	< 0.1	6.8	0.2— 1.5
c) *Böckstein (Bö)*				
Outdoors	0.4	< 0.1	2.0	0.1— 1.6
Indoors	2.2	< 0.1	16	0.7— 6

Due to the radioactive springs originating in Bg the median radon content outdoors is about twice as high as for Bh or Bö; for the latter two the median outdoor values correspond to the median urban level. The influence of the springs can also be seen in the histogram (Fig. 7B), where the data for Bg account for those 20 % of the outdoor radon values exceeding 2 pCi/l.

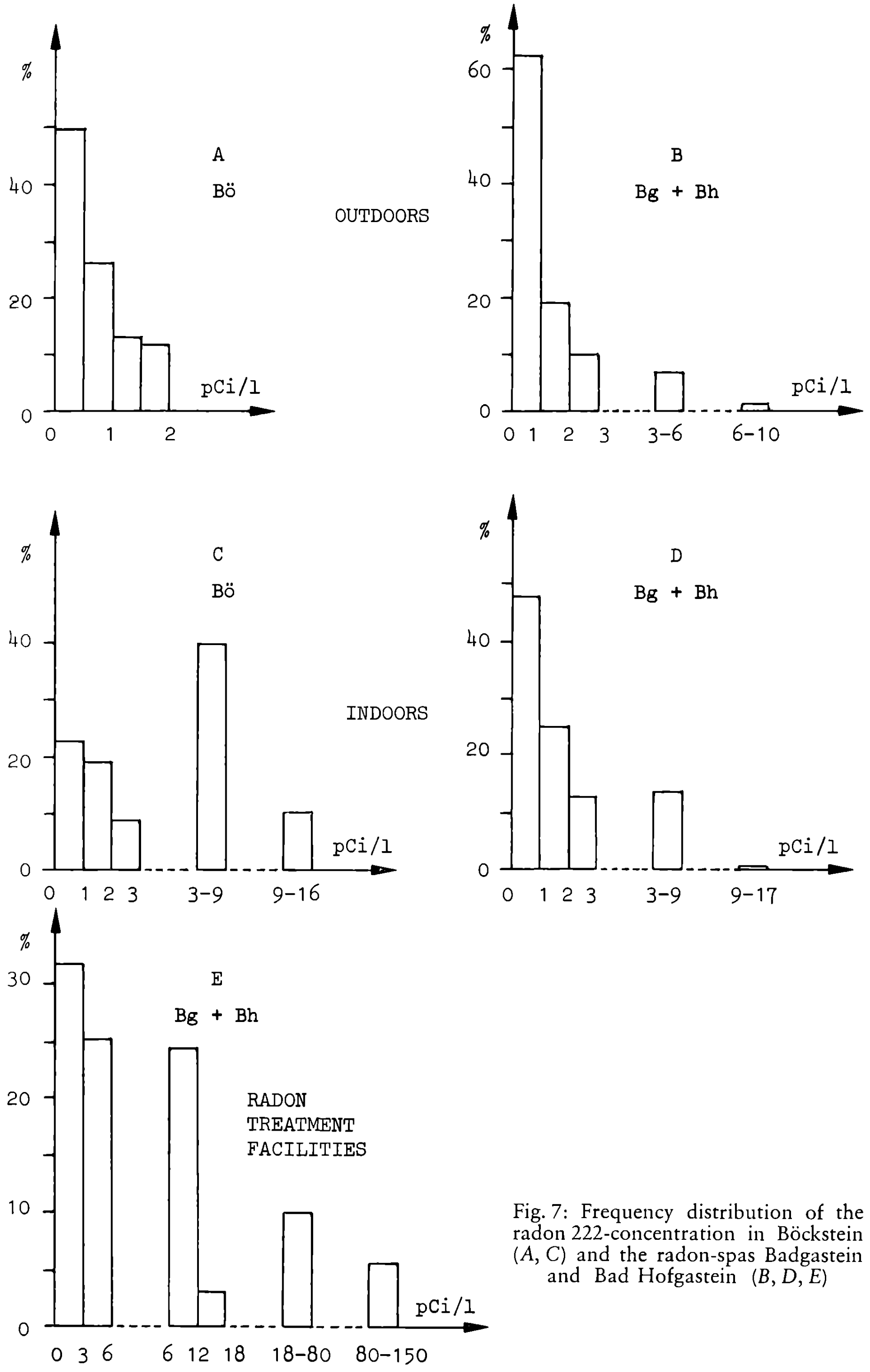

Fig. 7: Frequency distribution of the radon 222-concentration in Böckstein (*A*, *C*) and the radon-spas Badgastein and Bad Hofgastein (*B*, *D*, *E*)

Fig. 7 C, D show the frequency distribution of the indoor radon concentration in private and public buildings, not directly related to spa activities (homes, offices, shops, etc.) in Bg and Bh, together with data from Bö, which has neither radioactive springs nor treatment facilities. About 70 % of the living- and working-rooms in the spas — compared to 45 % for Bö — have an indoor radon concentration of less or equal to 2 pCi/l. For about 15 % of the rooms in Bg and Bh, but 40 % for Bö, the radon concentration ranges from 3 to 9 pCi/l; in Bö 10 % of the rooms even exceed 9 pCi/l.

The median indoor level in building with no radon water supply is only slightly higher in Bh than in the urban environment of Salzburg (see Tab. 6). Therefore the radon treatment in a spa house shows only little influence on the indoor radon level in other buildings.

The corresponding values for Bg are higher. This may be caused mainly by the presence of the radioactive springs and the thermal water reservoirs in the center of the town. It could also be attributed to the large number of spa hotels in the center, which have a high consumption of thermal water.

In Bö the construction material and the subsoil contain an elevated content of natural radionuclides, causing an increased exposure rate D_γ' (see Tab. 4) and also elevated exhalation of radon from the walls indoors. This leads to a median indoor radon concentration more than five times the value for Salzburg city.

In spa hotels and treatment centers of Bg and Bh the median radon concentration is higher by almost 400 % than in rooms of other buildings in the spa area (Tab. 8). About 55 % have a radon concentration between 3 and 18 pCi/l (Fig. 7 E). The rest of the data presented in this figure account for the situation in Bg only, i. e. rooms with radon concentration between 18 and 150 pCi/l, since the maximum radon value for Bh is 17 pCi/l. The median radon concentration in spa hotels and treatment centers of Bg is 6.4 pCi/l, which is similar to conditions in non-uranium mines. Furthermore it is higher by more than a factor 3 compared to Bh.

Radon decay products were measured indoors in private and public buildings as well as in spa hotels and treatment centers (altogether 150 measurements). The mean ratio ^{214}Pb ^{222}Rn for both data pools is 0.5 ± 0.3 in agreement with the corresponding values determined for buildings in the urban- and mining-environment.

4.3 Radionuclides in food and drinking water

The results from the gammaspectrometric investigation of the radionuclide content of food and agricultural products are contained in Tab. 9. In general both groups of samples show low concentration of natural radionuclides in the order of 100 fCi/g, resp. pCi/g for ^{40}K. In many cases, especially for ^{238}U and ^{228}Th, the nuclide concentration of the sample is even below the lower limit of detection.

Corresponding to the low natural radioactivity of Salzburg city also the ^{222}Rn and ^{226}Ra content of the drinking water is low. The nuclide concentration in the water at a given site shows pronounced short- and long-term variations. As an example Fig. 8 shows the seasonal variations of ^{222}Rn with a minimum during springs months and a maximum in the winter. Applying linear correlation theory rainfall and snow cover of the ground in the supply area showed statistically significant influence on the nuclide concentration in the drinking water [32]. Therefore only long-term measurements permit the determination of statistically significant mean values.

Table 9

Natural radioactive nuclides in agricultural products and food

Sample	Nuclide concentration in pCi/g				
	^{238}U	^{226}Ra	^{232}Th	^{228}Th	^{40}K
Agricultural products:					
Oats	2.0 ± 1.0	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	3.3 ± 0.3
Maize	1.5 ± 1.5	0.1 ± 0.1	0.1 ± 0.1	< 0.1	2.6 ± 0.3
Barley	0.5 ± 0.3	1.0 ± 0.4	< 0.1	< 0.1	3.9 ± 0.3
Wheat	< 0.5	< 0.1	< 0.1	< 0.1	3.6 ± 0.3
Rye	< 0.5	< 0.1	< 0.1	< 0.1	2.3 ± 0.3
Food:					
Flour	3.0 ± 2.0	0.1 ± 0.05	0.1 ± 0.05	0.3 ± 0.1	5.0 ± 0.3
Farinaceous products	< 0.5	0.1 ± 0.1	< 0.1	0.1 ± 0.1	1.5 ± 0.2
Crumble	< 0.5	0.4 ± 0.3	< 0.1	< 0.1	1.0 ± 0.3
Rice	< 0.5	0.1 ± 0.05	0.1 ± 0.05	0.1 ± 0.05	< 0.5
Sugar	< 0.5	0.1 ± 0.05	< 0.1	0.1 ± 0.05	< 0.5
Dried milk	< 0.5	0.3 ± 0.1	< 0.1	< 0.1	14 ± 0.8
Freeze dried coffee	< 0.5	0.2 ± 0.1	< 0.1	2.4 ± 0.1	7.8 ± 0.4
Tea (Ceylon)	< 0.5	0.2 ± 0.1	0.1 ± 0.05	0.3 ± 0.1	9.9 ± 0.5
Mushrooms (leukopl. c.)	< 0.5	< 0.1	< 0.1	0.5 ± 0.1	32 ± 1.2
Mushroom-soup (powder)	< 0.5	0.7 ± 0.1	0.1 ± 0.06	< 0.1	2.3 ± 0.3

Table 10

Median (μ), extreme values and central range of data (crd) of the radon 222- and radium 226-concentration at 6 control stations of the urban drinking water system of Salzburg city

Nuclide	Concentration (pCi/l)			
	μ	min	max	crd
Radon 222	15	< 0.1	131	4 —60
Radium 226	1.5	< 0.1	8.2	0.3— 7

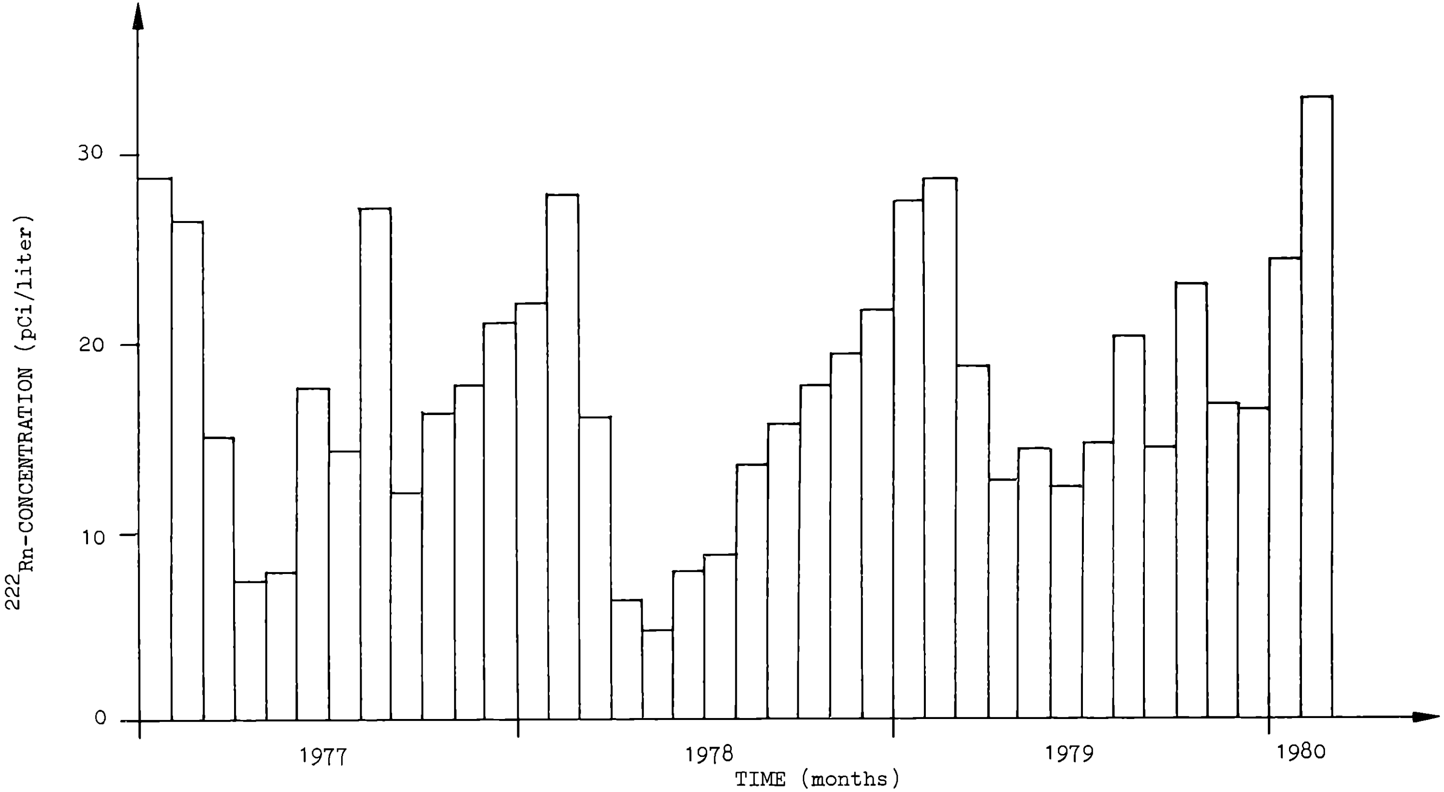

Fig. 8: Temporal changes of monthly mean ^{222}Rn-concentration in drinking water at control station No. 1 Salzburg/Austria (565 measurements)

The median radon- and radium concentration of the drinking water is 15 pCi/l, resp. 1.5 pCi/l (Tab. 10). It is interesting to note the large range of radon values, covering three orders of magnitude. The range of radium values is smaller, indicating the lower variability of the radium content of drinking water due to changing environmental influences. The median radon and radium concentration of the well- and groundwater-samples are not staistically different from each other and were found to be 28 pCi/l for ^{222}Rn, resp. 0.8 pCi/l for ^{226}Ra.

5. Dose distribution in the human organism due to external and internal sources

5.1 Dose due to external irradiation

The annual dose contribution to all organs resulting from cosmic radiation (D_c) was calculated from published data [4]; Taking into consideration altitude above sea-level and geomagnetic latitude the following values were used: D_c (Salzburg city) = 38 mrem; D_c (open-pit mines) = 40 mrem; D_c (Gastein area) = 45 mrem; D_c (underground mines) was considered neglegible because of cosmic ray absorption by bedrock layers between surface and underground work-site.

The measured exposure dose due to external gamma radiation (D_γ', see 4.1) is converted into the organ-specific annual absorbed dose (D_γ) by the following equation:

$$D_\gamma = C\,(F_b\,\Sigma\,D_{b,i}\,t_i + F_{\mathrm{out}}\,\Sigma\,D_{\mathrm{out},i}\,t_i) \qquad (1)$$

where:

D_γ	mean annual organ gamma dose (μrad)
$C = 0.96$	factor for transformation of D_γ' (μR/hr) into D_γ (μrad/hr)
F_b, F_{out}	organ-specific gamma dose attenuation factor in buildings, resp. outdoors
$D_{b,i}$, $D_{\mathrm{out},i}$	exposure rate at site i in buildings, resp. outdoors (μR/hr)
t_i	time spent at site i (hrs); $\Sigma\,t_i = 8760$ hrs

Attenuation factors F_b, F_{out} were applied for 7 different organs and tissues, differentiating between male and female [33].

5.2 Dose due to inhalation of radon and decay products

For the calculation of the dose distribution in the respiratory tract a suitable mathematical lung model ("LUMO") was used, which permits the determination of the probability for the deposition of inhaled radionuclides. With the use of a hybrid-computer the influence on the nuclide deposition was studied for the following parameters: age, sex, body size, weight, physical activity and aerosol characteristics [34]. It could be shown that children receive an increased radiation burden up to 2.7 times the dose of adults living under the same environmental conditions. Fig. 9 shows as an example the dose as a function of age for the tissue with the highest radiation burden (see below); however, also the dose to all other organs is age-dependent.

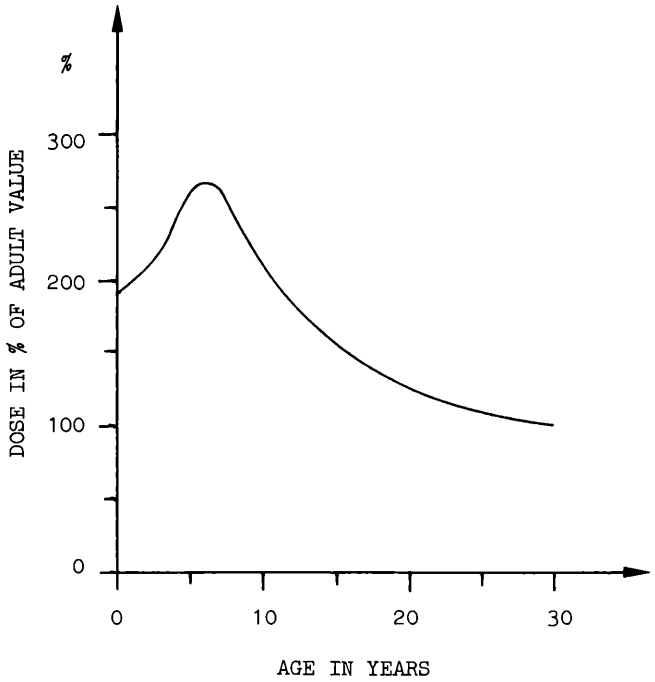

Fig. 9: The dose to the basal cells of the segmental and subsegmental bronchioles as a function of age under constant nuclide concentration in the respiratory air and aerosol characteristics

Continuous inhalation of constant levels of atmospheric radionuclide concentration results in a dynamic equilibrium condition between deposition, clearance and radioactive decay of the particles inhaled. This equilibrium activity is the basis for all further dose calculations for different parts of the respiratory tract as well as for other organs.

Maximum nuclide deposition occurs at the segmental and subsegmental bronchioles. The basal cells of the bronchial epithelium are considered to be the critical target for the induction of lung cancer due to inhaled radon and decay products. Therefore — besides the assessment of doses to different lung compartments (e. g. pulmonary or tracheo-bronchial compartment) — it is necessary to take into consideration the local distribution of the radiation energy absorbed at the cellular level in order to quantify radiation-induced biological effects [35, 36].

Based on dose calculations for adults [37] the annual organ-specific dose due to inhaled radon and decay products was calculated as a function of age, sex and weight (D_{asw}) using the equation:

$$D_{asw} = A \, \Sigma \, Rn_i t_i + B_{asw} \, \Sigma \, Rn_i z_i t_i \, \frac{\Phi_i \, (a)}{\Phi_n} \, d_{rel} \, \frac{\Phi_i}{\Phi_n} \tag{2}$$

where:

A, B_{asw}	organ-specific dose conversion factors[1]
Rn_i	radon concentration at site i (pCi/l)
t_i	time spent at site i; $\Sigma \, t_i = 8760$ hrs
Φ_n	annual mean respiratory minute volume for Reference Man (= 13.8 l/min)
$\Phi_i \, (a)$	actual respiratory minute volume for a given age (a) according to the physical activity at site i
Φ_i	actual adult respiratory minute volume according to his physical activity
z_i	factor calculated from decay product ratio at site i
d_{rel}	mean relative deposition value [34]

The factors z_i are a function of the atmospheric decay product concentration [37].

5.3 Dose due to ingestion

The content on natural radionuclides of food and water samples from Salzburg did not differ significantly from values reported in the literature for various population groups living in "normal" environments [4]. Therefore published data were used for overall dose contribution to gonads, bones and bone marrow from ingested nuclides (D_d), which is only small and amounts to less than 1 mrem/yr from each of the radionuclides ^{14}C, ^{87}Rb, ^{226}Ra, ^{228}Ra, ^{210}Po, ^{238}U [38, 39]. Only in the case of ^{40}K the corresponding organ dose values range from 15 to 19 mrem/yr.

6. Results of dose calculations

6.1 Dose frequency distributions for an urban environment

The mean annual contribution of the single organ-specific dose components were calculated for each of the 729 test persons in Salzburg city, using the dosimetric methods described (see 5.). The sum of the dose contributions (D_c, D_γ, D_d, D_{asw}) represents the mean total dose D the subject receives

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Contained in Tab. 1, Ref. [37], and applying age-dependent dose modifying factors from Tab. 2, Ref. [61].

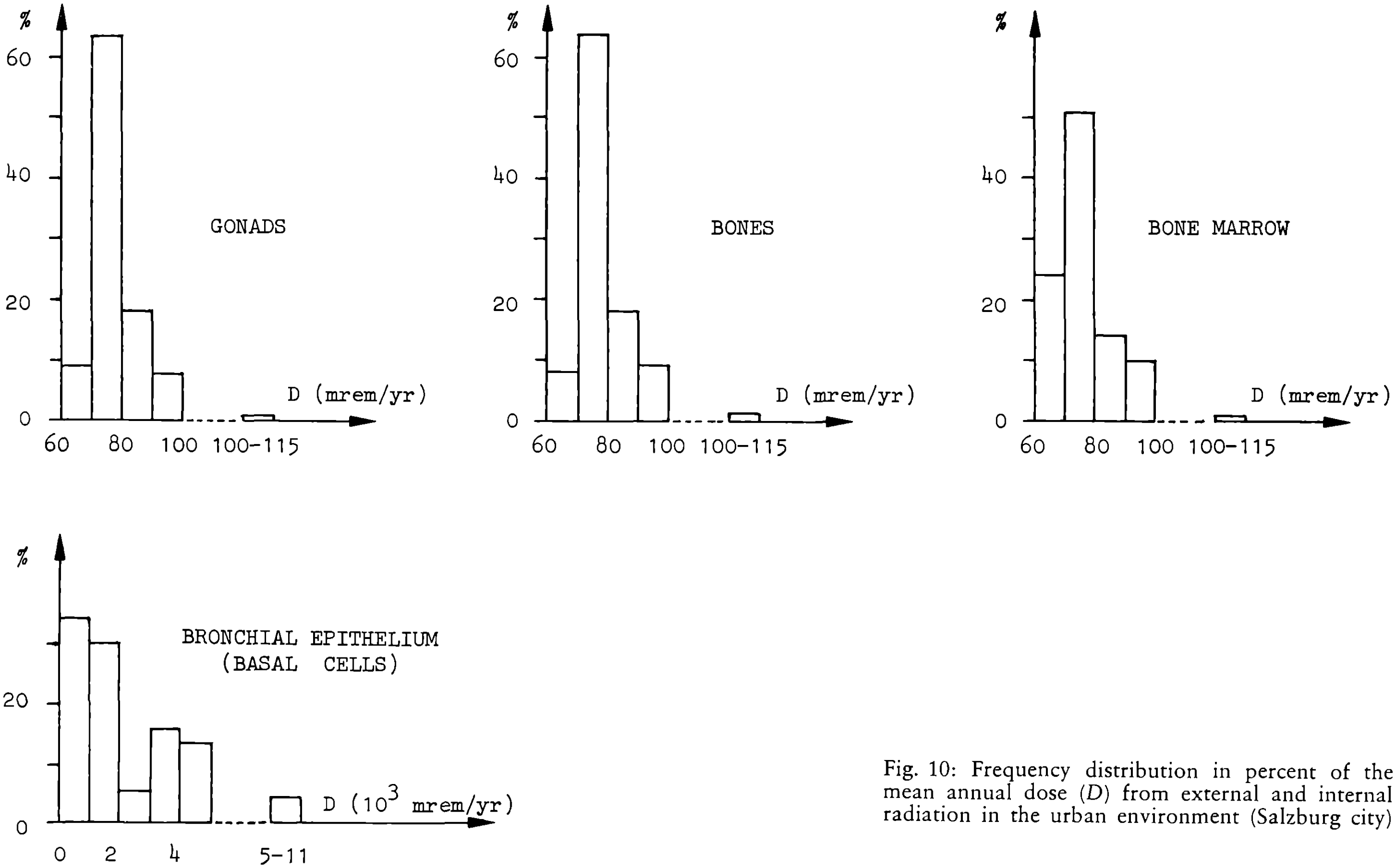

Fig. 10: Frequency distribution in percent of the mean annual dose (*D*) from external and internal radiation in the urban environment (Salzburg city)

from the urban NRE. With the individual values D histograms were computed for selected radiation sensitive tissues and organs, applying quality factors of 1 for γ- and 10 for α-radiation (Fig. 10).

The dose range for those organs which are predominately influenced by external radiation (D_c, D_γ), i. e. gonads, bones and bone marrow, is only 1.7. For liver, blood, kidneys and alveolar tissue the dose range was found to be 60—135, 60—190, 60—325 and 100—3900 respectively. This indicates the increasing influence of inhaled radon decay products in sequence of the mentioned organs. For the respiratory tract the contribution from D_{asw} is significantly higher than for all other components. This causes the dose values to cover the range of 92 for the bronchial epithelium, although the population lives in the same, relatively small urban environment.

Whilst gonads, bones and bone marrow receive an annual dose in the range from 60 to about 115 mrem, the critical target for lung cancer induction — the basal cell layer — receives a dose more than an order of magnitude higher. Although the general level of the NRE in Salzburg is low, it is remarkable that for these cells 1/3 of the population receive between 2000 and 5000 mrem/yr. Almost 3 %, i. e. over 3000 people, are exposed to levels ranging from 5000 to 10700 mrem/yr. This large range of individual doses is only caused by differences in the radionuclide content of the construction materials and architectural style of dwellings. Since this heterogenity is also typical for many other European cities, similar results can be expected for those areas.

6.2 Radiation burden for employees in the mining industry

Based on the data from external terrestrial gamma radiation (D_γ') and internal exposure from inhaled radon decay products the occupational dose was calculated for two model miners. In the case of "disadvantageous working conditions" it was assumed that mainly heavy physical work is carried out in underground mines with low ventilation rates. "Typical working conditions" described the case of an employee in an underground mine with median exposure levels of D_γ and median atmospheric radon- and decay product concentration. The model parameters are defined in Tab. 11. For these two cases the accumulated occupational dose was calculated for the basal cells of the bronchial epithelium.

Under normal circumstances the dose due to the occupational exposure of a miner is of the same magnitude as for a citizen, i. e. 1—2 rem/yr. However, under disadvantageous working conditions the dose exceeds this "typical" dose level up to 300 %. This can lead to an accumulated occupational dose of almost 40 rem in an employment period of ten years.

In the case of open-pit mines both the external gamma dose rate (D_γ') and the atmospheric radon and decay product concentration are low and of the same order as the data for the urban environment. Therefore the occupational dose for employees in this industry is not significantly different from the NRE-exposure of a citizen.

Table 11

Parameters used for the calculation of radiation-dose ranges, assuming typical and disadvantageous working conditions in an underground non-uranium mine

Parameter	Working conditions Typical	Disadvantageous
Radon-concentration (pCi/l)	5	10
Decay-product-ratio RaA RaB RaC	0.9 0.4 0.3	1 0.6 0.4
Gamma dose rate (mR/a)	25	60
Respiratory minute volume (l/min)	43	43
Age at start of employment (years)	20	20
Annual working time (hours)	1920	1920
Annual dose to the basal cells of the bronchial epithelium (rem)	1.5	4

6.3 Radiation exposure for inhabitants and workers in a radon spa

Whilst for the 4-year subproject "urban NRE" (Salzburg) the continuous assistance of several laboratory technicians was available, for technical reasons the subproject "radon spa NRE" could be carried out only during summer/autumn-vacation times and additional short periods during other seasons. Therefore the demoscopical method used for the determination of dose frequency distributions in Salzburg was substituted by subdividing the population of Badgastein, Bad Hofgastein and Böckstein into characteristic groups of inhabitants and workers (see 3.1)[1]. The specific NRE was characterized by both the median (μ) levels for denoting "typical" exposures, as well as the central range of NRE data (crd). In this manner also the range of probable dose values due to the NRE-exposure was determined. The persons are defined to be adult male, carrying out light physical work (respiratory minute volume: 27.6 l/min) for 1920 hours per year. It was assumed that in the area of residence 90 % of the time is spent indoors and 10 % outdoors. The results represent the range of probable dose values received by adult inhabitants and workers in the Gastein area (Tab. 12). In the case of children age dependency of absorbed dose can increase these values by 240 % [24]. It is emphasized that these dose values do not represent extreme values expe-

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[1] Individual doses were calculated for 122 persons in the investigation on chromosome aberrations [58]. However, part of this group includes staff of the "Thermal Gallery" (see footnote 1), chapter 3.1/c). Therefore none of these individual dose values could be used in this paper.

rienced by only a small percentage of the population, since they are based on the 90%-central range of typical data (see 4.1/a).

The values in Tab. 12 refer to adults only. As already mentioned in section 5.2 the dose values have to be multiplied with age-dependent dose modifying factors in the case of children, who are in all population groups mentioned.

Table 12

Median (D_μ) and central range of values (D_{crd}) of the total dose D from the exposure to all external and internal radiation sources of the NRE in the Gastein area for gonads and basal cells of the bronchial epithelium for different population groups (Adults only)

Person	D (mrem/yr)			
	Gonads		Bronch. epithelium	
	D_μ	D_{crd}	D_μ	D_{crd}
Badgastein:				
(I) Living and working in radon spa hotels or treatment centers	140	120—160	5300	1300—21 900
(II) Working as above and living in other buildings	140	110—160	3000	750—11 900
(III) Living and working in buildings (in the center) without radon water supply	130	100—180	1600	600— 4 400
(IV) Living and working as above, but in the periphery	130	120—160	1000	350— 3 200
Bad Hofgastein:				
(I) Living and working in radon spa hotels or treatment centers	110	100—130	1600	350— 8 200
(II) Working as above and living in other buildings	110	100—130	1100	300— 4 500
(III) Living and working in buildings without radon water supply	110	100—130	500	250— 1 400
Böckstein:				
(I) Inhabitant	160	130—200	1900	800— 4 800

Residence in the Gastein area results in an increased radiation dose from the NRE as compared to residence in the urban environment of Salzburg city. The typical gonad dose for a person living in Badgastein is higher than the maximum dose received by a Salzburg citizen. This is not only due to the characteristics of the spa, since the corresponding value for an inhabitant of Böckstein is of the same order of magnitude.

The influence of the radioactive springs on the atmospheric radon content is indicated in the about 50 % higher dose value of the bronchial epithelium (basal cells) for an inhabitant in the center of Badgastein compared to a resident in the periphery. However, as high a dose can be caused by either an elevated radionuclide content of the construction material or increased radon exhalation from the subsoil as in the case of Böckstein, i. e. up to 5000 mrem/yr.

7. Risk assessment

Exposure of man to ionizing radiation represents a quantifiable risk for the induction of somatic and genetic damage in the biological target. However, whilst genetic mutations from low-level gonadal exposure of man (31—39 rem) have not been observed [40], new results report about a relationship of incidence of cancer death with external natural background radiation [41]. In recent years it has generally been recognized that the risk of inducing cancer at low doses of radiation is as great or even far greater than the genetic risk [42]. Therefore in the following the emphasis is on the assessment of risks for cancer induction.

Since every human action is associated with a certain level of risk, it is appropriate to judge levels of risk due to radiation exposure by comparing them with risks from other non-radiation environmental hazardous agents. This approach is prevailing in the revised assessment of occupational radiation protection criteria by the International Commission on Radiological Protection (ICRP). This Commission compares risk in radiation work with that for "safe" industries, i. e. annual mortality less or equal to 10^{-4} [6]. The inherent advantage of the ICPR-risk proposal is the possibility to determine the total risk to man resulting from the exposure to various environmental hazardous sources.

7.1 Somatic risk due to inhaled radon decay products

Inhalation of radon and its short-lived decay products causes the highest radiation burden to man from all sources of the NRE. Even in a "normal" urban environment the median dose to parts of the respiratory tract exceeds the corresponding gonadal dose by a factor of 13, for some persons it can be higher by more than a factor of 100. Therefore inhalation of short-lived radon daughters represents the greatest risk from all natural radiation sources.

At present the only reliable data available for risk assessments from radon daughter exposure are derived from epidemiological studies of uranium miners. The exposure conditions of these miners resemble those of non-uranium miners, except for the magnitude of the exposure. However, applying the information derived from the correlation of past exposure and lung cancer induction amongst miners to NRE-exposure indoors or in radon spas is a controversial issue for the following reasons [43]:

a) Quality of radiation data:

The base for any risk assessment from inhaled radionuclides is the quantitative information on the atmospheric nuclide concentration and aerosol characteristics. However, the quality of the data describing the past radon and decay products content, fraction of unattached atoms, and particle size distribution in uranium mine atmospheres is insufficient, e. g. the data are derived from a few or even single measurements per year in some sectors of a given mine, thereby disregarding large temporal an local variations.

b) Environmental characteristics:

Extrapolation to the general population of risk factors derived from the lung cancer rate among miners may be invalid because of large differences in the environments:

- the suspected or known carcinogenic agents (ore dust, acid-, diesel fumes) contained in the uranium mine atmosphere are different to the pollution- and aerosol characteristics of the indoor atmosphere in dwellings and radon spas, also with regards to the air pollution due to industrial activities and traffic;
- breathing rates of occupants of dwellings differ largely from those of miners, influencing the deposition pattern of inhaled radionuclides;
- levels of atmospheric radon daughter concentration in homes and public buildings differ typically by one or two orders of magnitude from those in uranium mines; this, however, is not valid for some parts of radon spas;
- typical equilibrium factors for radon daughters in mines and indoor environments of homes differ by a factor of two;
- the respective contribution of radon 222- and radon 220-daughters may be quite different in mining environments and indoor environments of houses;
- occupancy factors are about 0.8—0.9 for inhabitants of houses, but only 0.3 for workers in mines.

c) Absolute, relative and competing risk models:

- results of the risk assessments even for comparable pupulations of American and Czechoslovakian uranium miners are unsatisfactory. Applying the absolute risk concept, the analysis of the lung cancer data revealed that the absolute risk coefficient for the Czechoslovakian data is higher by a factor of 8 than for the U. S. data [44]. Only by substituting the relative for the absolute risk concept, i. e. by assuming that the additional lung cancer mortality is a function of the lung cancer mortality expected in the absence of radiation, reduces the discrepancy between the risk coefficients for the data sets to a factor of 1.8. However, reservations have been expressed on the use of the relative risk model [45];

- neither risk evaluation has taken into account the effect of lethal risks other than radiation-induced cancer. This requires the consideration of competing risks in the analysis of the dose-response relationship [46];
- radon exposure of the uranium miner between induction of lung cancer and death ("wasted exposure") is unknown and causes an underestimation of the true risk factor.

With regard to the influence of smoking it has been found amongst CSR-uranium miners that the portion of smokers amongst miners was equal to the frequency in the general male population [47]. Since it is indicated that decreasing exposure rates are accompanied by an increasing risk of lung cancer induction per unit of cumulative radiation exposure [48], the use of the risk assessment for uranium miners is not likely to overestimate greatly the actual risk for low-level exposure in urban or spa environments. Based on the latest UNSCEAR report [4] the lifetime risk factor (r_t) for lung cancer induction from the inhalation of radon daughters ranges from $200—450 . 10^{-6}$ per WLM[1] exposure of the bronchial epithelium. The exposure of 1 WLM corresponds according to the lung model by HOFMANN et al. [24, 60] to a dose of about 4 rem for a mean respiratory minute volume of about 20 l/min. Taking into consideration the above mentioned differences between urban, spa and uranium mining environment, the lower risk value r_t was used in the following calculations, i. e. $r_t = 50 \quad 10^{-6}$ per rem. However, it has to be emphasized that these risk estimates do not represent precise numbers but are associated with large uncertainties due to incomplete or inconclusive data. Also the quantitatively unknown synergistic action of radon and daughters with non-radioactive environmental pollutants or carcinogens adds to the above mentioned uncertainties in the risk assessment from inhaled radon daughters only [49].

7.2 Lung cancer incidence

The present average lung cancer rate in Salzburg-Land (r_S) is $r_S = 344 \quad 10^{-6}$/yr [50]. In order to assess the contribution from radon daughter exposure only (r_{Rn}) it is necessary to determine the annual number of "spontaneous" lung cancer cases[2] in a non-smoking population (r_{sp}). Risk from

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[1] One Working Level Month (WLM) corresponds to the amount of short-lived radon decay products in one liter of air, releasing the total alpha energy of $1.3 \quad 10^5$ MeV. This corresponds to the equilibrium radon concentration of 100 pCi/l. The exposure of 1 WL during 168 hours is defined as 1 WLM.

[2] But it has to be considered that "spontaneous" lung cancer rate comprises the cancer cases due to the influence of air pollution and radon decay products in a "normal" environment.

smoking can be assumed to represent a major contribution to the overall induction of lung cancer, since statistical analysis of data from five different countries showed that a 15 % increment in the average lung cancer death rate was due to cigarette smoking per 10^3 cigarettes/yr [51]. Taking into consideration the age distribution of the population and applying appropriate risk factors the annual spontaneous lung cancer of non-smokers ranges from $30 \leqq r_{sp} \leqq 100 \quad 10^{-6}$/yr [52—54]. Under the above assumptions these values represent the upper limit for the number of lung cancer cases attributable to inhalation of environmental levels of radon and decay products.

An important parameter in the assessment of risk factors for lung cancer induction is the mean latency period (L) for the tumor development. At present information on variation with large age is scarce, however, it is indicated that the excess lung cancer rate for workers exposed to high radon levels is considerably higher, if exposure occurs at ages over 40 years as compared to under 30 years of age [47]. Furthermore, the latency period is shorter by 6—7 years for smokers exposed to elevated radon levels than for non-smokers [55]. Analysis of US- and CSR-uranium miner data show that the mean latency period is about 15 years [44].

For the population groups investigated the annual number of lung cancer cases (r_{Rn}) due to radon and radon daughter exposure was assessed under the following assumptions:

1. The risk for the induction of lung cancer cases (LC) in a population of a given size (N) due to the accumulative exposure (resulting in an absorbed dose D_{asw}, see 5.2) is described by the absolute risk concept, i. e. the standardized individual probability (r_t) for radiation induced death per dose unit

$$r_t = \frac{LC}{N\, D_{asw}} \tag{3}$$

2. The mean latency period (L) is independent of the age (a) at the onset of exposure and

$$L = 15 \text{ years.}$$

3. The full expression of the total carcinogenic effect on lung tissue requires a period (t) of about 40 years [4].
4. The mean age ($\bar{a}$) of all population groups in 40 years.
5. The relationship between exposure and lung cancer induction is linear.

From the above r_{Rn} can be calculated as:

$$r_{Rn} = \frac{r_t}{t}\, D_{asw}\, N\, (\bar{a} - L) \tag{4}$$

For the urban population of Salzburg the total number of annual lung cancer cases due to radon daughter exposure ($r_{Rn,\,\text{histo}}$) was calculated for each dose interval of the histogram in Fig. 10 and summed over all intervals. It was found that 50 lung cancer cases per million people can be attributed annually to radon daughter exposure in the urban environment. About the same number is obtained, if the median exposure (1.5 rem/yr) is used for the risk calculations. Since dose frequency histograms are not available for the other population groups investigated, risk calculations were carried out based on the exposure data derived from the crd range of data (see Tab. 8, 11)[1]. For comparison, this method was also applied on the urban crd-data of Salzburg city in addition to the histogram-derived risk assessment ($r_{Rn,\,\mathrm{crd}}$). The total risk for miners (occupational plus spare-time NRE-exposure) was calculated assuming residence in a low-level NRE-area like Salzburg.

It can be seen from Tab. 13 that in the urban environment most "spontaneous" lung cancer cases $30 \leqq r_{sp} \leqq 100$ (see above) can be attributed to the exposure to radon decay products in an urban environment like Salzburg ($r_{Rn,\,\mathrm{histo}} = 50$).

For non-uranium miners of the mines investigated the risk for lung cancer induction due to professional exposure to elevated levels of radon decay products can be increased up to 300 % compared to a "citizen", depending on the radon levels and ventilation conditions at the work site. However, under advantageous conditions, i. e. lower values of the crd-range of NRE-data, the additional occupational risk is small.

Inhabitants of the Gastein area are exposed to a wide range of risk values (r_{Rn}) with lower and upper differing up to a factor of 25. This is due to their different occupations and place of residence. The group with the highest risk are people living and working in spa hotels and treatment centers, especially in Badgastein. For some people in this group — using the data from Fig. 7 and Tab. 8 — the risk for lung cancer is about twice is high as the observed lung cancer rate (r_S). However, since the total number of persons exposed in this group is only in the order of several hundred, it is very difficult to observe any potentially increased lung cancer rate with epidemiological methods due to statistical problems.

The risk r_{Rn} is reduced by about 50 % for those spa workers, who take residence in other buildings without radon treatment facilities. Other spa inhabitants and workers, who live and work in buildings of the latter type, are exposed to higher risks than in an urban environment only, if these buildings are located in the center of Badgastein. However, equal risk can result from residence and employment in Böckstein due to the generally elevated NRE-levels in this village.

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[1] This implies a conservative approach to the risk assessment, since the crd-exposure data are a measure for the dispersion of the median value; therefore also the resulting risk value represents a description of the median ("typical") risk, resp. its dispersion for the group concerned. However, the risk for those group members exposed to the upper and lower range of NRE-levels differs significantly from this median risk.

In Tab. 13 the risk r_{Rn} for different population groups is compared to mortality rates from exposure to other health risks. It can be seen that the risk from exposure even to "normal" environmental levels of radon and decay products exceeds by almost one order of magnitude lethal risks from man-made radiation of chemical pollutants and can be of the same magnitude as the use of motorized vehicles. It can to be pointed out that these risk assessments for radiation induced lung cancer do not consider different radiation

Table 13

Comparison of standardized annual fatal risks (r) from different hazardous agents per million people to the number of lung cancer cases due to inhalation of radon and decay products (r_{Rn})[1]

Hazard	Risk r (10^{-6}/yr)
Lung cancer from inhaled radon decay products (r_{Rn}):	
Non-uranium miners	50—160
Radon spa area Gastein — Adults only	
Badgastein	
Living and working in radon spa hotels or treatment centers	40—680
Working as above and living in other buildings	20—370
Living and working in buildings (in the center) without thermal water	20—140
Living and working as above (in the periphery)	10—100
Bad Hofgastein	
Living and working in radon spa hotels or treatment centers	10—250
Working as above and living in other buildings	10—140
Living and working in buildings without thermal water	10— 40
Böckstein	
Inhabitants	20—150
Salzburg city ($r_{Rn,\,crd}$)	10— 90
Salzburg city ($r_{Rn,\,histo}$) — based on age- and sex-dependent dose frequency distributions	50
Estimated spont. lung cancer rate for nonsmokers (r_{sp})	30—100
Observed lung cancer, Salzburg-Land (r_S)	344
Lung cancer from benzo(A)pyrene (1 ng/m^3) in city air (57)	24
Lung cancer from medical diagnostic X-ray (4)	5— 10
Traffic accidents, Salzburg city	150

[1] The range of risk values for each group refers to the dispersion of the median Since in the case of the inhabitants of Salzburg city individual dose assessments were carried out, it was possible to calculate the risk based on the dose frequency distribution.

sensitivity of children. According to investigations amongst A-bomb survivors the risk factor for children (0—10 years) may be higher up to a factor of 8 than for adults [56].

8. Conclusions

Exposure of man to the natural radiation environment results in a quantifiable risk for somatic damage. This risk is mainly due to the inhalation of radon and its decay products. Exposure to these nuclides may account up to 100 % of all spontaneous, non-smoking related lung cancer cases, even in an urban environment with generally low natural radioactivity like Salzburg city. It is probable that synergistic effects with other carcinogenic agents exist. Therefore the influence of radon decay products in the NRE is of increasing importance in the future with the anticipated higher atmospheric concentration of chemical pollutants.

The magnitude of this somatic risk can exceed other radiation- or non-radiation related risks. Whilst there is justified public concern about cancer-causing drugs, pollutants and man-made radiation exposure, the health impact of the "natural pollutant" radon is greatly underestimated. It seems probable that future exposure of man to radon and its decay products will increase:

1. energy conservation measures demand the reduction of ventilation rates and the increased use of air-recirculation. This will cause an increase of both, radon levels and the dose determining equilibrium factor between radon and decay products;
2. concern about the environmental impact of large amounts of industrial waste products from e. g. coal power production, mining- and phosphate industry, stimulates the recycling of these materials as building material. Due to technological enrichment processes some of these new construction materials show a high content of ^{226}Ra, leading to increased radon exhalation into the room atmosphere.

It will require extensive risk-benefit-cost analytical methods to assess appropriate action levels against any undesirable contamination of the environment with the natural carcinogen radon and its decay products.

The risk in radon spas, especially for workers in the treatment facilities, is unacceptably high. The reduction of the atmospheric content of radon decay products by suitable ventilation techniques should be as common practice in spas as it has been in the past in uranium and other mines.

Major efforts are undertaken at national and international level concerning the assessment of dose limits and action levels for man-made radiation in accordance with the ICRP-ALARA principle ("as low as reasonally achievable"). It should be taken into consideration that this risk from man-made exposure is considerably smaller than the risk man is exposed to from the natural radiation environment — and the biological target "man" cannot discriminate between the two.

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Address of author: Univ.-Doz. Dr. F. STEINHÄUSLER
Abteilung für Biophysik
Erzabt-Klotz-Straße 11
A-5020 Salzburg
Austria

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