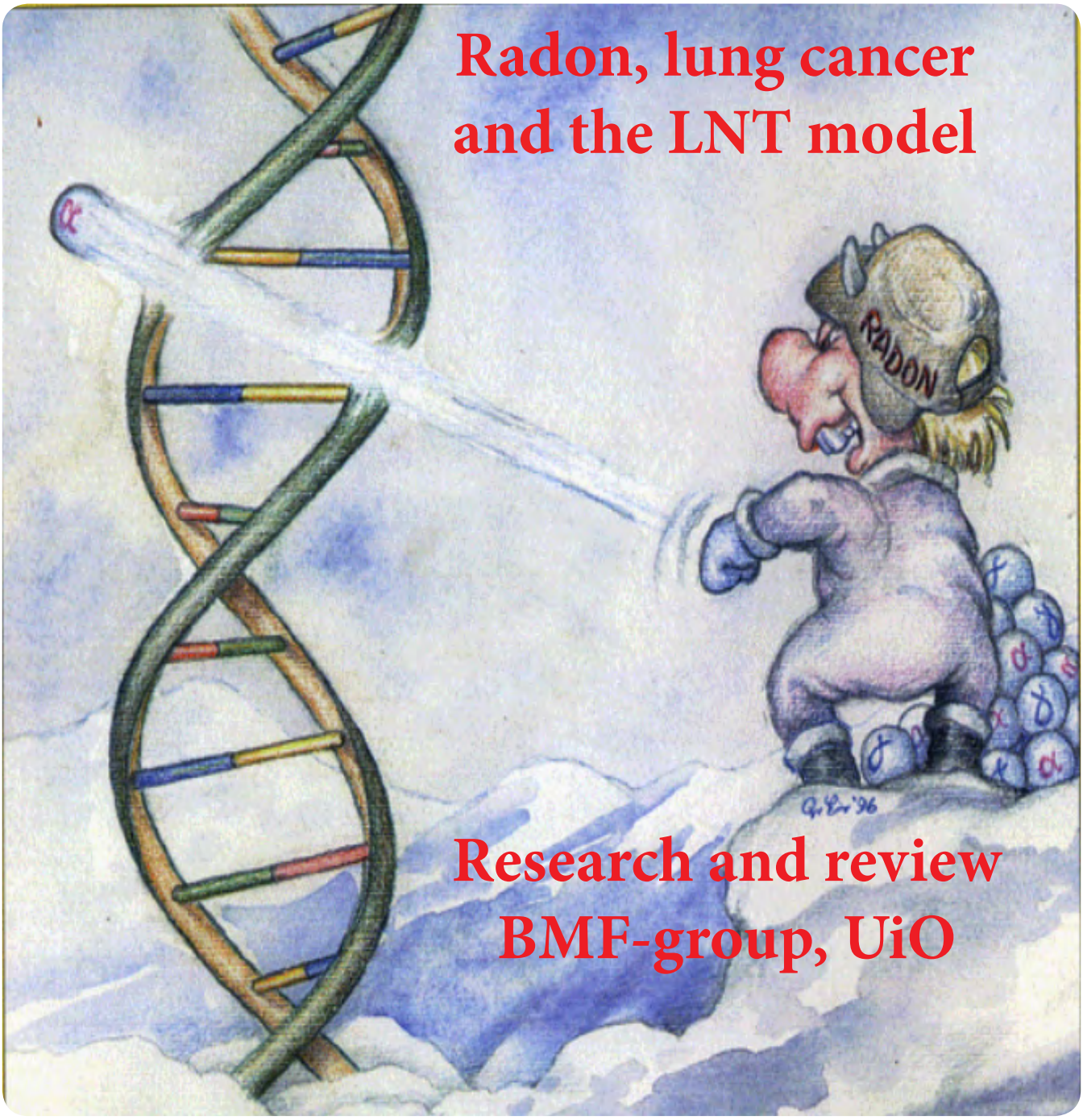
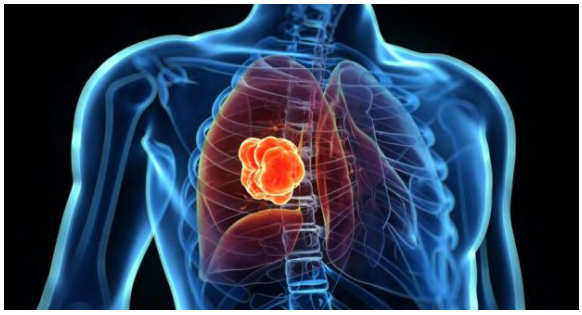
Radon, lung cancer and the LNT model



Research and review BMF-group, UiO



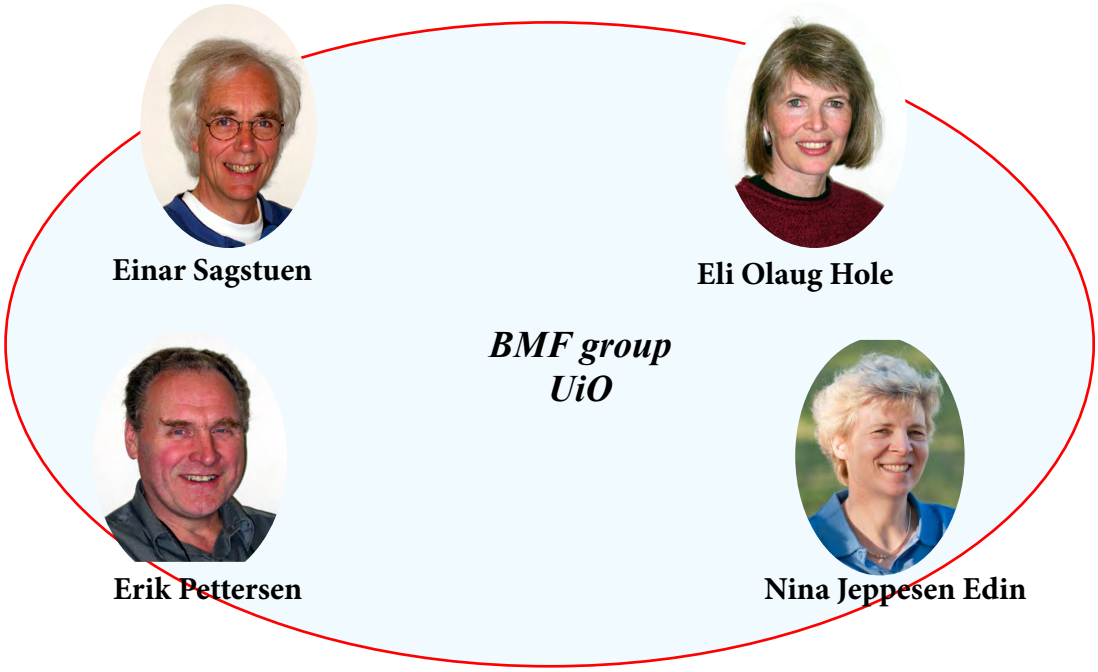
This is an update on radon and lung cancer. It is also a discussion on the rise and fall of the famous LNT (linear no threshold) theory. The theory has caused much anxiety and has prevented a reasonable use of nuclear power in the fight for CO_2-free energy.

Preface

In this update on radon and lung cancer we present a model for the **lungs cleaning system** and discuss the rise and fall of the "linear no threshold" (LNT) theory. We shall review the old experiments that introduced this theory, and we shall go through the modern radio-biological research that seem to nullify the same theory. The discussion was initiated since the LNT theory is the basis for the "International Commission on Radiation Protection" (ICRP) and the "World Health Organization" (WHO) when they discuss the problem with radon in homes and its possible cause for lung cancer.

A new model for the lungs cleaning system was introduced in 2012. This model can in a significant way influence the radiation dose to the lungs from α and β -particles and the whole dosimetry for radon becomes extremely uncertain.

November 2016



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Introduction

Radon and lung cancer are usually described by the "***linear no threshold theory***" (LNT). In our opinion this theory is wrong and the basics need to be discussed. The theory was quite well accepted from the 1950-ties up to late 1980-ties, when the deleterious effects of the Chernobyl accident were debated. The implications of this accident questioned an otherwise reasonable use of LNT. Today it is a burden to the society that halters our regulations on radon and prevents countries from using nuclear power in the attempt to reduce global temperature increase.
Radiation authorities such as ICRP (International Commission on Radiological Protection), WHO (World Health Organization) and of course different public groups, still use the LNT theory in relation to the small extra doses given at small dose-rates from accidents like Fukushima. It is now even used for predictions of biological consequences of low dose-rate radiation such as radon in homes and other types of background radiation. As the LNT model is correct regarding the production of damaged macromolecules, it is far from correct when it comes to ***biological*** consequences of the small doses. We feel it necessary to go through the fundamentals of the theory, and will do this in combination with a new update on radon and radon daughters where we in particular discuss the lung doses from the radon daughters.
If the LNT theory is accepted, it includes the use of ***collective doses***; i.e. the sum of small doses to a large number of people to predict the number of people which will get a certain disease from this radiation. The procedure usually results in large collective doses – that according to the LNT would give deleterious effects to some members of the group. As an example we can calculate the cancer deaths of the background radiation. Thus, if we assume that the background average dose to the world population is around 5 mSv per year, the use of LNT (with the gradient for the straight line like that attained from the Hiroshima bombing) would result in about 1.8 million cancer deaths per year and radon would be the major cause for this.
The problem with this calculation is that the DNA damage by the normal metabolism is very much higher than that by the background radiation. Furthermore, our cells and tissue have ways of avoiding the effect of these damages by repair, by cell suicide and stem cell proliferation. The notion of collective doses is not valid for the low dose field.

The use of collective doses and the LNT-theory has recently been condemned by UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation). They express this as;

"*the Scientific Committee does not recommend multiplying very low doses by large numbers of individuals to estimate numbers of radiation-induced health effects within a population exposed to incremental doses at levels equivalent to or lower than natural background levels.*"

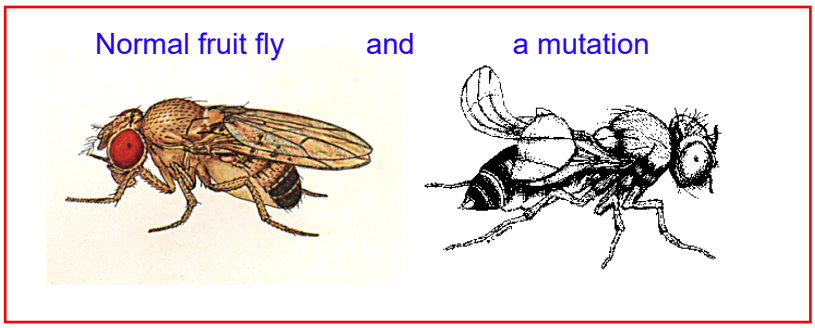
ICRP and WHO still use the LNT theory for small radiation doses given at low dose-rates. However, it should be mentioned that ICRP in their publication 103 from 2007 expressed the following with regard to the collective doses:

"Collective effective dose is an instrument for optimisation, for comparing radiological technologies and protection procedures. Collective effective dose is not intended as a tool for epidemiological studies, and it is inappropriate to use it in risk projections. This is because the assumptions implicit in the calculation of collective effective dose (e.g., when applying the LNT model) conceal large biological and statistical uncertainties. Specifically, the computation of cancer deaths based on collective effective doses involving trivial exposures to large populations is not reasonable and should be avoided."

When the LNT is used for the lowest dose regions ICRP often introduce a "***dose and dose-rate efficiency factor***" (DDREF), which reduces the gradient in the low dose region. A factor of 2 has been used.

ICRP, WHO and several national radiation authorities, as well as other groups still assume that LNT is valid. The model has introduced a number of unnecessary rules and regulations which are negative to the society. LNT is more or less responsible for the fear of nuclear power, that otherwise can save us from climate changes. In the following we shall discuss the rise and fall of this theory.

Radiation effects in the fruit fly and dose effect curves

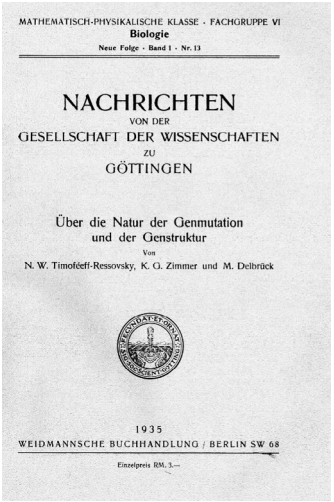


We start this journey in the beginning of the 1930-ties. Experimental radio-biology in those days very often used the fruit fly "Drosophila melanogaster" as a biological model. Females and males can be easily distinguished and they have a lifespan of 30 days at 29 ° C. The females lay about 400 eggs and the generation time is short. The fruit flies were used in heredity studies (by the famous Thomas Hunt Morgan) from around 1910. The mutations are easily observed by a magnifying glass and the different mutations that appeared spontaneously were detected.
In Hermann J. Muller's 1927 paper; "***Artificial Transmutation of the Gene***" he demonstrated for the first time that x-rays could increase the frequency of mutations in the fruit fly. In a few weeks' time Muller was able to artificially induce more than 100 mutations – about half the number of all mutations discovered in Drosophila over the previous fifteen years. In these first radiation induced mutation experiments **no** dose measurements were carried out that can be used to document mutation versus dose. Muller got the 1946 Nobel prize for his observation.

The more quantitative experiments on radiation induced mutations in the fruit fly were done in the famous work by Timofeev-Resovsky, Zimmer and Delbrûck.

The historic work by Timofeev-Resovsky, Zimmer and Delbrûck

One of the giants within the genetics of the fruit fly was the Russian scientist Nikolay Timofeev-Resovsky. He worked in Berlin and started a work together with K. G. Zimmer and Max Delbrûck. They were both physicists and Zimmer was familiar with dose-measurements. They worked with the fruit fly and x-rays and Zimmer measured the doses. The three scientists introduced the ***target theory*** where the biological effect (gene mutation) was the result of a "hit" – ***and the number of hits increases linearly with the radiation dose (LNT).*** From a radiobiological point of view this is parallel to the statement that the number of damaged macromolecules increases linearly with the radiation dose. This is a starting point of controversy. The controversy arises when this is brought a step further to state that the number of biological responders such as the number of cancer incidences also increases linearly with the number of damaged macromolecules for all damage number and all rates of damage appearance.
The title of their famous work from June 1935 was "***On the Nature of Gene Mutation and Gene Structure***". The paper had a great impact on the early molecular genetics. Long known as the "Green Pamphlet" or the "three-man-paper". The paper originated mainly in Berlin-Buch.

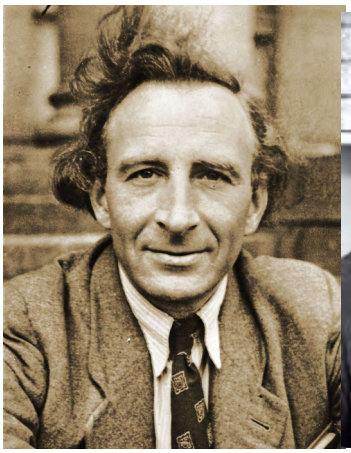

MATHEMATISCH-PHYSIKALISCHE KLASSE · FACHGRUPPE VI
Biologie
Neue Folge · Band 1 · Nr. 13

NACHRICHTEN
VON DER
GESELLSCHAFT DER WISSENSCHAFTEN
ZU
GÖTTINGEN

Über die Natur der Genmutation
und der Genstruktur
Von
N. W. Timoféeff-Ressovsky, K. G. Zimmer und M. Delbrück

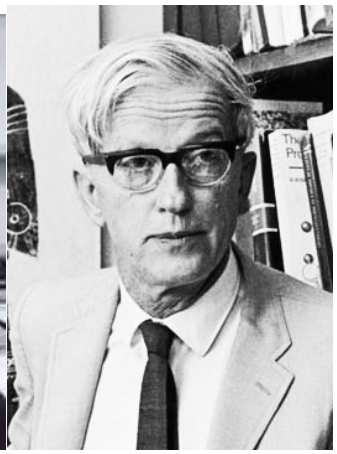
1935
WEIDMANNSCHE BUCHHANDLUNG / BERLIN SW 68
Einzelpreis RM. 3.—

Timofeeff-Ressovsky, describes the mutagenic effects of x-rays and gamma rays on fruit flies. K.G. Zimmer, analyses Timofeeff-Ressovsky's results theoretically and Delbruck describes a model of genetic mutation based on atomic physics.



Nikolay Timofeev-Resovsky
(1900 – 1981)

Karl G. Zimmer
(1911 – 1988)



Max Delbrück
(1906 – 1981)

They described the target (the gene) in the following way; "*We view the gene as an assemblage of atoms within which a mutation can proceed as a rearrangement of atoms or a dissociation of bonds (triggered by thermal fluctuations or external infusion of energy) and which is largely autonomous in its operations and in relation to other genes*". (Remember, that in 1935 we had very little information about the structure of DNA, genes and chromosomes.)
It can be mentioned that this paper provided much of the material for Erwin Schrödinger's wonderful book ***What is Life?*** (1944).

Dose measurements

K.G. Zimmer was responsible for the dose measurements. The doses were measured in the old unit "roentgens" (R) and the data are given in the figure on the next page.
We do not know the dose-rate, but the smallest dose was approximately 800 R, which is about 7.7 Gy. Both the dose region and the dose rate used in these studies are far outside the dose level which is of interest in the discussion on radon in houses and other background radiation sources.

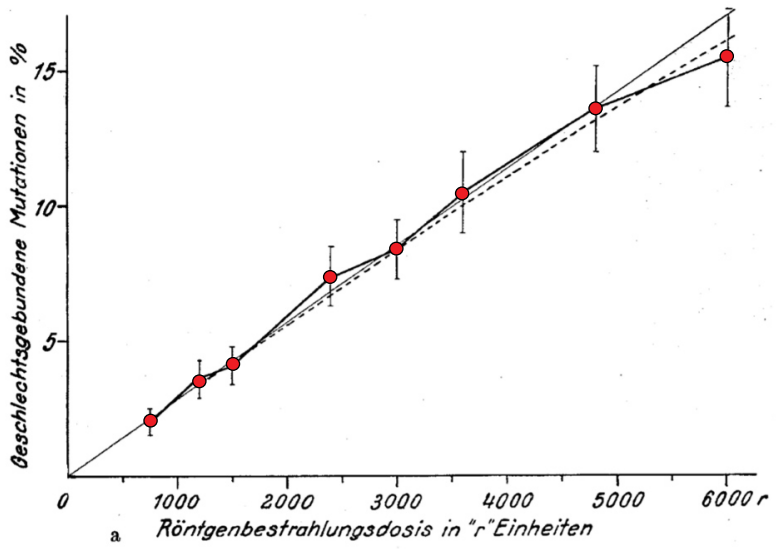
The results in the 1935-paper are presented by the figure on the next page. As you can see the results are seemingly in line with the LNT-theory. The theory has thereafter been assumed to be valid and has been used **for all dose levels, even for doses and dose rates down to background radiation**.

In 1928, the *roentgen unit* (abbreviated R) was adopted. 1 R means the amount of x- or γ-radiation that is required to liberate positive and negative charges of one electrostatic unit of charge (esu) in 1 cm^3 of dry air at standard temperature and pressure (STP). This corresponds to;

1 R = 2.58 • 10^{-4} coulomb per kg of ions generated in air

1 Gy = 1 joule absorbed energy per kg

To calculate the radiation dose (in Gy) from an exposure of 1 R depends on the energy of the x- or γ-radiation and the composition of the irradiated material. For example, if soft tissue is exposed to γ-radiation of 1 R, the radiation dose will be approximately 9.3 milligray (mGy).,



The results of the 1935 paper. The dose is measured and given in the old unit, roentgen (R). The smallest dose in the figure is about 800 R or about 7.7 Gy. The data makes it reasonable to be fitted by a straight line through zero dose. This is LNT.

We have very little information whether they discussed the curve for small doses given at a low dose-rate. However, Hermann Joseph Muller in his Nobel lecture in December 1946 discussed smaller doses down to 3.8 Gy given at a dose-rate of 5.8 mGy per hour and concluded "*They leave, we believe, no escape from the conclusion that there is* ***no threshold dose****, and that the individual mutations result from individual "hits", producing genetic effects in their immediate neighbourhood*".

After the second world war several people and organizations tried to stop the nuclear bomb tests and it was therefore important to carry out experiments at much lower doses and dose-rates – mainly to confirm that the LNT could be used down to the lowest doses.
Again the fruit flies were used and the most tedious and well done experiments were carried out by Ernst Caspari and Curt Stern.

Ernst Caspari and Curt Stern paper

Ernst Caspari and Curt Stern carried out a significant work on the mutations in fruit flies (GENETICS 33: 75, January 1948) which strongly are in **contrast** to Mullers statement of no threshold. The purpose of the paper was to test the linearity for low doses and dose-rates.

They used γ -radiation from radium and the flies were irradiated at a distance of 27.5 cm from the source (10 mCi or $3.7 \cdot 10^8$ Bq). The dose-rate was 2.5 R (23 mGy) per day. The total dose after 21 days was approximately 500 mGy. The controls went through the same procedure, but protected by a 5 cm thick lead plate. Even then, the controls got a γ -dose of 0.03 R/day (0,29 mGy) and a total dose of 6 mGy. Thus, both the irradiated and the controls got a radiation dose far above background.

Ernst Caspari
(1909 – 1988)

The effect studied was lethal mutations in the X chromosome of the strain Canton Special.

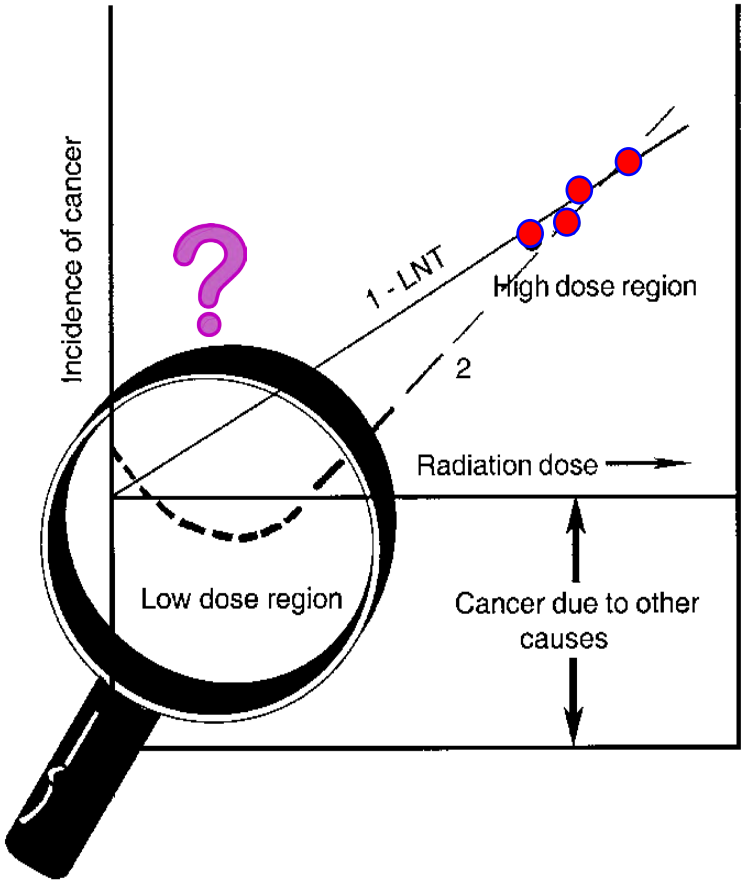
Casparis experiments showed that the difference between the mutation rates of irradiated and non-irradiated sperm is, with a high degree of probability, smaller if the radiation is distributed over 21 days than if the same dose is given at once. **Thus, the experiments demonstrated a clear dose-rate effect.**
Furthermore, in a total material of 108,215 chromosomes tested, no significant difference between irradiated and controls was found.
Thus the results in this low dose region do not follow the LNT-theory, but rather indicate a threshold for low dose rates.

Other experiments that violate the LNT theory

A large number of experiments can be mentioned that violate the LNT (linear no threshold) theory. This is also realized by ICRP. They do not go away from LNT, but as mentioned above introduces a DDREF (dose and dose-rate efficiency factor) for use when the dose and dose-rate is small. This factor reduces the slope of the curve in the low-dose region, but LNT is still the curve to be used. In several discussions a value for DDREF have been suggested. Very often the value 2 has been used.

Epidemiological studies

Most studies on the effect of ionizing radiation are presented in the form of dose response curves; i.e. we give the dose on the horizontal axis and the biological effect on the vertical axis. Different possibilities for a dose-effect curve is given below.



In the figure to the left, cancer is the detrimental effect. Radiation induced cancer is given as a function of the radiation dose.
*The curve marked 1-LNT is the well known "**linear no-threshold model**" for radiation damage.*

*The curve marked 2 has an alternative form, including both a threshold as well as a "**hormetic**" part for the smallest doses.*

The filled circles indicate assumed observed data for the large dose region. The LNT-curve is easily drawn from the observed data at high doses.

We do not know the biological effects of the dose level included under the magnifying glass.

Most epidemiologists are concerned about the vertical axis and less attention is paid to the dose and the dose determination. An effect such as cancer is studied years after the irradiation, whereas the radiation dose should be measured when the radiation takes place. The data on cancer used by ICRP are mostly related to the Hiroshima bomb. The irradiation lasted only seconds whereas the cancers are observed years afterwards.

The radiation from the bombs consisted of γ -radiation and neutrons. The dose was given at a high dose-rate. No measurements were carried out at the time and all doses have been determined after interviews with those involved – often years afterwards. The γ -radiation is so-called low LET (Linear Energy Transfer) radiation that is stopped by all kinds of materials it has to penetrate before hitting a person. The neutrons are so-called high LET radiation and ICRP usually convert the physical dose measured in Gy to a biological dose measured in Sv by introducing a RBE-factor (Relative Biological Efficiency). For neutrons in Hiroshima a factor of 10 have been used. The doses have been determined in 1957, 1965, 1986 and in 2002 (DS02). Almost all radiation induced cancers have been assigned the LNT-curve and data from Hiroshima have been used to determine the curve (the slope of the straight line).

We give these details to show that dose determination is extremely difficult. In this paper we are discussing radon doses and lung cancer and you will soon realize that in this field it is even more difficult to arrive at the lung doses. The main reason for this is the fact that the main part of the radiation is from α -particles that have a range in tissue of less than 100 μ m. Consequently, the disintegrations must take place when the radon daughters are within the lungs and airways, – and of course it is the radiation doses to the lungs that are important with regard to radiation induced lung cancer .

We conclude that the most difficult and uncertain parameter in all the epidemiological studies is the dose determination.

Now we shall mention some studies where the dose and dose-rate is determined with results that are in conflict with LNT. Probably, the "radium dial painters " is the best known.

The radium dial painters

In the first part of the 20th century, the numerals and hands on some clocks were painted with radium. Radium paint was still used in dials as late as the 1960s. Women were employed to do the painting. Sometimes they ingested small amounts of radium because they "pointed" their brushes by licking them.

Radium is a bone seeker and some of the women contracted bone cancer later in life.

This is extensively described in a report by R.E. Rowland from Argonne National Laboratory in 1994.

In the 1990s three books about the dial painters were published: *"Radium Halos", "Radium Girls" and "Deadly Glow".*

To the right is an illustration from D.W. Gregorys play "***Radium girls***".


An illustration of radium painters

Let us try to give some of the main points. From about 1917 it became an industry in USA to paint the dials and numbers on the clocks with a mixture of radium and fluorescent materials. It was mainly young girls (20 – 30 years old) that did the painting.
The radioactive paint consisted of a mixture of Ra–226 (from the Uranium series) and Ra–228 (from the Thorium series). The α-particles from the radioactive isotopes bombarded luminous materials such as barium bromide (BaBr), zinc sulfide (ZnS) and others – which resulted in a constant glow that could be seen in the dark.
More than 2000 young women were engaged. Each girl handled about 1 mCi radium per month (37 MBq). In this work the girls were exposed to external as well as internal radiation which included both α, β and γ-radiation. We are faced with the following radiation scenario:

1. The radium isotopes resulted in radon. The radon level in the working room was about **2000 Bq/m^3.**

2. The girls were exposed to external γ-radiation from the radium sources. The dose level has been calculated to be up to **460 mGy/year**. The breasts are most exposed.

3. The girls were exposed to α-radiation from the intake of Ra–226 and Ra–228.

Ra-226 from the Uranium series has a half-life of 1600 years. It ends up in the stable isotope Pb–206. In the decay processes 10 α-particles are involved. Ra 228 from the Thorium series has a half-life of 5.8 years. It ends up in Pb–208. In the decay scheme 6 α-particles are involved.

We can conclude that the dose-rate is rather low, and completely different from the atomic bombs in Japan.

When these isotopes are inside the body it is the α-particles that give the main contribution to the radiation dose. However, it is the γ-radiation from the decay processes that can reach the outside and consequently give the basis for measurements.

A large amount of work has been carried out to localize those working in this industry and which have been exposed to radiation. The total number identified was 4133 (3637 women). Approximately 2500 were measured in order to determine the radiation doses.

A significant part of the work with the radiation doses has been carried out by Robley D. Evans. He introduced the method to use the γ-radiation to determine the radium in the body. They used NaI-crystals to observe the γ -radiation. From the amount of radium in the body they tried to calculate the dose in Gy. "***Center for Human Radiobiology at Argonne National Laboratory***" was established in 1968. They published the work on "***Radium in humans***" in 1994. The radium dial painters were a considerable part of this work.

The work with the dial painters (all those exposed to radium) included the following items;

1). To identify all the dial painters,

2). To measure the radioactivity in the body and thus **estimate** the total intake.

3). To determine the health history for those exposed.

Let us note that a significant intake in the case of the dial painters was due to the fact that the girls licked the brushes to sharpen the tip. In 1926 it was urged that the girls should stop this licking – which certainly helped. **No** cancers were observed for those starting after 1926 (see figure next page).

Measurements

Radium is taken up and deposited mainly in the bones. In order to calculate total doses to the individuals, both radioactive decay as well as biological excretion must be considered, i.e. we try to find a biological half-life. Keane and Evans reported an average biological half life of 28 ± 8 yr for a group of twenty subjects, while Miller and Finkel found an average of 15 yr for the biological half life in eight patients for the period 19–33 yr after injection. This implies that the intake of radium can be roughly estimated from measurements at later times – and this again can give an estimate of the accumulated body dose. The total skeletal dose varied considerably with the highest values up to 280 Gy.

In the large Argonne work altogether about 6000 people are included. The names of about 5000 are known, 3500 have been localized and about 2500 have been measured.

Robley D. Evans
(1907 – 1995)

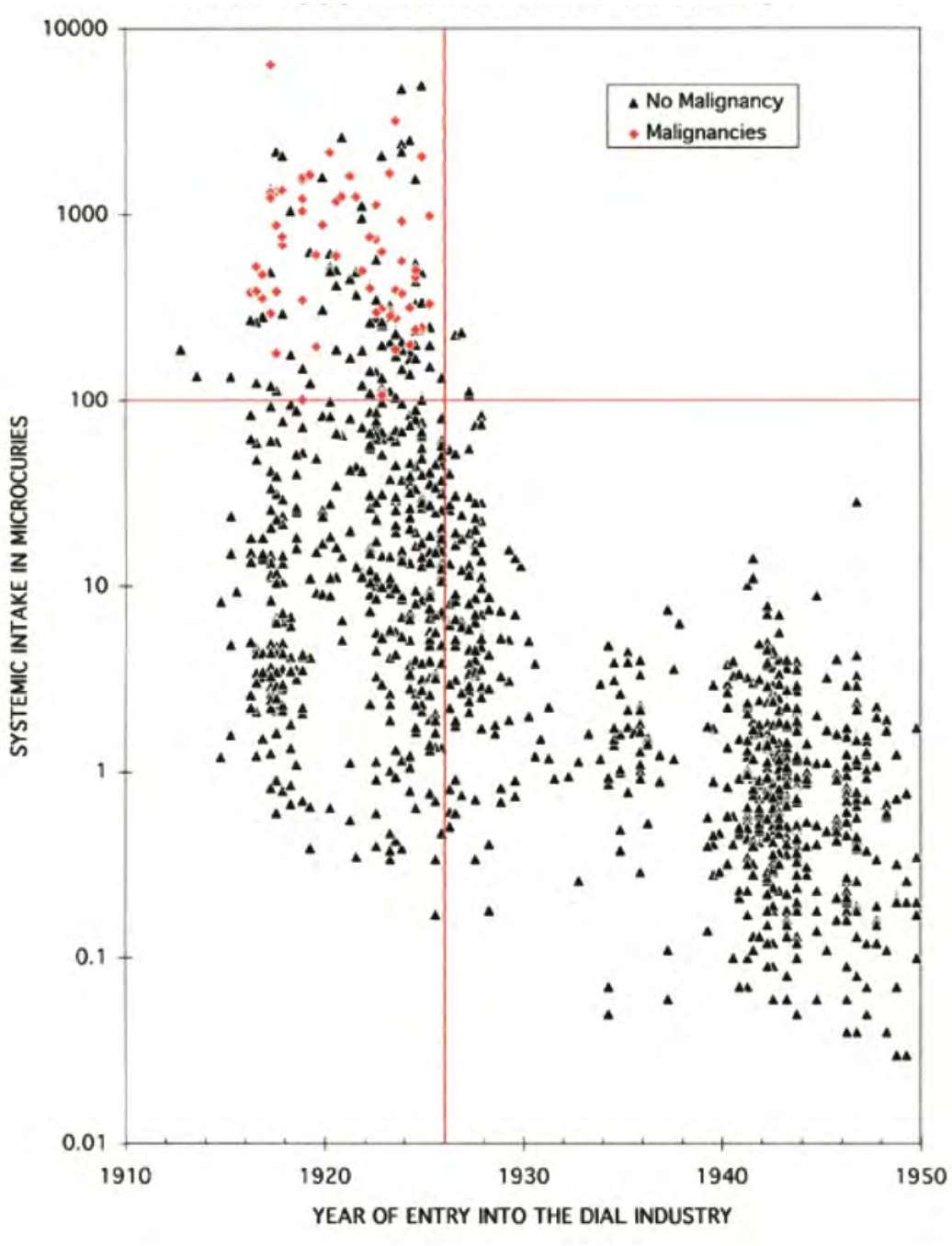
Health effects – cancer

The great majority of radium dial painters went through life with no recognizable consequences of their exposures.
They lived as long as, and apparently in as good health as, their unexposed neighbours. This fact seems to have been little appreciated and seldom mentioned, but it may be the most important finding of the entire study.

No leukemia, no breast cancer and no lung cancer in spite of the rather large doses given at a low dose rate.

Only two types of cancer have been diagnosed – 64 bone sarcomas and 32 head carcinomas. These cancers are otherwise very rare. The total doses for those with bone sarcomas varied from 11 to 278 Gy – and for those with head and neck carcinomas the total calculated dose varied from 8.6 to 158 Gy.

On the next page we present the results for the radium dial painters in an interesting way. All the persons measured are given by a point – those with malignancies in red and all with no malignancy in black.



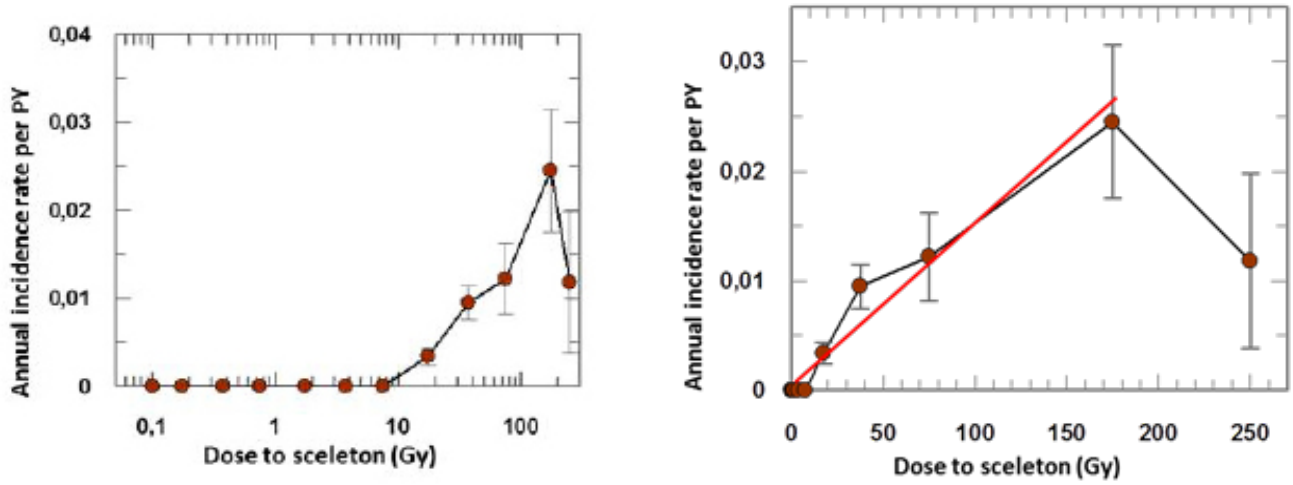
This is the figure presented for the radium dial painters. Along the abscissa is the year each one started with the painting. Along the vertical axis is the measured amount of radium intake (scale is in μ Ci). All those that got cancer is marked in red. The vertical red line on 1926 is drawn since after this time it was forbidden to lick on the brushes to point them.
Due to the work by Evans the μ Ci axis can be given in the dose unit Gy.
The data here presented clearly show that we have a threshold value and that the LNT can not be used. It is of interest to note that in this case the main part of the dose was from α -particles. For radon and lung cancer it is also α -particles that is responsible for the dose to the lungs.

From a population of 2,383 cases for whom reliable body content measurements have been done – ***all the 64 bone sarcoma cases occurred in the 264 cases with more than 10 Gy, while no sarcomas appeared in the 2,119 radium cases with less than 10 Gy.***

The bone cancer data (osteosarcomas) are presented in two different ways in the figures below. It is of course the same data in both figures, but the abscissa (the dose axis) is presented in two ways. The dose axis in the left figure is logarithmic, whereas in the right figure it is linear. On a linear dose axis all the low dose data are compressed and appears almost as a single point.

In such a plot we have the impression that the data are in line with the LNT curve.

In spite of the seemingly good agreement with the LNT-hypothesis (right figure) ***no one has claimed that these data follow the LNT curve.*** Even the most keen supporters of the LNT-hypothesis seem to have accepted that in the case of the dial painters there is a dose threshold value.



Bone cancer data (osteosarcomas) for the radium dial painters. Annual incidence rate per person and year after intake of radium as a function of the total amount of radium in the body. The dose to the skeleton (given in Gy) is plotted along the abscissa. In the left figure the scale is logarithmic, whereas in the right figure the scale is linear. A straight line can be fitted to the data between 0.1 Gy and 175 Gy (i.e. the origin is not included as a data point). We get the impression that the data follows the LNT-hypothesis, except for the last point at 250 Gy.

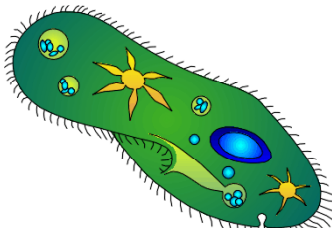
Conclusions

On page 6 we presented the data for mutations in the fruit flies for the dose range from 8 to 55 Gy on a linear scale. These data fitted a straight line and were used in support of the LNT-theory. If we could include the data from Caspari and Stern it would have been clear that we also for the fruit flies had a threshold. The data from the dial painters clearly show a threshold, but the figure above shows that we can be fooled.

The results so far show that the dose-effect curve for radiation damage to fruit flies and radium dial painters have a threshold and thus violates the LNT-theory. The question whether we have a hormetic effect is discussed in the following experiments.

Planels studies on the growth of Paramecium

Planel and coworkers studied in the 1980-ties the growth of *Paramecium* (the small "slipper shaped" cells living in water) by carrying out the following experiments:



A drawing of Paramecium

A. Cultures of paramecium were put into a 5 to 10 cm thick lead chamber that reduced the background radiation to almost zero. The result was that cell growth was reduced. The same result was obtained when the experiment was carried out in an underground laboratory where the radiation background was very small.

B. The next step in the experiment was the introduction of radioactive sources.

The radiation from the sources resulted in a radiation level which yielded an annual dose of from 2 to 7 mGy (comparable to normal background radiation). The result was that the cell growth ***increased*** back to "normal."

Conclusion

Radiation in small amounts given at a low dose-rate is positive for paramecium. The same holds true for a number of later studies on bacteria.

The Taiwan cohort and γ -radiation

In 2006, W.L. Chen and coworkers published the paper ***"Effects of Cobalt-60 Exposure on Health of Taiwan Residents Suggest New Approach Needed in Radiation Protection".***

The paper is about an almost unbelievable story from Taipei in Taiwan. It was observed, accidentally, that a number of apartments had been contaminated with Co-60 gamma-radiation.
Approximately 10,000 people occupied these buildings and received a rather large radiation dose during a period of up to 20 years!

The apartments were built mainly in 1983 and they used recycled steel, accidentally contaminated with cobalt-60. The first "radioactive" apartments were discovered in 1993, and later more apartments, altogether more than 1700 were found. The contaminated buildings included both public and private schools as well as some small businesses, in Taipei City and nearby counties. About ten thousand people occupied these buildings for 9 to 22 years.

Co-60 has a half-life of 5.27 years. It decays by emitting one β-particle – followed by the emission of two γ-ray photons with energies of 1.17 MeV and 1.33 MeV respectively. It is possible to calculate the dose-rate in each apartment from the measurements carried out in 1996 – from the start in 1983.

The γ-radiation is "whole body irradiation" and the dose level in the houses during the period 1983 to 1996 was determined. The whole body doses to the residents in these apartments are of course quite uncertain and depend on the time spent in the different apartments. A crude estimate of the average 1996 dose for 3 different cohorts is as follows:

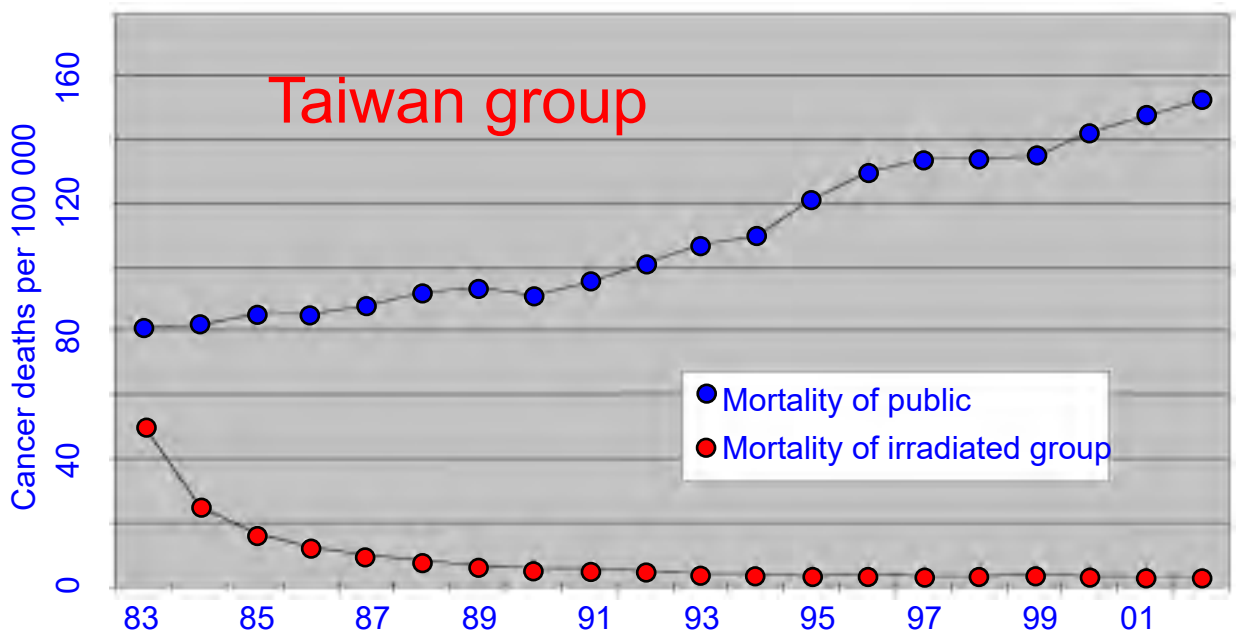
1. High cohort (~ 1100 people) = 87.5 mGy
2. Medium cohort (~ 900 people) = 10 mGy
3. Low cohort (~ 8000 people) = 3 mGy

The calculated mean annual dose received by all the residents in 1996 was about 13 mGy. It can easily be calculated that the 1983 dose was approximately 74 mGy.
We can use this and get an information of the ***accumulated doses*** to the residents in the three groups or cohorts.

Residents with annual doses above 5 mGy were examined in AEC (Atomic Energy Commission) hospitals. The examinations revealed **no** harmful radiation sicknesses. The harmful effects in question were cancer and congenital malformations (birth defects).
The mean cancer mortality in Taiwan in the period 1983 – 2002 was 116 deaths per 100,000 person-years. It increased in this period as seen in the figure below. In Norway the cancer mortality is higher with about 210 deaths per 100 000 person-years.

For a population of 10,000 the number of cancer deaths expected, according to LNT, for the 20 year period 1983 –2002 is 232.
The observed cancer deaths for the Taiwan cohort is given in the figure below. ***The total cancer deaths for the cohort was 7 – only 3 % of that expected for the general population.***

Congenital malformation was the other harmful effect studied. There is no official statistics with regard to the rate of congenital malfunctions in Taiwan, but an incidence of 46 children was expected. Only 3 children with congenital malformations were found in the cohort (heart disease). This is about 6.5 % of the rate for the general population.



The results of the Taiwan study strongly suggest that whole-body chronic irradiation, in the dose rate range that the apartment residents received, ***caused no symptomatic adverse health effects***, such as radiation sickness, or increased cancer or increased congenital disease such as predicted by ICRP theories. On the contrary, those who were exposed had lower incidences of cancer mortality and congenital malformations.

We quote from the Chen et al. paper.
The medical evidence from this study clearly suggests that current radiation protection policies and standards are inappropriate. We therefore recommend that the radiation protection authorities change them to accurately reflect the actual benefits and hazards of exposures to radiation. This would have very important consequences for all the nuclear risk assessments carried out and the public attitudes toward all applications of nuclear and other technologies that involve ionizing radiation. Fear of small doses of radiation is the basis for political barriers blocking the construction of nuclear power plants and nuclear waste management facilities.

Adaptive Response

If you give a biological system a small radiation dose at a low dose-rate before a more significant radiation dose, you can often observe that the effect of the large dose is reduced. It is somewhat like a vaccination which can protect a biological system from a more significant damage.

Sheldon Wolff
(1929 – 2008)

Adaptive response was first observed in 1984 by G. Olivieri, J. Bodycote and S. Wolff at University of California. They worked with human lymphocytes and observed chromosome aberration. The experiment was carried out in the following way.

The lymphocytes were cultured with ^{3}H-labeled thymidine (^{3}H–TdR) that was incorporated directly in the DNA-molecule and served as a source of ***low-level chronic radiation***. Tritium (^{3}H or H-3) is radioactive with a half-life of 12.3 years. It emits a β-particle with maximum energy of 18.6 keV.
The cells were then irradiated with x-rays to a dose of 1.5 Gy and the yield of chromosome aberrations were recorded.

It was found that the number of chromosome aberrations were ***fewer*** after exposure to ***both*** sources (tritium β-particles as well as x-rays) than after x-rays alone. These results indicated that low levels of radiation can start or induce increased repair of radiation induced chromosome breaks.

Throughout the 1990s a large number of experiments were published on different systems that demonstrate an adaptive response. A number of end points have been studied such as cell killing, micro-nucleus formation, induction of chromosome aberrations, induction of mutations and neoplastic transformations. The adaptive response has been detected when cells have been exposed to a small dose (10 -100 mGy) and then challenged with a much higher dose.

Cell research in Oslo during the last years

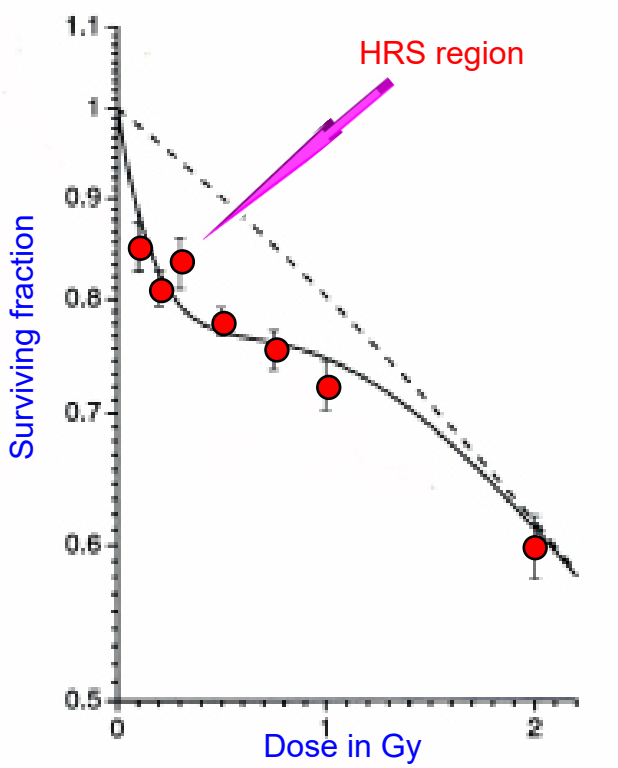
Erik Pettersen and Nina Jeppesen Edin

In the group for biophysics and medical physics at the University of Oslo, experiments are carried out which have a rather strong connection to the field discussed above. Let us therefore try to convey some of the ideas and results here. Those more interested should consult the original work.

Erik Pettersen and Nina Jeppesen Edin are the main scientists in this group.
The group is working with different types of mammalian (mostly human) cells cultivated in the laboratory. In the figure below T–47D cells (human breast cancer cells), have been irradiated with Co-60 γ -rays and the survival curves have been observed.
A surviving cell in this connection is a cancer cell that has maintained its ability to divide an unlimited number of times. Thus, since we talk about cancer, it means that the cell has maintained its potential ability to kill a patient. A cell that has been "killed" has lost this ability, it may be able to divide a few times, but will not be able to form a visible colony of descendants (or a tumor) and has therefore lost its potential to kill a patient.

The curve in the figure to the right is obtained when the irradiation takes place at the **high dose-rate** of 40 Gy per hour (or 0.67 Gy per minute). At such high dose rate cells are not given time to repair complicated molecular damages during irradiation.

The resulting survival curve showed a form that deviates from the linear–quadratic form (stippled curve) at the smallest doses. Here we observe a steep decay. This steep decay in survival at low doses is denoted "**low dose hypersensitivity**" (HRS). The HRS-region is followed by a region with increased radio-resistance. For doses above about 2 Gy the survival curve follows the usual linear-quadratic form.



In this figure is given the results of Co-60 γ -radiation on asynchronous T–47D cells. The doserate was 40 Gy/h (0.67 Gy per minute).

The form of the survival curve depends on the **dose-rate.** Thus, if the cells are irradiated with a dose-rate of 0.3 Gy/h the survival follows the linear-quadratic form even in the HRS-region.
When these phenomena were first discovered it was thought that the explanation had to do with the rate of repair compared to the rate of formation of damages. From these early speculations it turned out that the form of the curve is connected to the cell cycle and that this cycle is influenced by the radiation.

Checkpoints in the cell cycle

Early observations of patients with the heritable disease Ataxia Telangiectasia (AT) indicated that increased radio-sensitivity could be due to loss of repair capacity for DNA damage. These patients are extremely radio-sensitive and their cells have reduced repair after radiation. For decades it was believed that the molecular machinery for DNA repair was lacking or not complete in their cells. However, it turned out that the capacity for DNA repair was normal. The explanation was different and had nothing to do with the repair capacity itself, but rather with the length of time available for repair.

In fact, what we have learned over the last 30 years from molecular biology is the DNA is far less stable than it was thought to be. ***At 37 °C spontaneous errors in DNA arise at a frequency of several hundred per second in every cell in the body***. Without a DNA repair machinery that is largely intact and highly activated at any time, life itself cannot exist. Still, there was no doubt that cells from AT-patients did not complete DNA repair induced by ionizing radiation to a degree comparable to that of normal cells. ***The explanation had to do with the control of the cell cycle by cell-cycle checkpoint control.*** The AT-patients have a non-functional gene called ATM (ataxia telangiectasia mutated) which senses DNA double strand breaks and thereby activates cell-cycle arrest in a cell-cycle checkpoint.

In the last 20 years we have known that the cell cycle is controlled in a few places along the cell cycle. Both G_1–S and G_2–M phase transitions are under constant observations in order to protect the cells from different errors, and among these are lethal effects due to all types of DNA-damaging agents (not only radiation). The checkpoints are vital to proliferating cells since some damages in DNA are usually aggravated if they are not repaired before the cell starts DNA-synthesis or mitosis. The checkpoints are therefore controlled by enzymes which are activated by certain DNA damages to stop the cell cycle before either S-phase or mitosis in order to allow time for repair.

The importance of checkpoint control for cellular radio-sensitivity has turned out to be vital for the HRS-effect (see figure on page above) and induced radio-resistance at low doses. Long before the discovery of the ATM-gene and the isolation of the ATM-protein it was known that irradiation induces arrest in the G_2 phase of the cell cycle in the so-called "Sinclair checkpoint". It was also known that this cell cycle inhibition gave the cells time for repair before the start of mitosis. After the discovery of HRS in 1993 the researchers have had problems with explaining the induced resistance for doses above 0.3 Gy. In 2002, however Bo Xu and coworkers discovered a new checkpoint in the G_2-phase of the cell cycle which could explain even the mechanism for induced resistance.

Bo Xu

The Sinclair checkpoint is in reality a slow-responding mechanism. The arrest is not activated in cells that are in G_2 during irradiation. It is activated in cells that are in S-phase or in late G_1 during irradiation, and these cells progress through the cell cycle with their DNA-damages largely unrepaired and are arrested when they reach G_2 just before mitosis. While arrested in G_2 they can complete repair of double strand breaks in their DNA by so-called homologues recombination repair. This repair which results in perfect restoration of the DNA-sequence can only be performed in G_2, and not earlier in the cell cycle. The checkpoint discovered by Xu et al is, in contrast to the Sinclair checkpoint, **activated shortly after irradiation** i.e. it stops even cells that are in G_2 during acute irradiation.
The activation of the checkpoint is **dose-dependent**, meaning that a certain dose level is needed for the arrest to be activated. Thus, cells irradiated while in G_2 are not arrested unless the radiation dose is above a certain threshold of about 0.3 Gy. The mechanism for this threshold is well known today, and it has to do with the activation of the ATM-gene product.

The ATM-protein is large, consisting of about 3000 amino acids. It is held inactive in unirradiated cells as a dimer or higher-order multimer. Cellular irradiation causes dimer dissociation and initiates cellular ATM kinase activity which seems to be an initiating event in cellular responses.

The new G_2-checkpoint is only activated after a certain amount of ATM has been activated. The threshold dose for activating the G_2 checkpoint depends somewhat on the cell line, but the lower dose limit seems to be 0.2 Gy (200 mGy). Cells in G_2 receiving doses below this level will not be arrested in the early G_2 checkpoint, but enter mitosis with unrepaired damage resulting in mitotic death or apoptosis. Thus, the cells that are inactivated in the hyper-radiosensitive dose region are cells that are irradiated while in G_2.

Priming doses

The Oslo group has been particularly interested in studying a phenomenon related to radiation with doses in the HRS region which can best be denoted as a sort of radiation memory of cells: If cells have once been irradiated with a small dose of say 0.3 Gy and have survived, they are protected against lethal effects by later irradiation. The protective small dose is denoted a **priming dose**.

In line with the experiments showing adaptive effect (see above), experiments were carried out with priming doses; i.e. a small dose is given some time before the larger challenge dose.

The Oslo-group used a priming dose of 0.3 Gy. This dose is not very low, but it had a significant effect. Thus, if the "priming dose" **was given 6 hours ahead of the challenge dose the HRS could not be observed.**
The duration of this effect was found to depend on the **dose-rate used for priming**. Thus, for a dose-rate of 40 Gy/h the effect lasted for about 24 hours. However for a dose-rate of 0.3 Gy/h the abolition of the HRS seems to last forever (so far it has been observed for more than 5 years in cultured human T-47D-cells). The experiments strongly suggest that a small dose-rate has much larger and longer-lasting effect than higher dose-rates. **Thus, an increased background dose seems to be positive.**

Experiments with surprising results

Experiments were carried out with cells given priming doses – both at a **high** dose-rate (40 Gy/h) and at a **low** dose-rate (300 mGy/h). Then the **medium** from these cells was harvested and transferred to **un-irradiated** T–47D cells. **Then** the challenge dose was given.

It appeared that the medium from high dose-rate primed cells had **no** effect on HRS (the low dose hypersensitivity) of the recipient cells – but the medium from the low dose-rate primed cells not only removed the HRS of the recipient cells, but those recipient cells that received small doses of challenge irradiation below 0.3 Gy had a **higher** survival than the control recipient cells.

These results indicate that low dose-rate irradiation induced a factor (a protein) to the medium that made the cells more resistant against later irradiation.

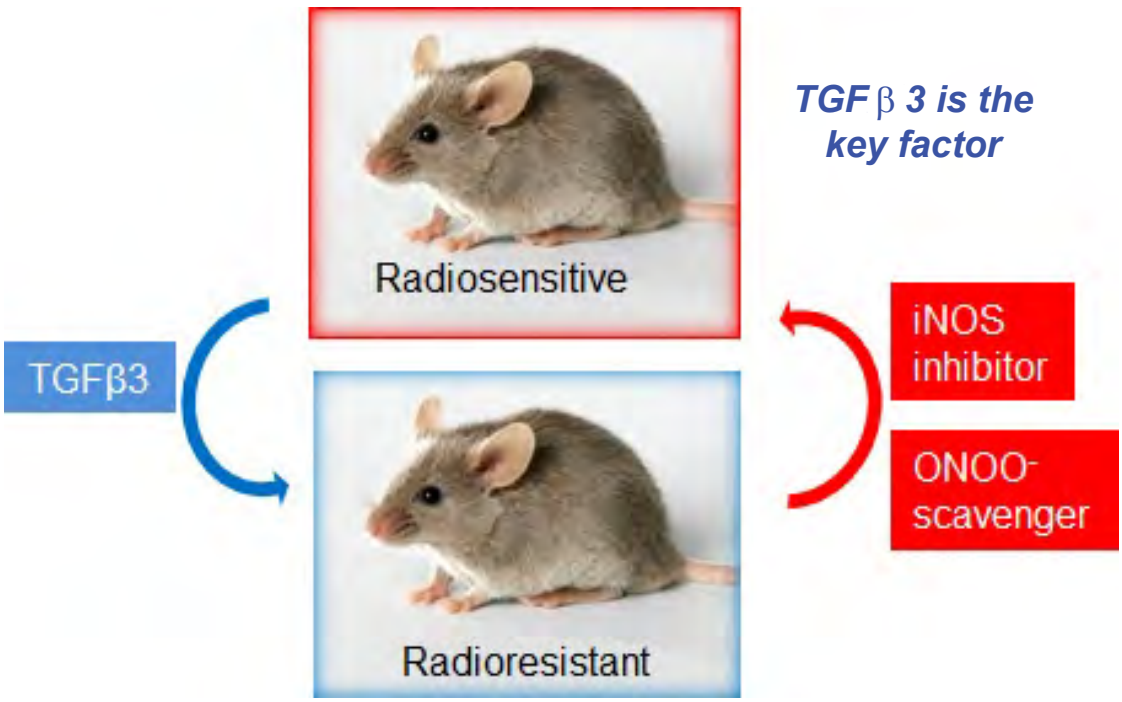
The Oslo-group have also found that this factor is formed by whole-body irradiation of **living mice for 1 hour** with either 300 or 30 mGy. When serum from these mice are added to recipient human T-47D-cells and these are irradiated with doses up to 0.3Gy, the cells show no HRS, and interestingly: **They also show increased resistance to high doses of radiation.**

The mechanism

The Oslo group have identified some of the factors involved in transforming cells from the sensitive HRS response to a more radio-resistant form and vice versa (see the figure below). A key protein is TGF β 3 (Transforming growth factor β -3) which has been shown to abolish HRS when added in an active form. Inhibition of this protein after priming stops the inhibition of HRS.

Explanations to the mechanism

TGF β 3 is a type of a protein, known as a cytokine, which is involved in cell differentiation, embryogenesis and development. The factor is activated by radiation via ROS (reactive oxygen species – radicals such as hydroxyl OH, superoxide anion O_2^- and others). TGF β 3 is only stabilized in an active form via peroxynitrite formed by the NO-radical and superoxide. The NO radical can be synthesized on demand for short periods of time (seconds to minutes) following enzyme activation induced by low dose-rate irradiation. iNOS (inducible nitric oxide synthease) is one of a family of enzymes that catalyse the production of nitric oxide (NO) from L-arginine.
An important question within cancer treatment with radiation is whether radioresistant cells can be transferred to a more sensitive stage? The figure below indicates that this may be achieved by using compounds that inhibit NO-production by iNOS or remove its final product peroxynitrite. The possibility to sensitize resistant cells are of course important in cancer radiation therapy, because in the central parts of all solid tumors we find hypoxic cells which are radioresistant. It would be very important if we could transform these cells into a radiosensitive stage.



The figure indicate how you can switch between the radiosensitive and the more radioresistant response. ***The more resistant response is turned on by the factor TGF*** **β *3.*** *The resistance can be turned off again by an inhibitor of iNOS or a scavenger of peroxynitrite ($ONOO^-$).*
The TGF β 3 factor is activated by low dose-rate irradiation or can be added to the cells from previously irradiated medium or by serum for irradiated mice. Hypoxic cells also activate TGF β 3.

The mechanism outlined above may have significant importance in cancer research as well as in radiation protection. **The data suggest that a small radiation dose given with a small dose-rate enhances the defense mechanisms.**

The model also indicate that it is possible to go the other way and force hypoxic cells or cells with previous history of radiation into a more radiosensitive stage which is important in radiotherapy of cancer.

Conclusions

All the last mentioned works; Paramecium-studies, adaptive response studies, cell-research studies clearly show that a small dose given at a low dose-rate (even a constant high level of background radiation) will reduce the deleterious effect of radiation.

This finding can explane the surprising results found by W.L. Chen and coworkers for the Taiwan group.

The cell research work has given a lot of information about the cellular mechanisms and how the cells can cope with errors and damage. We have learned a lot about the mechanisms going on in the cell cycle and that several checkpoints must be passed. The checkpoints are guarded by enzymes and the genes for these enzymes should be free from errors. This is very important in cancer biology.

We can sum up some of the important findings in the following way:

1. The cells have repair systems which are bound to function in all living cells. Important to the repair system are the enzymes that guard the cellular checkpoints to give cells enough time for repair.

2. The cells have a programmed death system (apoptosis), that can take out and kill cells which may pose a danger for later malignant development.

Radon in homes and lung cancer

We have so far discussed LNT and have concluded that it is not useful for small radiation doses given at a low dose-rate. We therefore think that it is wrong to base regulations on the background radiation on this theory. However, this is presently done by ICRP and WHO in the case of radon in homes.

In the rest of this paper we shall try to discuss lung cancer from radon and radon daughters in the homes. Presently the regulations introduced in Norway as well as in USA are based on LNT.

It is a historical fact that a number of old miners in middle Europe got lung cancer. Today we know that they worked in mines with a very large radon content. The conclusion is that radon and radon daughters can induce lung cancer. ICRP and WHO use this in combination with LNT with the conclusion that even the normal radon content in the homes would give lung cancer. Their conclusion is that radon in homes represents the next largest cause (after smoking) for the lung cancer in the world, and is responsible for up to 10 percent of all the lung cancer incidents.

The radiation from radon and daughters is special since it consists mainly of α -particles, which have a very short range in tissue (less than 100 μ m). Consequently, the daughters must disintegrate when they still are within the lungs and airways in order to give a radiation dose to the lungs. This is not always the case since the lungs have a defense system; i.e. a cleaning system that can wipe out foreign particles. So far, **no** epidemiological studies have included the effect of this cleaning system on the radiation dose to the lungs, mainly because we lack information on the system. Recently (2012) a model of the cleaning system was published, and we make use of this in the following dose considerations.

In the present work we discuss the cleaning system and a number of epidemiological studies. We end up with the conclusion that the strong regulations introduced in some countries like Norway, based on WHOs recommendations, are in conflict with the radiobiology and should be changed.

Problems with radon doses and lung cancer

1. The radiation takes place when the radon daughters in the lungs and airways disintegrate. The main part of the radiation dose (about 82 %) is due to α -particles. These particles have an extremely short range in tissue (less than 100 μ m). Consequently, the radon daughters must be in the lungs when they disintegrate.

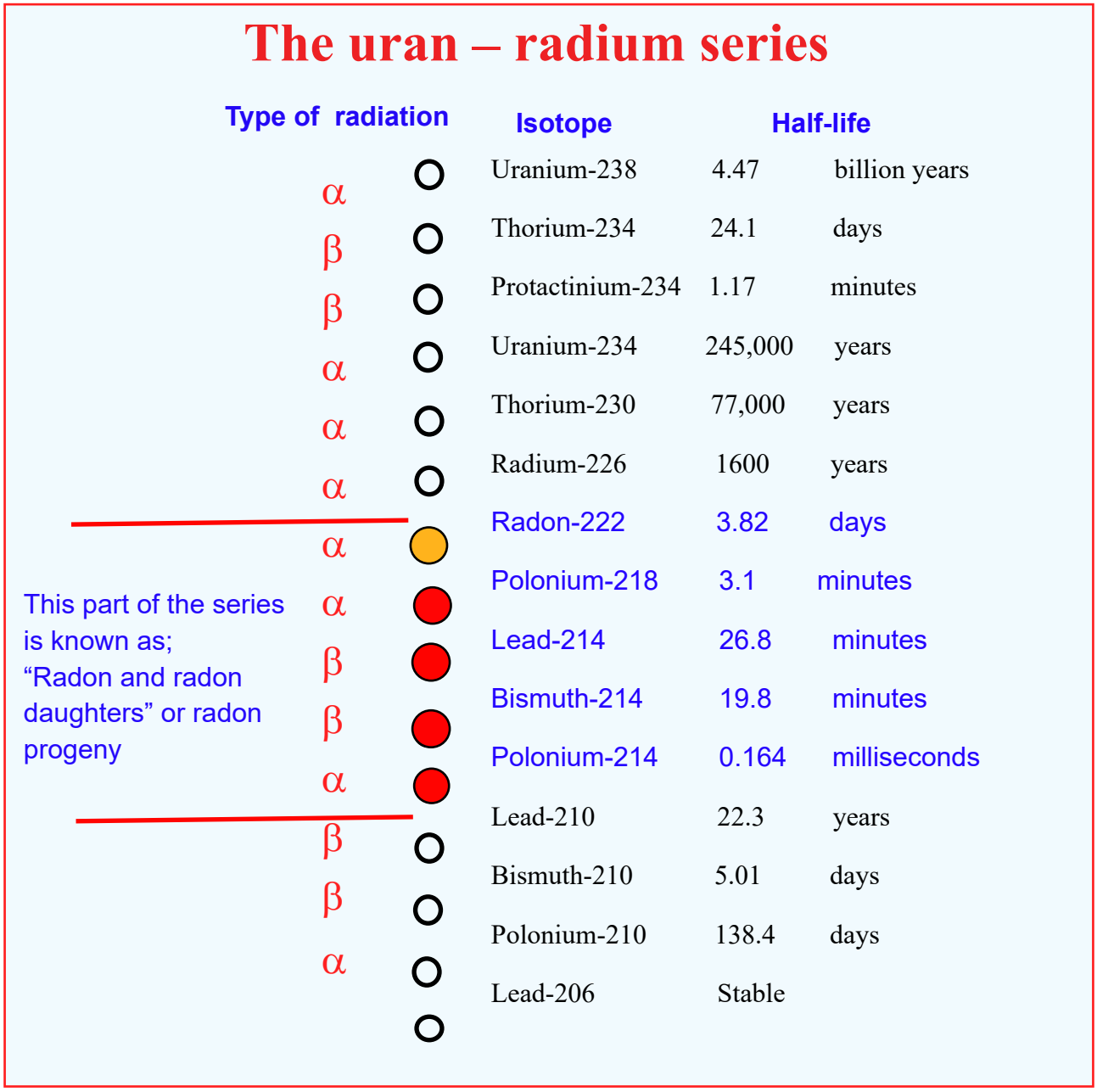
2. The lungs have a "**cleaning system"**. This system can wipe out virus, bacteria and carcinogens, including dust with radon daughters, from the lungs and airways. Up to now it has been ignored by all epidemiologists when they discuss radon and lung cancer. We show here that if the system is working normally, the dose can be reduced by up to 50 %.

3. We are exposed to radon all the time from we are born. In spite of this, lung cancer is not found among children or young people that have been irradiated for 20 – 30 and even 40 years. Lung cancer is found among people above 50 years of age.

4. A description of the connection between radon and lung cancer should include: a) Dosimetry used for radon in old mines and for radon in homes. b) The lungs cleaning system, c) Epidemiological studies, d) Rules and regulations.

Radon and the radon family in the environment

We start this discussion by presenting the uran–radium family which starts with uranium-238 and ends with the stable lead-206 isotope. In the middle of this series we find 5 isotopes with short half-lives. It is radon-222 and the following isotopes Po-218, Pb-214, Bi-214 and Po-214. This is the radon family. ***What is special about the family is that Rn-222 is a nobel gas***. This implies that it can break off from where it is formed and come into the air – both inside and outside houses. The radon daughters will be formed while Rn-222 is still in the air.

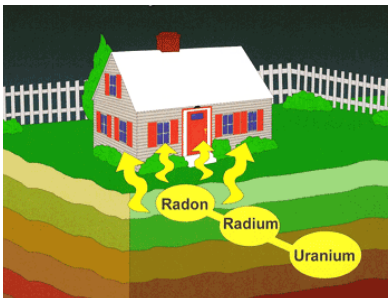


Uranium-radium-series. The start of the series is U-238 and the end point is Pb-206. Radon and the radon decay products (the 5 isotopes marked and placed between the two red horizontal lines), have rather short half-lives. Radon is a noble gas that can break out from the series and come into the atmosphere and also leak into houses. The decay products are metal ions that become attached to water and dust in the air. It can be mentioned that γ -radiation from Bi-214 is used to detect Uranium.

Radon (the isotope Rn-222) and its first 4 decay products, with rather short half-lives, are called the "*radon family*". We find one radon family in the uranium-radium series, and another family in the thorium-series (also called the "*thoron family*").

In a radioactive series there is radioactive equilibrium, which implies:

$$N_1\lambda_1 = N_2\lambda_2 = N_i\lambda_i \quad \text{where} \quad \lambda = \frac{\ln 2}{t_{1/2}}$$



N_i is the number of atoms for (isotope i), λ is the disintegration constant, and $t_{1/2}$ is the half-life. Consequently, it follows that ***the amount of each species follows the half-life.***

Radon is a ***noble gas and does not combine chemically with other atoms or molecules.*** Consequently, radon can break out from both series (i.e. released from the place where it is formed) and come into the atmosphere, both in the outside air as well as into houses. Quite rapidly a new equilibrium will build up within the radon family and we will have radioactive equilibrium inside the house.

The half-life for Rn-222 is 3.82 days, whereas Rn-220 (in the thorium series) has a half-life of only 55.6 seconds. This implies that Rn-220 has a much smaller time to break away and enter the houses.

Some of the daughter ions may become attached to water molecules in the air and get a diameter of about 5 nm. In this form the radon daughters are considered to be ***free***. The majority of the radon daughters however, become attached to larger aerosol particles in the air (from 50 – 500 nm in diameter). Both the free and the bound daughters will deposit on the walls, roof and floor inside and to the ground, trees, plants, houses, etc. outside. Thus the equilibrium between radon daughters and radon in the air is about a factor 0.4 – 0.5 inside of the houses and a factor of about 0.8 outside.

Range of the radiation in air and tissue

The radiation from radon and its daughters (often called progeny) is a mixture of α-particles, β-particles and γ-radiation. As long as radon and the radon family is ***outside the body***, only the γ-radiation will contribute to the body dose. It is a part of the external γ -radiation.

However, when the isotopes come ***inside*** the body, all types of radiation contribute. Because of the very short range of α and β -particles in tissue, it is extremely important where in the body the radioactive disintegration takes place. The α -particles, with a range of less than 100 μ m, only reach the cells lining the airways and lungs. In a recent study on the lungs cleaning system (see below), it appears that a considerable part of the dust with radioactive radon daughters may be swept out of the lung system **before** they disintegrate. The dust cleaned out, will either become spit out or deposited in the stomach. For disintegration in the stomach the α -particles will hardly reach any important cells and have thus minor biological importance.

For a long time we have been aware of the health risks associated with working in underground mines with high radon values. For a long time the radon level inside houses was of little interest. In the late 1970-ties some scientists began to realize that indoor radon exposures could be quite high, because the local concentration of uranium and/or thorium might be high. At the same time ICRP introduced ***the radiation weight factor of 20*** for the α-particles in the radon family, and consequently the assumed doses to the lungs increased by a factor 20.

In the following we shall try to present some information about the radon families – the physical aspects, measurements both outdoors and in dwellings, and finally discuss the relation between radon in houses and lung cancer.

The physical aspects of the radon families

Most of the physical aspects are given in the two tables below. In the second column the decay type is given. Furthermore, γ-radiation is very often emitted together with the β -particle.
The energy of the different particles and γ-radiation is given in the last column. In the case of the β-particles the maximum energy is given. We remind you that the average β-energy is approximately 1/3 of the maximum energy. The α-particles have the largest energies (in the range from 5.49 to 8.78 MeV). The range in soft tissue is about 50 to 80 µm.

The Uranium – radium series

Isotope	Decay type	Half-life	Energi released (in MeV)
Rn-222	α	3.82 days	α with energy 5.49
Po-218	α	3.1 minutes	α with energy 6.0
Pb-214	β	26.8 minutes	β with maximum 0.59 and 0.65 γ with energy 0.053 and 0.35
Bi-214	β	19.6 minutes	β with maximum 1.51, 1.0 and 3.18 γ with energy 0.61 and 2.42
Po-214	α	0.164 msec	α with energy 7,69
Pb-210	β	22.3 years	β with maximum 0.015 and 0.061
Bi-210	β	5.01 days	β with maximum 1.16
Po-210	α	138.4 days	α with energy 5.3
Pb-206	Stable	Stable	

*Because Pb-210 has a half-life of 22,3 years the last 3 members of the uranium series are not considered to be members of the radon family. Pb-214 and Bi-214 have several disintegration possibilities which are important when the average energy released upon disintegrations are calculated. For Pb-214 the **average** energy is approximately 0.5 MeV and for Bi-214 it is about 1.5 MeV.*

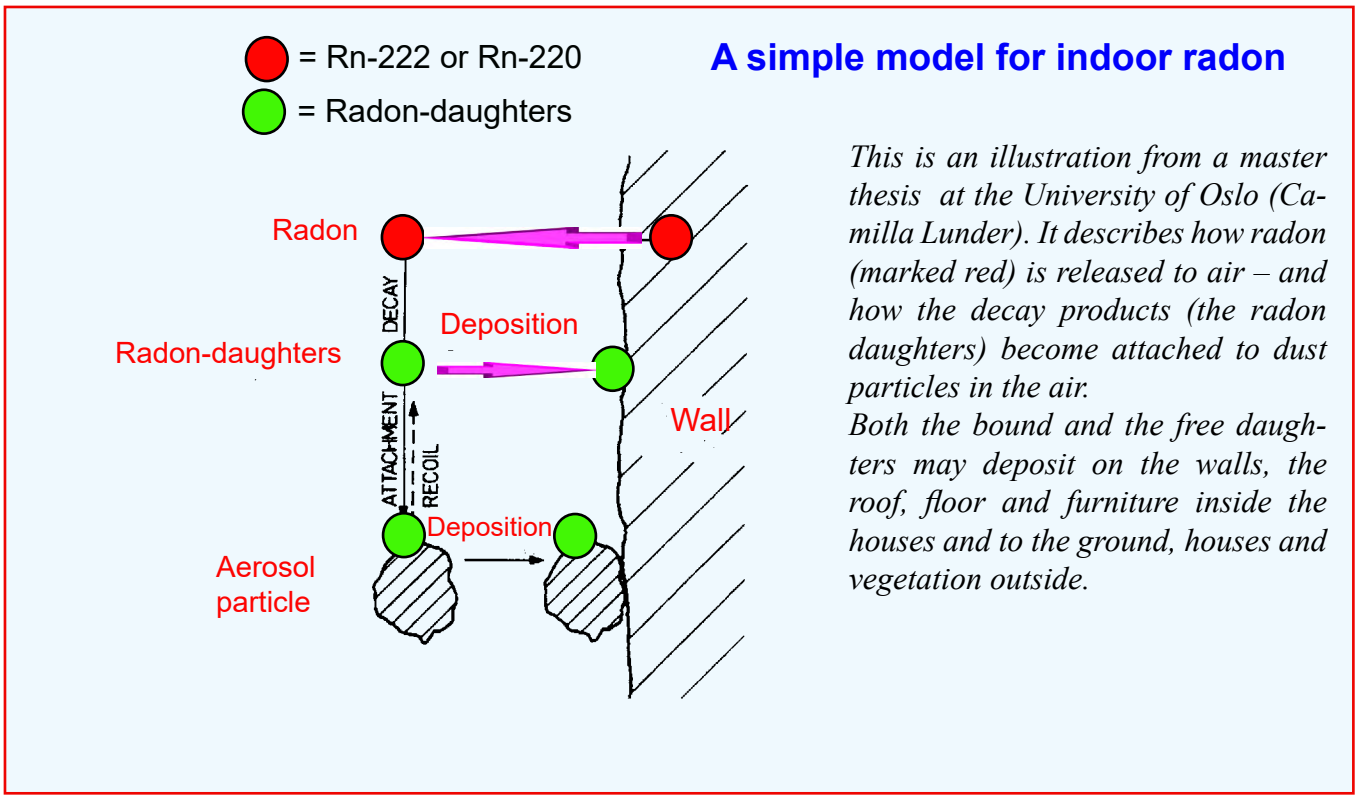
The Thorium series

Isotope	Decay-type	Half-life	Energy released (in MeV)
Rn-220	α	55.6 sec	α with energy 6.28
Po-216	α	0.156 sec	α with energy 6.78
Pb-212	β	10.6 hrs	β with maksimum 0.34 and 0.58 γ with energy 0.239
Bi-212	α (34 %) β (66 %)	60.6 min	α with energy 6.05 β with maksimum 2.25 γ with energy 0.04
Po-212	α	$3 \cdot 10^{-7}$ sec	α with energy 8.78
Pb-208	Stable	Stable	

Comments on thorium series

You see from the table that Bi-212 has two possibilities for decay; either α -decay (34 %) or β -decay (66 %). The α -decay yields Tl-208 which then by β -decay reaches Pb-208. The other possibility goes via Po-212, followed by α -decay and again the stable Pb-208 isotope is reached.

The Tl-208 isotope decays via β -particles (with max energies of 1,79, 1,28 and 1,52 MeV for the three most important) and accompanying γ -radiation. One of these γ -lines have an energy of 2.61 MeV. ***This line is used to identify the thorium series in a mixture of γ -radiation***.



The radon sources and measurements

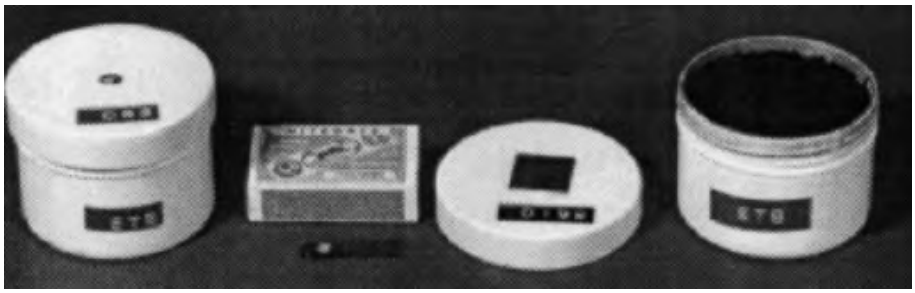
The radon concentration in the soil within a few meters of the surface, is important for the entry into the atmosphere. The main mechanism for this is molecular diffusion.

The concentrations of Rn-222 in soil vary over many orders of magnitude from place to place and show significant time variations at any given site. Because of the short half-life of thoron (Rn-220), a large fraction of these atoms will disintegrate before they reach the surface, and consequently the daughters will be trapped in the ground.

History. In 1900, Frederick Dorn, a German scientist, found that radium-226 was giving off a gas which he called “radium emanation” known today as Rn-222. In 1908, Ramsey and Whytlow-Gray isolated enough of the gas to study its physical properties and named it Niton (the shining one). In 1904, Heinrich Mache introduced the unit "mache" for the amount of radon in water. One mache corresponds to 13.45 Bq per liter.
The first measurements of radium emanation in Norway was carried out by K. Hansen in 1916. He observed that the concentration varied with air pressure and wind. The concentration varied between 1.1 to 13.7 Bq per m^3. These results are surprisingly good.

The methods used for radon measurements

The methods for measuring radon have developed considerable during the latter years. Today we have instruments that make it possible to follow the radon concentration as a function of time, the concentration of the different radon daughters, as well as the fraction not bound to particles.
For indoor radon measurements we can use charcoal canister sampling and thermoluminescence dosimeters (TLD). This method consists of a small box with carbon powder and two TLD crystals. One crystal is placed in the middle of the box whereas the other is outside the box. Radon daughters from the air will become trapped in the carbon powder and subsequently expose the crystal in the box. The crystal outside the box serves as a control for the cosmic radiation and gamma radiation from the walls of the room.
The difference between the two TLD-crystals yields information on the average radon concentration during the exposure period. The first mapping of radon in Norwegian dwellings was performed using the coal box method by A. Storruste and his students at the University of Oslo around 1960.



A picture of the coal box method used by Storruste in the first Norwegian indoor radon measurements. The matchbox gives the dimensions.

Another new and popular method is the solid-state nuclear track detectors. The method is based on the fact that α-particles create tracks in certain materials such as polymers, minerals or glass. The tracks are made visible upon etching and then examined microscopically. The size and shape of these tracks yield information about the mass, charge, energy and direction of motion of the particles.

The track detector has become the state-of-the-art for environmental radon monitoring.

To the left is a modern nuclear track detector.

The pictures of these detectors give rather little information about the measurements. However, they give an impression of the size of the detectors.

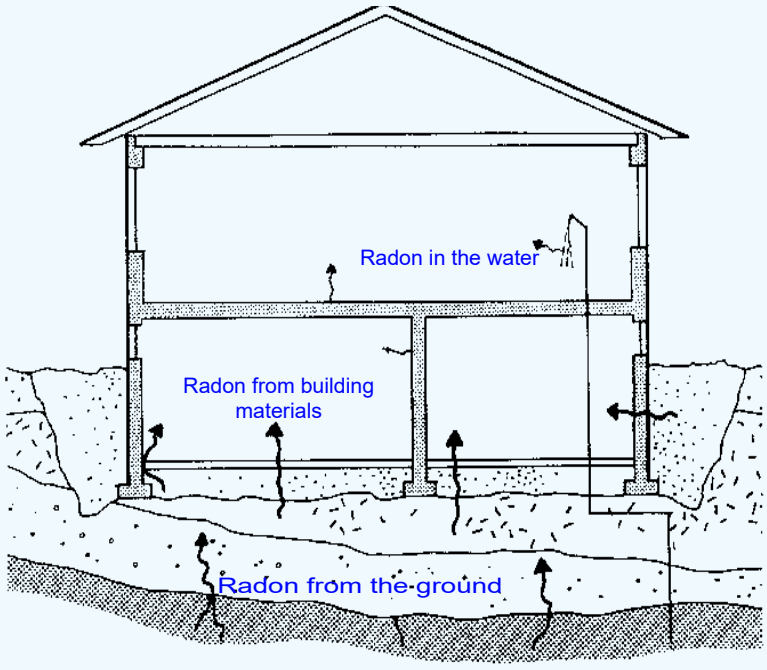
Radon values

The radon values cover a range from 1 Bq/m^3 to above a million Bq/m^3. Thus, at the shores of large oceans the value is typically 1 Bq/m^3. Radon trace concentration above oceans or in Antarctica can be lower than 0.1 Bq/m^3. The mean continental concentration in the open air is about 10 to 30 Bq/m^3. Based on a series of surveys, the global mean indoor radon concentration was some years ago estimated to be 46 Bq/m^3. It is likely that an average value will be reduced in the future when a larger fraction of the population is moving into apartments in tall buildings with a large number of floors. Very high radon concentrations (>1000 Bq/m^3) have been found in houses built on soils with a high uranium content and/or high permeability of the ground.
In Bad Gastein in Austria we find some old mines with an average radon content of 44 kBq/m^3 with maximum value of 160 kBq/m^3. These mines are used for healing purposes. In some unventilated uranium mines the radon concentration can reach 1,000,000 Bq/m^3.

Radon into the houses

Several possibilities exist for the release of radon into houses (see illustration below). The main sources are the rock or soil on which the house is built, as well as the water supply. The rock formations under a house always contain some radium and the radon gas can penetrate into the house through cracks in the floor and walls of the basement. Furthermore, the building materials are also a source for radon.

Another source for radon is the water supply. Water from wells, in particular in regions with radium-rich granite, may contain high radon concentrations. When water is the carrier, the radon gas is readily released.



This drawing illustrates how radon may enter a house. The radon gas comes into the house from the ground, from the building materials and sometimes from the water. Well water contains in some areas (for example in Finland) quite large amounts of radon which is released when used in showers or in the kitchen.

(Courtesy of Terje Strand, Norwegian Protection Agency)

The indoor radon concentrations usually show an annual variation with the largest values during the winter. This is quite usual in places with frost and snow on the ground. The frost makes it difficult for the gas to diffuse out of the surrounding ground and to be released directly into the air. Consequently, the radon gas is more likely to seep into the house. The radon concentration in a house can vary from room to room and with time.

Some people will meet a higher radon level on the workplace compared to that at home. Furthermore, free-time activities in indoor fitness centers may give a larger radon doserate compared to that at home. It is therefore difficult to determine the radon level you are exposed to. The annual radon dose to the lungs may be very much different from that calculated based on the radon level in your home.

Unless the radon level at home is much larger than that met otherwise we must include all places and activities when calculating the annual radon dose to the lungs.

Radon measurements around the world

UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation) has collected measurements carried out around the world and presented data in several reports. For example in the 2006 report with the address:
http://www.unscear.org/docs/reports/2006/09-81160_Report_Annex_E_2006_Web.pdf

This is a large manuscript (more than 300 pages). The main mechanism for the entry of radon into the atmosphere is diffusion. In the outdoor atmosphere, there is also some advection caused by wind and changes in barometric pressure. Furthermore the concentrations of Rn-222 in the soil gas vary over many orders of magnitude from place to place and show significant time variation at any given site.

According to UNSCEAR, the flux of Rn-222 to the atmosphere is of the order 0.02 – 0.03 Bq $m^{-2}s^{-1}$. From the **outdoor** radon measurements it appears that the concentrations of Rn-222 and Rn-220 are approximately 10 Bq/m^3 for each.

The **indoor** concentration vary considerably from place to place. UNSCEAR assume that the world average in the 2006 was 46 Bq/m^3. It varied from one country to another in some places the average indoor concentrations are far above 100 Bq/m^3 and values of more than 1000 Bq/m^3 can be found (for example in Ramsar in Iran).

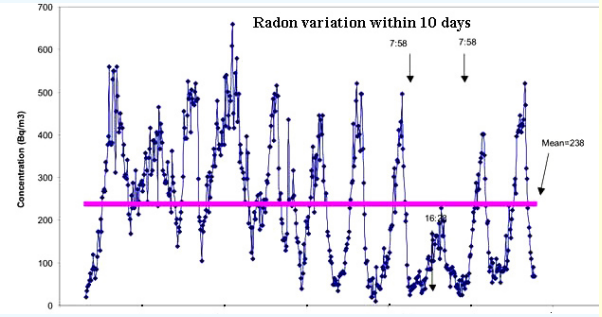
The Norwegian Radiation Authority found very high radon values in Kinsarvik in the western part of the country. Values above 50 000 Bq/m^3 inside and up to 287 Bq/m^3 outside (1 meter above the ground) have been measured!

On the next page are given a number of examples how the indoor radon content vary within the day, season and year. It can be mentioned that sleeping with an open window can reduce the radon level significantly.

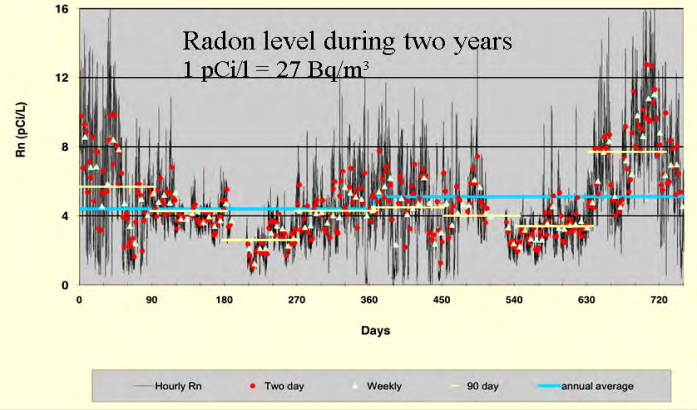
We can conclude that the inside radon level vary with the weather, time of the year and even time of the day – and of course with the airing system. We can measure the radon level quite well, but it is difficult to find an average level that can be used to calculate the exposure for people living in the house.

Examples of radon variation inside houses

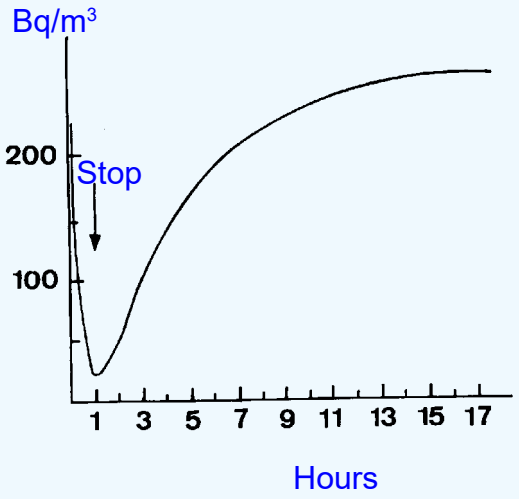
10 days



2 years



Result of an open window for 1 hour

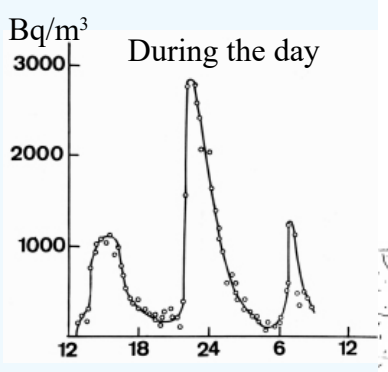


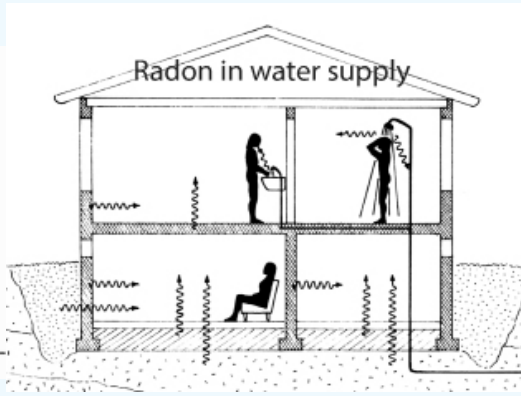
The indoor radon concentration varies widely during the day, week, month and year as the examples above demonstrate. Consequently, it is very difficult to give a value that is representative for the people living in the house.

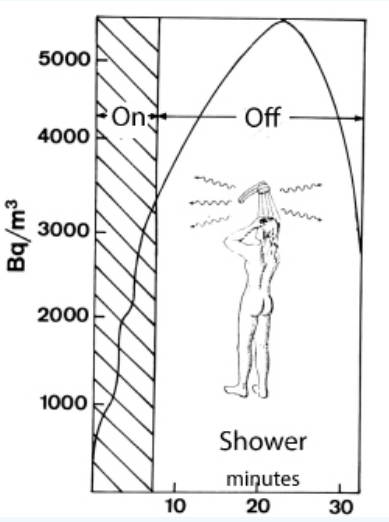
Sleeping with an open window reduces the radon level as seen to the left.

The bottom row of figures are from houses with radon in the water supply.

If the radon source is the water supply, the radon in the inside air will increase each time you open the water faucet.







The lung doses from radon

We intend to discuss the correlation between radon and lung cancer. Consequently, we need a system for determining the lung dose from radon and radon daughters.
For every inhalation of air we do, some radon and radon daughters enter the lungs and airways system. If these isotopes remain in the lung system until the radioactive daughters disintegrate we get a radiation dose from α - and β -particles as well as from the γ -radiation. However, there is a long way from radon measurements in the air, which can be very good, to the **radiation dose to the lungs**. We get a tiny dose for each inhalation we do indoors as well as outdoors. This goes on from cradle to grave.

The amount of radioactivity is proportional with the air volume inhaled and the radon content in the air (measured as Bq/m^3). The accumulated dose is the sum of all the tiny doses we get all the time and every day in life.

Radon in the old mines

For the old miners working in mines with radon levels far above that found in the homes (a factor 100 – 1000), it seems fair and reasonable to base the dose calculations only on the time spent on work. The radon dose during work is much larger than that attained elsewhere. This does not hold true for the radon in homes. Some people have working places with far more radon than that at home.

Radon in houses

It is the accumulated dose from radon in the air you breathe – at home, on the workplace and in your free time that is important. It is an impossible job to find that dose and in most epidemiological studies the dose determination has been reduced to that attained when you are at home. The only type of study where the total level of radon is included is the ecological studies by Bernhard Cohen (see later).

The lungs cleaning system

The radioactive radon daughters are attached to small dust particles. The particles are trapped in the airways and the lungs. If the isotopes disintegrate when the dust is trapped in the lungs, the airways and lungs get most of the radiation dose. However, if some of the particles have been wiped out by the lungs cleaning system before the radon daughters have disintegrated, the radiation will not reach the lungs since the α -particles have a very short range in tissue.

So far the **lungs cleaning system** have not been discussed in any epidemiological study, mainly because we have not had enough information to include it. A new model of the lungs cleaning system was presented in 2012 which makes it possible to discuss this subject. In the following we shall present the system and discuss the effect on the lung doses from the radon daughters.

Radon and lung cancer – dosimetry

The fundamental factor for radiation induced cancer is the radiation dose. The ionizations and excitations formed when radiation is absorbed, initiate the chain of reactions that finally give an observable tumor.

In the case of radon, the radiation dose to the lungs can not be measured with instruments like those used for radiation therapy and/or in radiobiological experiments. In all epidemiological studies, the dose has been replaced by another parameter which is used to hopefully obtain the radiation dose to the lungs. The parameters used are very alike, namely WLM and Bq/m^3 during life. In some studies (S. Darby) the period considered was 30 years.

1. In the studies on radon and lung cancer for miners the dose parameter (WLM) was the product of the level of α-particle energy, expressed as WL and the time on work (1 WLM corresponded to about 7400 Bq/m^3 in 170 hours). For most of the miners the radon dose attained at home and in the free time was very much smaller than that on the workplace and can therefore be ignored.

2. For radon in houses the epidemiological studies use the radon level in the house, expressed as Bq/ m^3. In most studies the dose attained at work and in the free time has been neglected. This may introduce a large error. Furthermore, attempts have been made to find the accumulated exposure for about 30 years.

In studies on radon in homes the individual dose is important. However, it is not possible to arrive at individual doses to the lungs from radon daughters, because we lack information on the lungs ***cleaning system***.

In ecological studies no individual doses are considered which seems to be an advantage.

We shall now make attempts to implement the lungs cleaning system, based on the model presented by Brian Button and coworkers.

We shall also present the radiobiological model for radiation induced cancer which is important for all interpretations of the dose-effect curves.

The lungs cleaning system

The lungs and airways have a cleaning system that prevent virus, bacteria, dust and other toxic compounds from invading the lungs. A new and extended model of the cleaning system was presented in Science in 2012. In the following we shall see that the cleaning system has great implications for the radiation doses to the lungs by the radon daughters. So far this has not been discussed.

The cover of Science, August 2012.

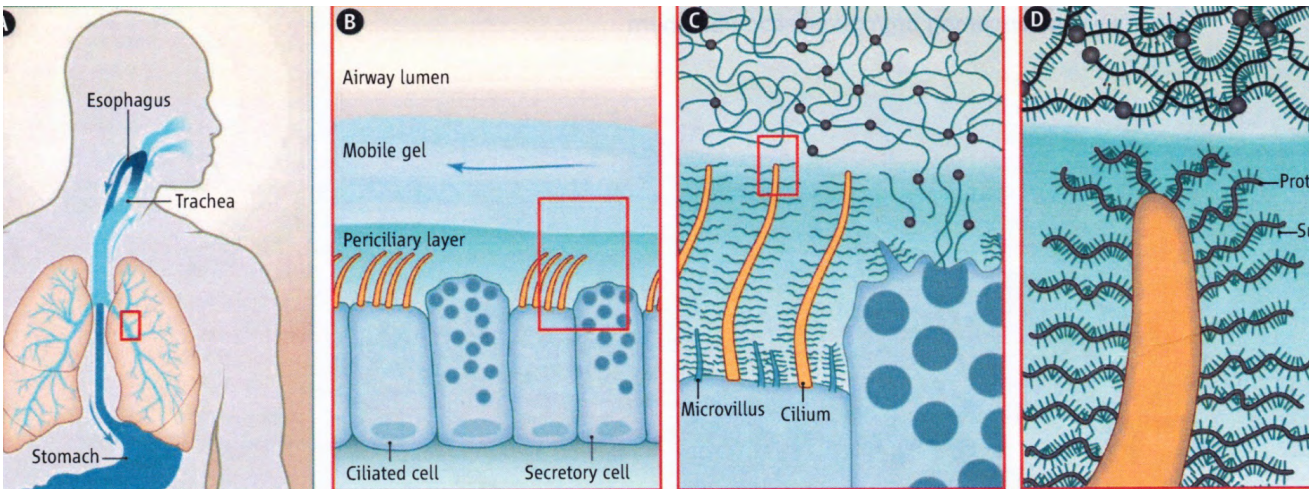
Yan Liang's (COVER Artist) rendering of the airway epithelial cell surface in human lungs.
The airway surface is lined by arrays of cylindrical cilia (shown as yellow projections) that are 7 micrometers long and 200 nanometers in diameter. The cilia and airway surface are covered by tethered biomacromolecules (shown as green hairs) that form dense, brushlike structures. These epithelial brushes protect the airways from infectious agents and ensure efficient flow of mucus from healthy lungs

If the cleaning system is effective the possibility exists that the radon daughters connected to dust particles (aerosols) in the air may be wiped out of the lungs and airways **before** they disintegrate. In order to test this possibility we have to compare the time for radioactive disintegration; i.e. how fast the radiation dose is given with the time for cleaning of the lungs and airways.

Time for cleaning versus time for disintegration of the radon daughters.

The cleaning system

The cleaning system consists of two components; a mucus layer that traps the inhaled radon daughters and a pericillary layer with embedded cilia that can transport the daughters out of the lungs. The gel-like mucus layer is propelled by the beating cilia (see part B on the figure next page). Brian Button and coworkers show that the pericillary layer has a macromolecular glyoconjugate structure with a higher density than the mobile gel layer and is grafted to the epithelial surface. The dense network in the pericillary layer consists of mucin, large glycosylated proteins. The dense packing of mucin in the pericillary layer tend to exclude unattached polymeric mucin in the mobile layer.
The model also helps to explain the coordination of the rhythmic beating of the cilia, which are coupled to the mucin. There is low friction between the pericillary layer and the mobile layer and dust and other particles are propelled out of the airways. In the illustration on the next page this cleaning system is shown.



Brian Button and coworkers at the University of North Carolina, published in Science 2012 a model for the lungs cleaning system (A periciliary brush promotes the lung health by separating the mucus layer from the airway epithelial). A mobile gel layer is propelled out by a pericilary brush of cilia. The gel layer is continuously renewed by secretion of mucin. In this illustration the red square in A is enlarged in B, and the square in B is enlarged in C, and again in D. The model shows that the two layers are separated. The mobile gel layer traps the dust and the tethered cilia propel the dust out. It can be compared with an escalator or a conveyor belt that brings the dust out. The length and frequency of the cilia determine the speed of the conveyor belt.

The length of the cilia is about 7 μ m and the frequency is about 15 – 20 Hz (about 1000 movements per minute). The frequency seems to depend on the air temperature. As a curiosity it can be wise to breath through the nose in cold weather because the nose works as a heat exchanger.
It is evident that smoke and air-pollution will influence the efficiency of the cleaning system. Both the frequency and perhaps the length of the cilia may be influenced. Heavy smoking seem to invalidate the cleaning system and the lungs and airways are open to all types of carcinogenic compounds.
We have no information on individual variation in the cleaning system, and we have no information about efficiency and age. It is reasonable to assume that the efficiency is reduced with age.
Furthermore, it is quite reasonable to assume that air pollution (smog in the cities) will have a negative effect, as well as infections (colds, bronchitis, asthma).

How fast is the cleaning system ?

The distance to be cleaned is trachea and the bronchus – about 20 cm.
With a cilia length of 7 μ m and a frequency of 22 Hz the maximum speed for the mobile layer would be about 200 μ m per second or about 12 mm per minute. The real speed is probably much smaller and is probably not the same in all parts of the airways. It appears that the cilia length decreases in the small bronchies.
A reasonable assumption is that an intact healthy cleaning system bring out dust particles with a speed of from 50 to 200 μ m per second. This would imply a transportation of the radioactive dust as follows:

Time	Length of cleaning
10 minutes	3 – 12 cm
30 minutes	**9 – 36 cm**
60 minutes	18 – 72 cm

Consequently; in 30 minutes a large fraction of dust with radon daughters are transported out of the airways and lungs.

How to calculate dose and doserate from radon daughters

When you breathe in an atmosphere with radon and radon daughters you get radioactive particles in the body. When the radioactive isotopes disintegrate you get a radiation dose from the α-particles, β-particles and the γ-radiation. The doserate is very much determined by the ***half-lives*** of the isotopes (see page 24). The place for the dose deposition is determined by the ***ranges*** of the α- and β-particles (which are very short).

We consider one inhalation

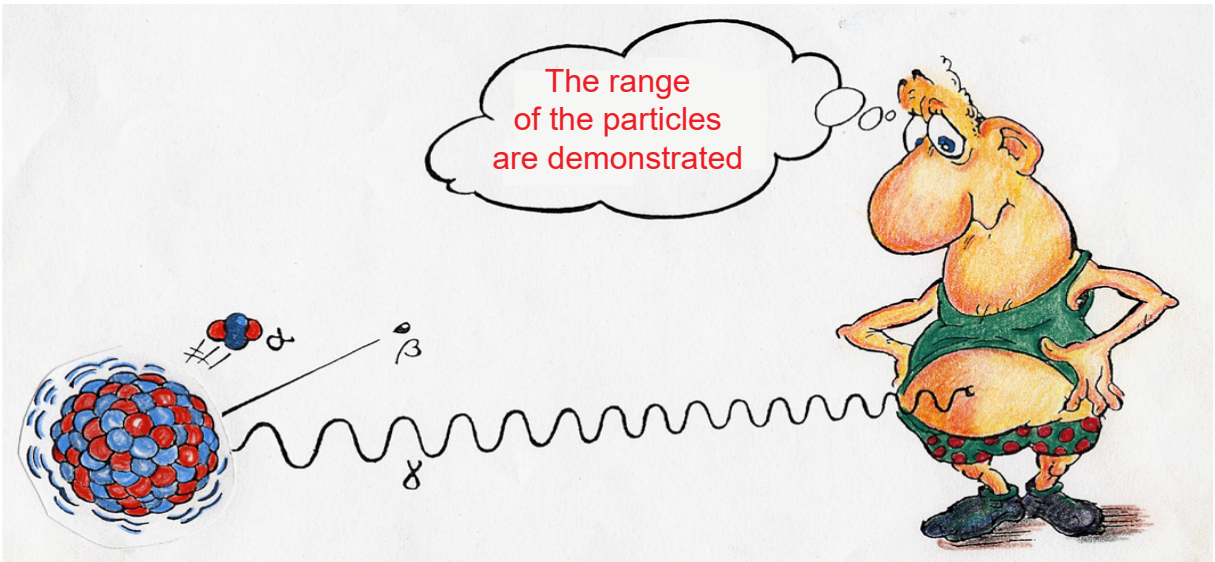
We can get information about the ***dose as a function of time*** by considering only one inhalation; i.e. one intake of radon (Rn-222) with its 4 daughters; Po-218, Pb-214, Bi-214 and Po-214. We are interested in the decay of the daughters; i.e. how fast the "dose" is given. We are breathing all the time, but now we shall study the fate of the radon daughters after one inhalation at time 0 (time is given in minutes). We ask the simple question how large fractions of the disintegration have occurred after 10, 30 and 60 minutes. As seen above, this is the timescale for a healthy cleaning system to wipe out a significant part of the dust (which in this case contain the radon daughters).

For the intake of Rn-222 and the 4 daughters we ***assume radioactive equilibrium for the daughters***. Rn-222 (the noble gas) will not adhere to the airways, but follow the air in the exhalation. A very few Rn-222 atoms will disintegrate when they are in the airway system, but the dose from these is negligible. The consequences of radioactive equilibrium for the daughters is that the amount of the different daughters follow the half-lives. Thus, if Po-218 have the amount N, Pb-214 will have the amount 8.6 N, Bi-214 the amount 6.4 N, whereas the amount of Po-214 is zero (or $8.8 \cdot 10^{-7}$ N). All daughters go through the same series of disintegrations.

$$^{218}Po \rightarrow {}^{214}Pb \rightarrow {}^{214}Bi \rightarrow {}^{214}Po \rightarrow {}^{210}Po$$

Range of the radiation

Very important aspect for the radon dose to the lungs, is the range of the different particles in tissue. As we know there are considerable differences in the range of α, β and γ-radiation. In the case of radon and radon daughters we have to consider all three types of particles – the most important are the α-particles (see the tables on page 24).

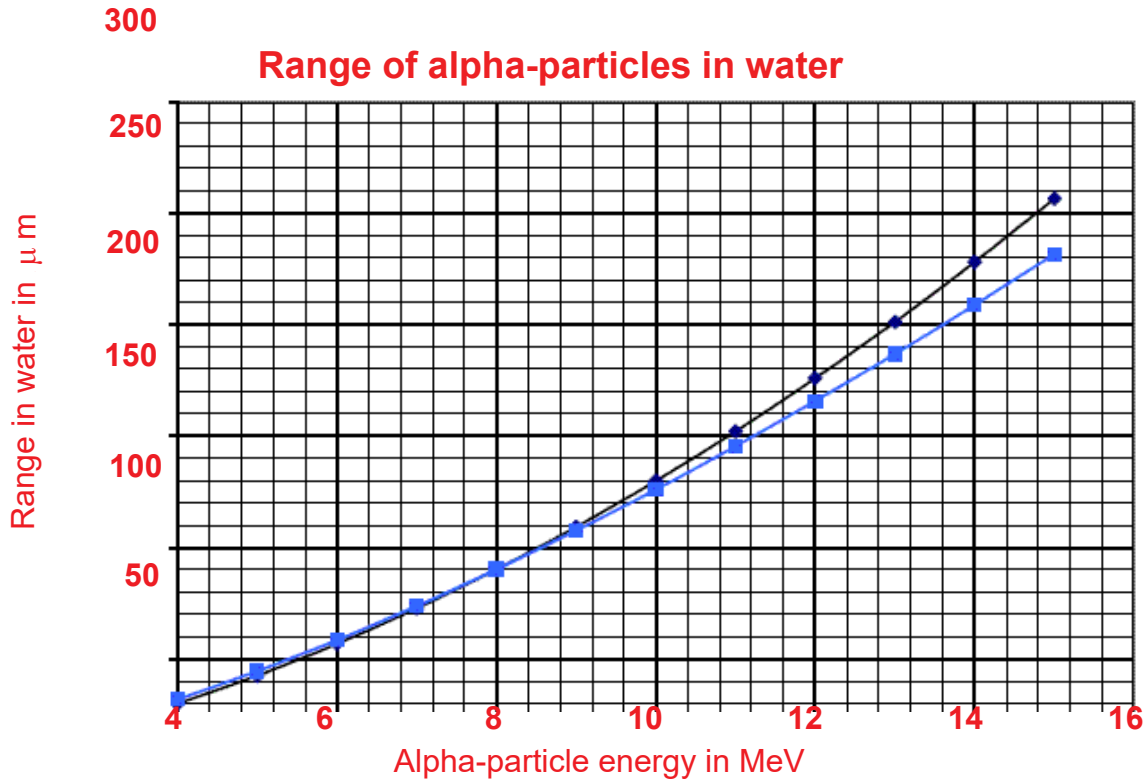


The α -particles in the Uran-radium series are from Po-218 and Po-214. Their energy is 6.0 MeV and 7.69 MeV respectively. From the Thorium-series we have three α -particles with energies 6.05, 6.78 and 8.76 MeV.
In the figure below we have given the results of range studies of α -particles in water (like tissue). Black points are from Lapp and Andrews, blue points from Sorenson and Phelps.
You see that for the α -particles from radondaughters the range in tissue is below 100 μ m. This implies that ***only cells in the immediate neighbourhood of the disintegrations will be irradiated.***
Pb-214 and Bi-214 disintegrate by emitting a β -particle + γ -radiation. It appears that a large number of disintegration ways are possible. The calculated average energy for each disintegration for Pb-214 is 0.5 MeV and for Bi-214 is 1.5 MeV. The range of these β -particles is in average about 1 mm. A few with maximum energy may reach about 5 mm from the dust particle.
The range of the γ -radiation is large (comparable to x-rays with high energy). This implies that part of the γ -radiation may go out of the body.

The conclusion is that the main part of the radiation dose (about 90 %) will go to the lungs and airways only when the dust particles are trapped in the lung system.

If the dust particles are in the stomach it is only that part which is irradiated. Since the distance to sensitive cells now is large, the radiation will have minor biological effect.
Below is a table with data for the radon daughters in one inhalation that are important for calculating the time lapse of the energy deposition (or dose).

Isotope	Amount initial	Disintegration	Energy (MeV)	$t_{1/2}$ (min)
Po-218	1,0 N	α	6,0	3,1
Pb-214	8,6 N	β + γ	0,5	26,8
Bi-214	6,4 N	β + γ	1,5	19,6
Po-214	0	α	7,69	0,164 msec



The timescale for the radiation dose in one inhalation

The total dose in one inhalation is the amount of energy released when all the radon daughters have disintegrated. This can be found from the above table and the fact that Po-218 disintegrates to Pb-214 and so on. Thus, the total amount of Pb-214 is (1.0 + 8.6)N = 9.6 N. For Bi-214 and Po-214 the total amount is (1.0 + 8.6 + 6.4)N or 16.0 N.

The total dose (the radiation energy given in MeV) in one inhalation is (from the table); (6,0 + 4,3 + 24,0 + 123,0)N = 157N (MeV)

The contribution from α -particles is about 82 %, from β -particles about 5 % and the rest 13 % is from γ -radiation.

Dose and time

The dose given in the time period (t) is the number of disintegrations in the period, multiplied with the energy per disintegration. Since all radioactive isotopes decay exponentially we have the number of isotopes at time t:

$$N_0 \cdot e^{-\lambda t} \text{ or } N_0 \cdot e^{-\frac{\ln 2}{t_{1/2}} t}$$

Here N_0 is the start amount and $t_{1/2}$ is the half-life. The number of disintegrations during the time t is given by:

$$N(t) = N_0(1 - e^{-\lambda t})$$

The energy per disintegration is set equal to E (given in the table above). The energy is therefore:

$$D = E \cdot N_0(1 - e^{-\frac{\ln 2}{t_{1/2}} \cdot t})$$

This procedure works nicely for Po-218, but become more problematic for the other radon daughters. The reason for this is that Po-218 become Pb-214. Consequently, the start amount for Pb-214, which is 8.6 N, increases when Po-218 disintegrates. Similar and even more complicated is the situation for Bi-214 and Po-214.
There has been worked out equations for this (Bateman equation), but it is rather complicated.

Harry Bateman
(1882 – 1946)

A simple solution is the following:
The start amount for the compound in question is set equal to (N_0 + x). Here x is the amount of the compound formed in the time interval t. In these calculations we used the x-value attained after the whole period t. This will give a slightly larger dose compared to the correct one, but this approximation is useful in a rough calculation.
The same procedure is used for the isotopes Pb-214, Bi-214 and Po-214. It is then possible to calculate the "dose" given in percent of the total dose after 10, 30, 60 and 120 minutes (as a function of time) after the inhalation. We give the data in the table presented on the next page.

The dose from the radondaughters as a function of time after an inhalation

Time	Dose already given	Dose still left
10 minutes	18 %	82 %
30 minutes	48 %	52 %
60 minutes	76 %	24 %
120 minutes	95 %	5 %

If we compare the above table with that for the lungs cleaning on page 32, we can conclude that the cleaning system must have a large effect on the radiation dose to the lungs and airway system when the radon daughters are considered.

The correlation between the efficiency of the cleaning system and the total disintegration of the radon daughters was based on one inhalation. We are breathing all the time and the cleaning system is working all the time. We can therefore conclude that the lungs cleaning system reduces the radiation dose to the lungs. With a healthy cleaning system a large fraction (about 50 %) of the radon dose will go outside the lungs (either in the stomach or spit out).

It is evident that the cleaning system is extremely important for the lung dose and consequently for all epidemiological studies on radon and lung cancer.

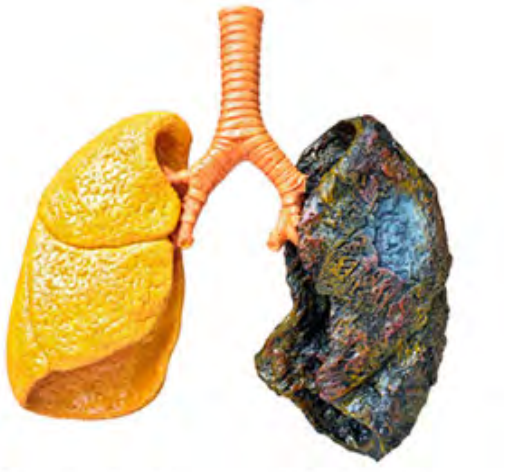
How is the lungs cleaning system influenced by smoking, age and air quality ?

1. We know that smoking has an effect on the cleaning system. A few seconds after smoking a cigarette, the ***cilia beating slows down***. Smoking can also ***reduce the number of cilia*** that clean the lungs. However, we do **not** know the quantitative relation between smoking (like number of cigarettes per day, or total length of smoking) and the quality of the cleaning system.

2. We have no information on the individual differences in the cleaning system, as well as the effect with age. It is reasonable to assume that the system is reduced with age.

3. It is reasonable to assume that air pollution in the large cities will influence the cleaning system to the inhabitants. It is difficult to find a healthy clean lung in the cities.
Furthermore, it is reasonable to assume that asthma and chronic bronchitis will weaken the cleaning system.

A weakened cleaning system will result in larger radon doses to the lungs.
Furthermore, the possibility for other carcinogens, like smoke, asbestos, diesel fumes, etc. will increase.



Healthy Lung Toxic Lung

Conclusion

It is a fact that we have a cleaning system for the airways and lungs. The efficiency of this system can ***not*** be measured. We have some vague ideas about how the cleaning system is influenced by smoking, air pollution and age.

The overall conclusion is that the lung radiation doses from indoor radon can not be determined.

In epidemiological studies the purpose is to compare the radiation dose to the lungs with lung cancer. The parameter for lung cancer is easy to obtain. However, the determination of the lung dose from radon daughters is extremely difficult, rather impossible, to determine. So far, in all studies the radiation dose **has been assumed equivalent with the radon content in the homes**. This is no longer the case since no attempts have been made to include the lungs cleaning system as well as to include the dose attained outside the home.

1). We agree that the ***case - control studies*** yield good information. A necessary condition is that case and control have the same radiation dose to the lungs. Since we do not know the lungs cleaning system for case and control, the power of this method collapses.

2). In ***ecological studies*** the average radon level in a district is compared to lung cancer in the same district. In this study the radon doses outside the homes are included. However, no correction is made for differences in the **average** lung cleaning system to the inhabitants. It is reasonable to assume a stronger cleaning system in areas with little pollution and it is reasonable to assume that air pollution in the big cities reduce the quality of the cleaning system.

Radiation and lung cancer

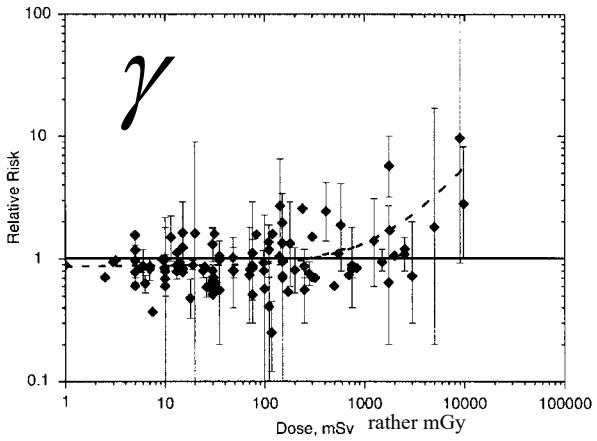
Lung cancer is by far the leading cause of cancer death among both men and women. In the Nordic countries Denmark is leading before Norway, Finland and Sweden. According to the cancer registrations lung cancer increased after the second world war. For men the curves have started to go down again, and for women it seems to have reached a maximum. Hopefully all curves will go down again since the smoking habits have changed drastically in recent years. Smoking is responsible for 80 – 90 percent of the lung cancer cases. The other carcinogens are asbestos, diesel fumes, radiation and life itself.

In all studies on radiation induced cancer the radiation dose is a crucial factor. As long as we can use physical dosimeters for the exact determination of the given dose and doserate, as for example in radiation therapy or in radiobiological experiments, solid conclusions can be drawn. However, in the case of radon and lung doses we are far from such a situation.

External exposure

Doses in connection to external radiation can be measured. Let us therefore start with external exposure to γ -radiation. A number of groups such as radiologists, x-ray technicians, fluoroscopy for tuberculosis patients, and a number of nuclear workers have been exposed to low LET radiation. Today, the doses could have been determined with high degree of accuracy, but for most of these groups the doses have been determined from calculations as well as from radiation badges. The dose–lung cancer incidence in 54 published epidemiological studies for different groups are given in the figure next page.

It can be noted that in the case of external low LET-radiation there is no linear correlation between lung cancer and radiation dose. A question that can be raised is if high LET-radiation as for radon daughters would give another result.



The figure is from the book of Charles L. Sanders: "Radiation Hormesis and the Linear-No-Threshold Assumption"

Here you see a number of epidemiological studies of the correlation between lung cancer and radiation dose.
In these studies the radiation is external and consists mainly of γ-radiation. It is low LET-radiation.

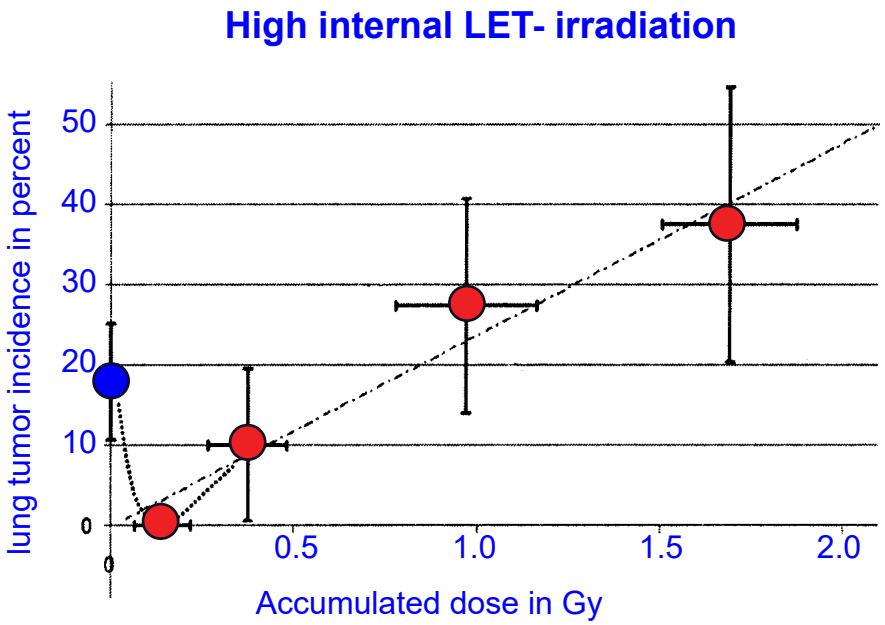
Although the data are heterogeneous, they indicate some type of radiation protection (radiation hormesis) for doses below approximately 500 – 700 mSv (or rather given in Gy - units).

Experiments with lung cancer formation by α -particles in dogs

Since about 1970 a group connected to Pacific Northwest National Laboratory in Washington have carried out life-span studies on dogs that inhaled plutonium oxide. The radioactive isotope is Pu-239, with half-life 24400 years. The decay scheme of Pu-239 is α -particles with energy 5.15 MeV and γ -radiation with a line of 53 keV, which makes it possible to observe the isotope from outside the body with a γ -camera.
The dogs were exposed until death.
The dose in Gy was fairly well determined – we can not give any dose in Sv since we operate with dogs.

The overall lung cancer incidence in 137 exposed dogs was best represented by a pure-quadratic equation. However, for accumulated doses below 2 Gy some interesting results appeared as shown in the figure next page.

The data for doses below 2 Gy supported a threshold effect for α -particle induced lung cancer. Un-irradiated dogs (the controls) exhibited a higher lung cancer level than those irradiated with doses up to about 0.7 – 0.8 Gy. The data showed that chronic low doses may be beneficial and give an advantage effect compared to unirradiated subjects.



The data indicated the likelihood that low doses of α-particle radiation protected and reduced the incidence of lung cancer relative to the controls. As you see no attempts have been made to evaluate the lungs cleaning system.

We would like to have these results for low and high LET-radiation in mind when we embark on the much more complicated issue to evaluate the effect of the indoor radon level on the induction of lung cancer.

Radon and underground miners

We shall not discuss radon and lung cancer for miners, but would like to mentioned the lung dose system that was used. Particularly in the old unventilated mines the radon levels have reached large values. We know that working in the old mines involved a health risk for the miners. As early as around 1500, lung disease was found in two regions of Germany and Czechoslovakia; Schneeberg and Joachimsthal, among miners.
The miners developed a deadly disease, called "Bergkrankheit". Between 1876 and 1938, 60 % to 80% of all miners died from the disease which, on average, lasted 25 years. Certain regions of the mines were known as "death pits," where all workers got sick. Bergkrankheit was mainly lung cancer and a result of their work and was recognized as an occupational disease.

It was mainly silver in the mines and silver coins were made (called "thaler" from the town of Joachimsthal). However, the mines contained pitchblende and consequently uranium, which at that time was considered to be of no value. From uranium the way to radon is clear and the mines contained radon and radondaughters.

The atmosphere in underground mines usually contains several *other* carcinogenic compounds, like arsenic and silica dust, and in more recent years, diesel exhaust from mining machinery. Furthermore, the majority of the miners were smokers.

The radon concentration in the old mines are unknown, but may have been very large. Thus, measurements published in 1924 confirmed that the air in the mines contained high concentrations of radon gas, the highest more than 18 000 picocuires per liter – or 666 000 Bq/m^3.
Today we have some socalled "health centers" (some of the old mines or caves) like those in Montana in USA and Bad Gastein in Austria with a radon level of about 45 – 60 kBq/m^3 with a maximum of 166 kBq/m^3. These mines are visited by a number of people every year. They stay in the mines for some hours.

The old miners worked for years in the mines and were exposed to radon and daughters. A normal monthly workingtime in the mines was 170 hours. It would be of interest to arrive at the exposure rate and accumulated lung doses to the miners. All dosimetry is carried out in recent years and consists of the product of the exposure level and time on work.

Exposure

The unit for exposure was called "***Working Level***" **(WL)**. The working level unit was defined as the amount of radon and radon daughters in 1 liter air that give a total α-particle energy of **$1{,}3 \cdot 10^5$ MeV.**

For an equilibrium factor between radon and radon daughters of 1.0, one WL correspond to 100 pCi per liter (or 3700 Bq/m^3), whereas for an equilibrium factor of 0.5 the WL unit correspond to 200 pCi per liter (7400 Bq/m^3).

Dose

The workers in those days worked 40 hours per week, or 170 hours per month. This gives the unit for total exposure or "dose"; called **"Working Level Month" (WLM)**.

1 WLM = 1 WL in 170 hours

Several attempts have been made to estimate a dose of 1 WLM into the more usual doseunits such as Gy and Sv. We shall not go more into these speculations !

Lung cancer for the miners

Several retrospective cohort studies have been made. They are all based on the accumulated WLM as dose parameter and conclusions are mainly drawn ***based on the LNT model.*** Of course the lungs' cleaning system is not mentioned. However, it can be concluded that the dose attained during work is very much larger than that attained at home. Therefore the "homedose" can be neglected.
Another point that should be mentioned is that the old German data seem to indicate that the risk was at a maximum in the period 15 – 24 years after exposure – indicating a latency period of that length.

The observation of lung cancer among miners seems to indicate a threshold value. Thus no cancers have been observed for non-smokers for accumulated doses below 100 WLM.

An α-particle dose of 300 WLM (probably a threshold dose) is equivalent with a lung dose of about 600 mGy. This is quite interesting when we compare with the experiments on dogs with a threshold dose of about 700 mGy.

Radon in homes and lung cancer

For all epidemiological studies on radon and lung cancer in homes the dose parameter used is Bq/m^3. As for the miners we are interested in an accumulated dose – either for a certain number of years (often 30 years are used) or from birth.
For example a constant radon level of 100 Bq/m^3 (day and night) give an accumulated annual dose of 0.75 WLM. The accumulated lifetime radon dose is usually about 20 WLM, ***which is much smaller than the threshold values for lung cancer for the underground miners.***

We have discussed above the lungs cleaning system and concluded that the dose parameter for radon given in Bq/m^3 is very weak. In spite of this we shall give some examples of two types of epidemiological studies based on this doseparameter.

Ecological studies

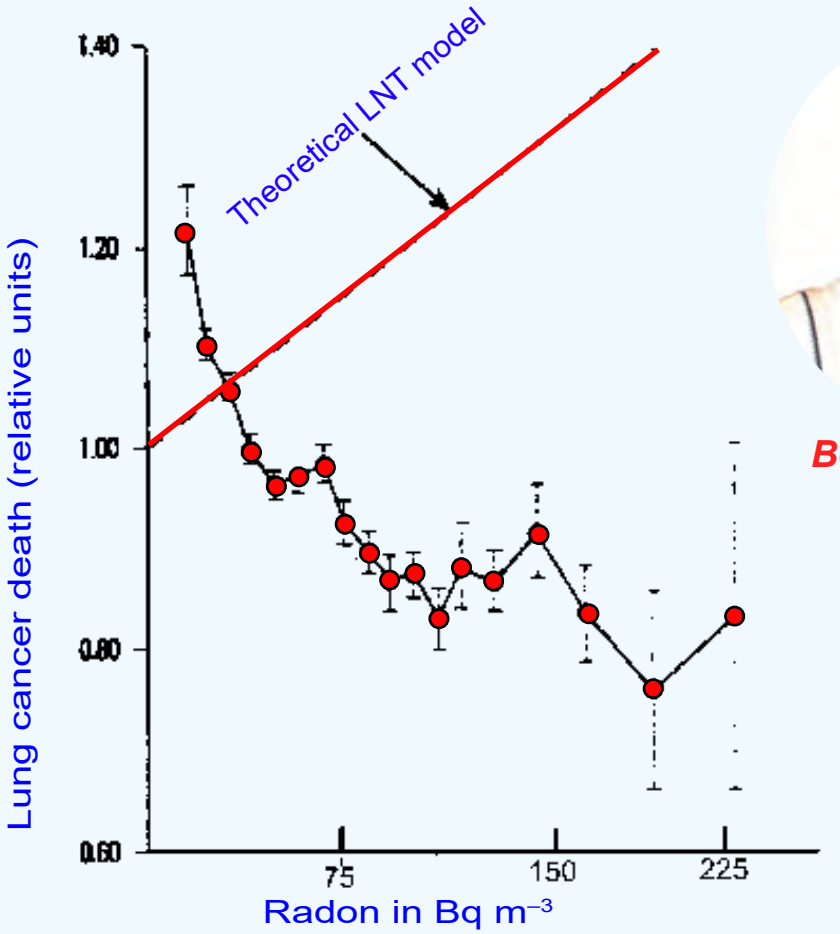
In 1995 Bernhard Cohen presented an ecological study from USA with rather surprising results. He expected to obtain a curve more or less in accordance to the LNT-hypothesis. People living in districts with high radon level would have more lung cancer than in districts with a low radon level. The dose parameter was Bq/m^3 measured as an ***average for the homes in the district***. No individual doses were estimated, but the reasonable assumption is that the accumulated dose for people in the district would follow the average radon level.

Cohens study involved about 90 % of the of the US population and about 330 000 radon measurements. In this study Cohen divided the country in 1729 counties or regions. The average radon level within each region was determined and compared to the incidence of lung cancer. No control groups, no assumptions on the cleaning system. The main results of these studies are given in the figure on the next page.
The results, which deviated significantly from the LNT-theory, came as a big surprise to Cohen himself. Cohens results have been ignored by the "LNT-group" – they have in general not mentioned the results.

Cohen tried to correct the data and took out some counties in California and Florida since a lot of retired people came to these areas. They had lived in other counties and got their "radondose" in another county than the one they got cancer. He also tried to correct for other factors such as smoking habits.

Cohen had no information about the lungs cleaning system. It is reasonable to assume that air pollution has an influence on the cleaning system and it is likely that people living in cities like Los Angeles and New York will have a reduced cleaning system and consequently attain larger radiation doses to the lungs. Furthermore, areas in the mountains may have cleaner air, better cleaning systems and reduced radiation doses. This would give a correction to the data in the figure.

However, the conclusion is that in spite of all possible corrections, it seems impossible to change or correct Cohens data to fit the LNT-curve.



Bernhard Cohen

(1924 – 2012)

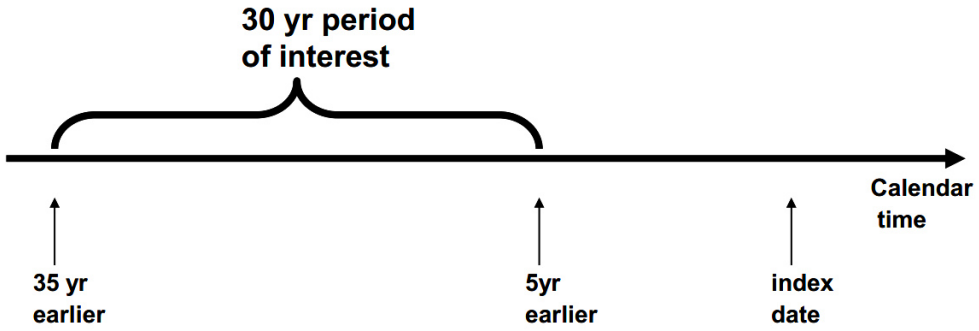
*The figure shows the main results of Bernhard L. Cohens investigations from 1995 and 2000. The main data are published in Health Physics **68 (2)**, 157 – 174 (1995).*
The data points from counties with almost the same radon level have been grouped together.

The data from 2000 include more recent cancer data. Furthermore, data for counties in Florida and California have been deleted because deaths there are frequently due to retirees who received their radon doses elsewhere. The results are however, not changed but are more or less equal to those presented above.

Case-control studies

In case-control studies we are into individual radiation doses to the lungs – and even more so, because the purpose is to compare case and control that have been exposed to the same lung doses. This is in fact an impossible task and the assumption that the case-control studies give the most and best information **is not valid.** It is more or less impossible to arrive at control groups since we can not evaluate the lungs cleaning system. Thus, two persons living with equal becquerel level may obtain very different radiation dose to the lungs – even if they are non-smokers.
Let us see in more detail into the dose parameter used. The figure below is from Sarah Darby.

Period of interest for radon concentrations



Time-weighted average measured radon concentration for each subject
Average no of years measured: 23/30
Estimates for years with no measurements

In Sarah Darbys study the radon level in a period 35 to 5 years before observation was considered (index date). For the 13 different studies included it involve cases from 1947 to 1960. Only the radon level in the homes were considered. For the Beir VI study it was assumed that those included stayed at home 70 % of the day. No attempts were made to evalute or measure the radon level each member of the group met outside the home either at work or in their free time. The radon level was measured on average for 23 years and estimated for the last 7 years. Smoking habits have been considered as well as the year-to-year radon variability. Nothing is mentioned about the lungs cleaning system.

Dose problems

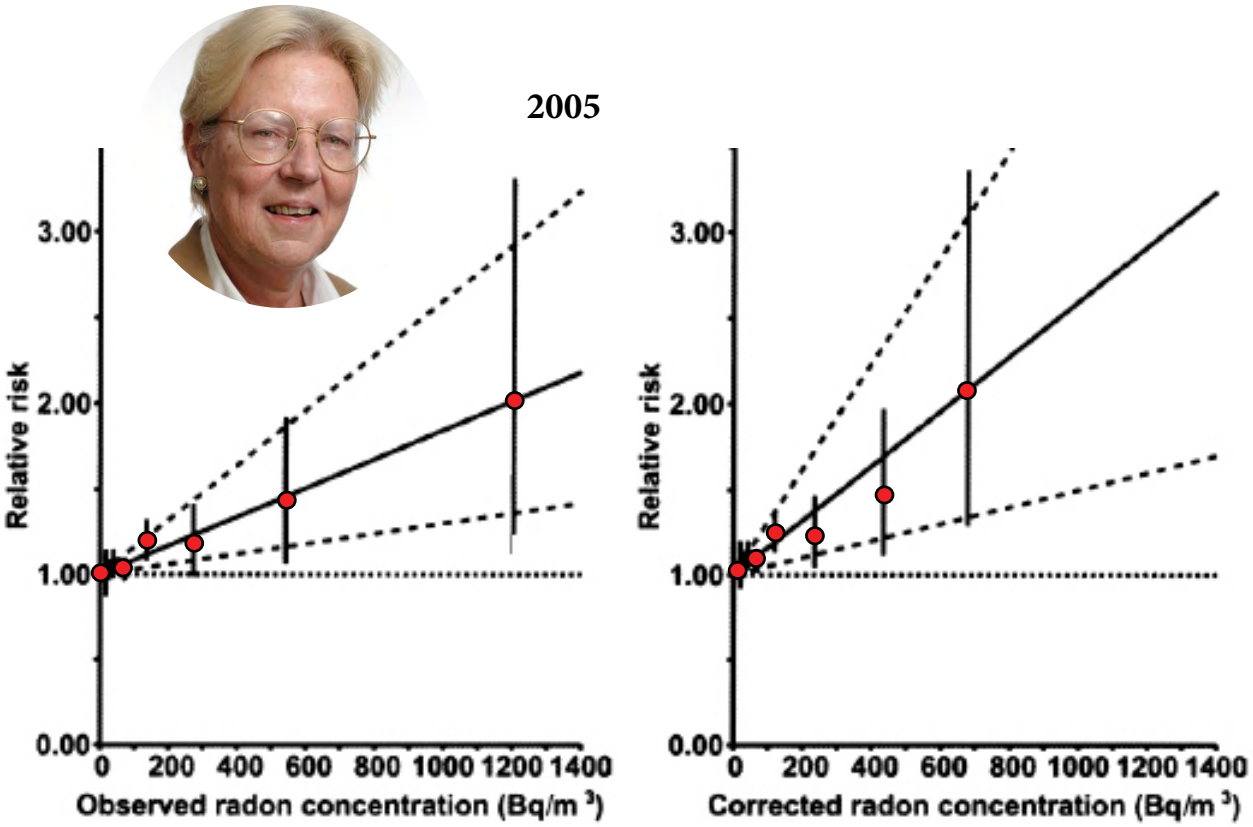
1. Since the lungs cleaning system is not evaluated, the dose may be off by a factor up to 2.

2. The radon dose attained outside the home may easily be large and can not be neglected. For example indoor training with heavy breathing may easily give a lung dose that cannot be neglected. The situation is very much different from the miners where the dose attained outside work can be neglected.

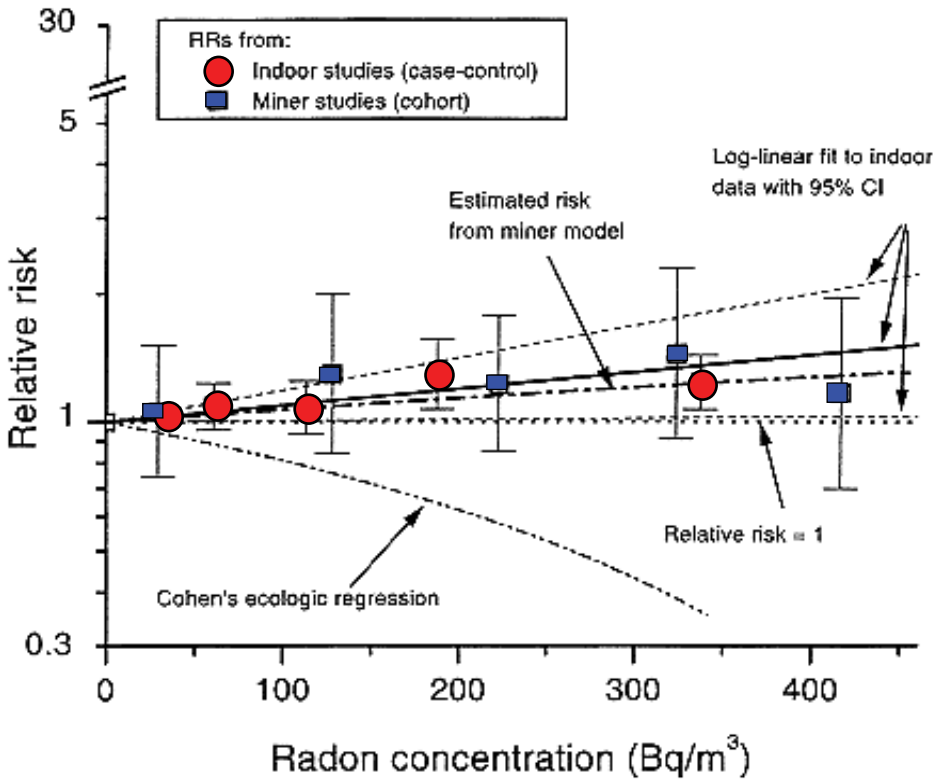
Sarah Darby and Daniel Krewski – pooled studies

Sarah Darby et. al.(2005) presented pooled data from 13 studies in 9 European countries including 7148 cases and 14208 controls. Daniel Krewski et.al. presented data from 7 studies in USA including 4420 cases and 5707 controls.
These studies can be presented together since they both have based the studies on the LNT-theory. Furthermore, it can be mentioned that these two studies represent the basis for WHO´s handbook on indoor radon, which has been adopted by the radiation authorities both in Norway and USA.

The main argument against these studies is not only the assumption of LNT, but also the poor determination of the lung dose from the radon daughters. They assume that the data should be given in a linear plot between lung cancer and the level of Bq per square meter in the homes. ***The purpose of the studies is to determine the increase in cancer incidence per 100 Bq/m³ increase in radon level.***



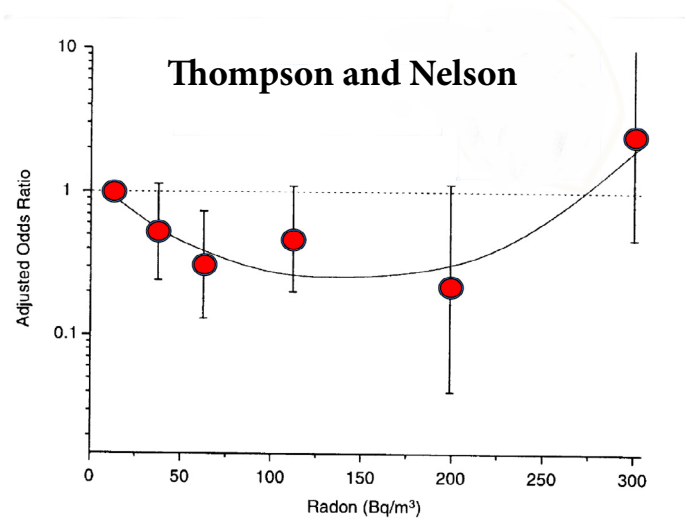
Above Darbys data are given. To the left is given the measured amount of radon in the homes in Bq per cubic meter. In the figure to the right the same data are given, but the "dose-axis" are corrected to imply the long term average of the radon content.
In these plots the risk for lung cancer increases by 8 % per 100 Bq/m³ whereas in the right figure the increase is 16% per 100 Bq/m³. For non-smokers no measurable increase was found.



The data presented by Krewski et. al. In this figure is also presented the data from the BEIR VI report. The miner data are extrapolated to the very low values of radon. The extrapolation is based on LNT. Furthermore, the dotted line include the data from Bernhard Cohens ecological studies (see above). The straight line indicate an increase in lung cancer of 9.6 % per 100 Bq/m³.

2. Richard Thompsons and Donald Nelsons studies from Massachusetts 2008

The number of cases in this study was much smaller than those above. Thus 200 cases and 397 controls. They divided the cases into 6 groups with regard to radon content in the homes. The lowest value 25 Bq/m³ was used as reference. All those included were from the same district. Few interviewers were used and more than one radon detector for the measuring point were used. No preassumption about LNT was made. The results are given below.



Here are the results from Massachusetts. It was a surprise that the data showed a clear hormetic effect. The range in "dose" or Bq/m³ is rather very limited.

Richard Thompson

Donald Nelson

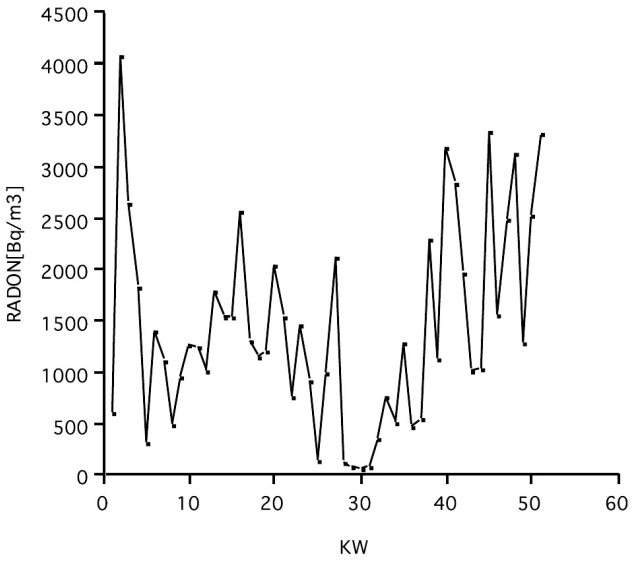
During the study, the research team in Massachusetts calculated radon level by installing radon monitors in areas of the home where the subjects spent most of their time awake, in the subjects' present and former bedrooms, and other areas where the subjects spent as little as one hour per week.
The subjects' exposures were then obtained by weighting the measurements according to the time typically spent near each detector. The results were adjusted to account for how subjects' home use changed with changing lifestyle, such as transitioning from full-time employment to retirement.

I**n this study the hormetic effect was observed up to about 250 Bq/m^3.**

The Schneeberg studies

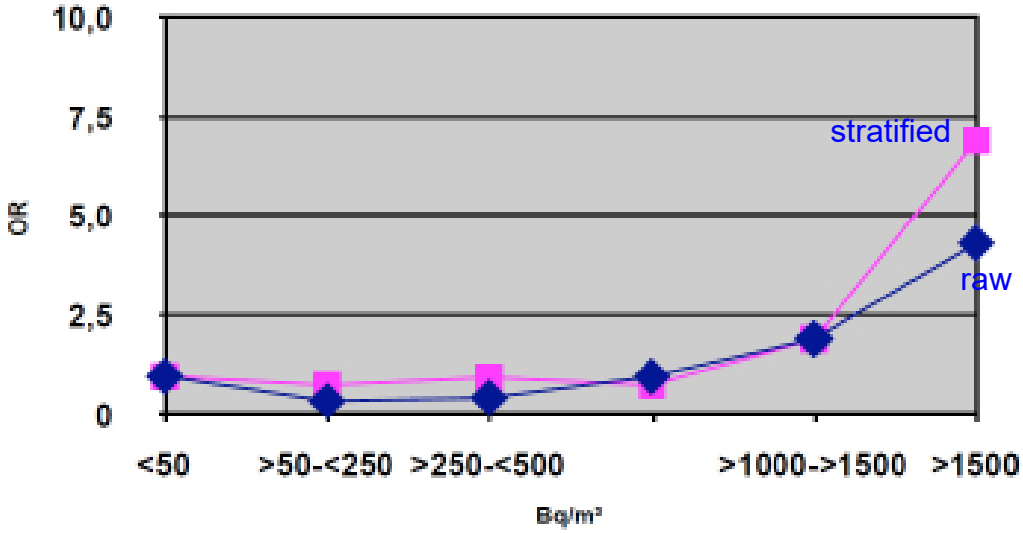
Schneeberg is a small German city close to the border of the Chech Republic. The city is known for high level of radon in the homes. Thus the radon level varied from 50 Bq/m^3 to more than 3000 Bq/m^3.
The radon studies in this area include only women that lived in these homes for more than 25 years.
Most of the women were non-smokers (only 22 % smokers). It can be mentioned that the self-reported smoking behavior of the women are made at time of diagnosis. Consequently, the data may be biased due to an obvious tendency to repress and minimise their smoking habit.
Only those with low mobility are included.

The radon level is measured by track-dosimeters for several years. The data could vary significantly through the year (see figure below). It was assumed that the time spend inside the homes was 68 % of the total. Furthermore the equilibrium factor was set to 0.4.
A number of cases were found not to fit the requirements and are therefore omitted.
There were 4 controls for each case. The results are given in several tables and also in the figure on the next page.



Here is the measured radon level in a home in Schneeberg. Along the abcissa is given the calender week. The measurements for each week is given by the dots. As seen the values varied from about 50 Bq/m^3 to 4000 Bq/m^3. The average value is used as the radon content for this house.

It is assumed that the person spent 68 % of the time inside the house. If the 22 % away from home is taken in particular weeks it will change the average value significantly.



The reference is the group with a radon level below 50 Bq/m³. It is clear that these data do not follow an increase of about 10 % per 100 Bq/m³ as found for Darbu and Krewskis studies. Only for values above 1000 Bq/m³ the risk seems to increase.

The risk estimation of the Schneeberg study for lung cancer from indoor radon is not in accordance with the studies by Darbu and Krewski. From the risk estimate of the Schneeberg study the threshold value was found to be in the range 1000 – 1.500 Bq/m³.

It was not the purpose of this particular study to test the LNT model. However, the evidence of the Schneeberg study strongly indicate that its results are not in accordance with the LNT assumption. The risk estimations for lung cancer due to indoor radon exposure are derived by direct observation in a key population for such research. The Schneeberg study is considered by its authors as a contribution to the growing body of scientific evidence that the LNT model might not be valid in the low dose range.

Comments on the case-control studies

The weakness of all radon studies is the determination of the radiation dose to the lungs by the parameter Bq/m³ of radon in the home, because;

1. The parameter do not take the lungs cleaning system into consideration.

2. The radon measurements can be made very well. However, because of the variation with time and place into the home it is impossible to reach at a representative value. Furthermore, sleeping with an open window would be quite important.

3. In most studies it has been assumed that you stay in the house for 16 to 18 hours per day. The time spent at home will vary with age – from about about 8 hours to almost 24 hours when you are old and retired.
Important in this case is that the dose attained outside the home is not taken into consideration.

For the miners the radon level outside the working place was 100 - 1000 times smaller than that in the mines and could therefore be neglected. **This is not the case for radon in the homes**.

All the factors discussed above including the lungs cleaning system, time period of observation, and breathing volume make it (in the opinion of the present author) impossible to find **cases** and **controls** which received the same radiation dose to the lungs.

The second point is that the LNT is no longer a useful risk theory. ***Consequently, interpretations and attempts to fit the data to this curve is wrong***.

The unbiased studies such as the external γ -radiation and the dog α -particle studies both indicated threshold lung doses of about 0.7 to 1.0 Gy for the formation of the lung cancer. All these points suggest that Bernhard Cohens data give the best information about radon in homes and lung cancer.

Is there a hormetic region?

Bernhard Cohens studies indicate that radon doses at the range of normal background levels stimulate lung tissue functions to protect against lung cancer. It can be mentioned that radiation-protection interests ignore these results simply by the fact that "they are ecological studies". There is no documented scientific criticism of Cohen's results, just general rationalizations of highly unlikely reasons why one study might not be valid. Nevertheless, radiation protection interests use unfounded statements to discredit and refute Dr. Cohen's data. Cohens data indicate a hormetic region up to about 225 Bq/m^3 (the highest value in the investigation). Cohens data include up to 90 % of the American public. With regard to number this is far more than all the other studies together.

In the case-control studies from Massachusetts we observe that the hormetic region goes up to about 250 - 300 Bq/m^3. For the case-control studies in Scneeberg the hormetic region was stretched out to more than 1000 Bq/m^3.

Data from the Ramsar Health Network show that both crude lung cancer rate and adjusted lung cancer rate in one district with the **highest** recorded levels (up to 3700 Bq/m^3) of external radiation and radon concentration are lower than those of the other seven districts. The conclusion was that the lung cancer rate showed a negative correlation with natural radon concentration.

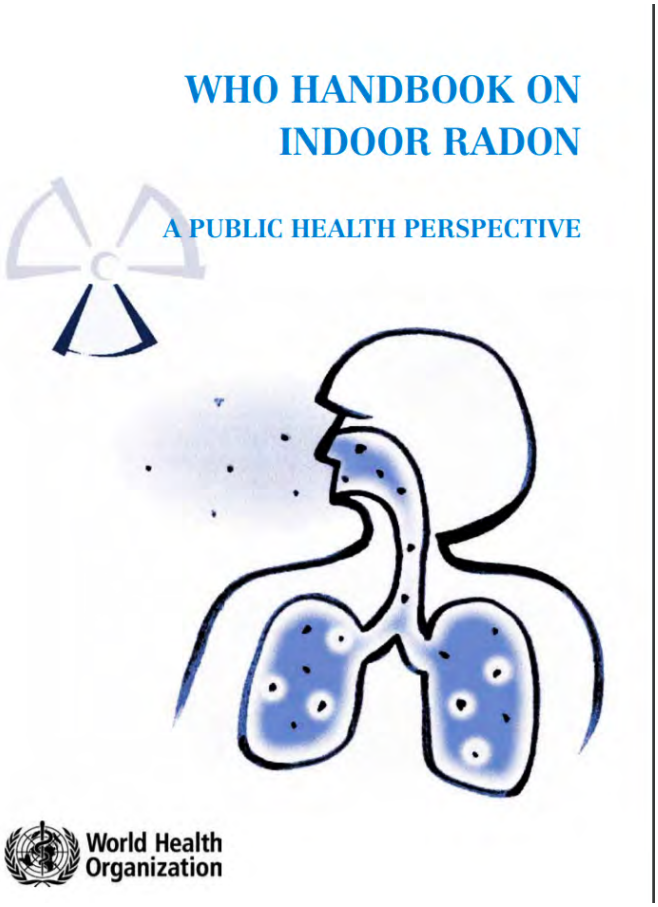
Smoking

In this paper we have mentioned that smoking invalidate the lungs cleaning system. The cilia are slowed down and even stopped and the carcinogen particles are not wiped out to the same extent. It is quite obvious that smoking has a large effect on the radiation dose to the lungs from radon daughters connected to the dust particles. BUT – we can not give any quantitative data for this – and how it will vary from one person to another. Smoking increases the lung doses and increases the number of lung cancer. However, all carcinogens to the lungs will increase when the cleaning system collapses partly or fully. It is therefore impossible to distinguish the effect of radon from the other carcinogens.
It is quite clear that the largest effect against lung cancer would be to reduce and/or nullify the smoking habits in the world. The money spent on reducing the radon level in the homes would be better used in the fight for a smoke-free world.

Radon regulations

In 2009 **WHO** (World Health Organization) presented "***WHO Handbook on indoor radon***" (with the address: http://whqlibdoc.who.int/publications/2009/9789241547673_eng.pdf).

This book has served as a guide for several national authorities, including Norway, with regard to the radon regulations implemented in the country.



WHO health group with Sarah Darby as chair of "Working group on health effects" (Daniel Krewski is also in this committee) base their recommendations on the following;

1). The LNT-model

2). The case-control studies of Sara Darby and Daniel Krewski (as shown above).

All other studies have been disregarded.

WHO recommendations

To limit the risk to individuals, a national reference level of 100 Bq/m^3 is recommended. Wherever this is not possible, the chosen level should not exceed 300 Bq/m^3.

To reduce the risk to the overall population, building codes should be implemented that require radon prevention measures in homes under construction.
Radon measurements are needed because building codes alone cannot guarantee that radon concentrations will be below the reference level.

The power of the recommendations is only valid if the dose-effect curve is linear (if LNT is valid). It would then, and only then, be possibe to talk about and to introduce cost-effective remedial actions.

Present situation

In USA. EPA (United States Environmental Protection Agency) uses the LNT-theory and the BEIR VI report. They assumes that radon in US-homes is responsible for about 20 000 lung cancer deaths per year (between 6 000 and 30 000).
In USA the regulations require that the radon level in schools and public buildings should be below 4 pCi per liter which is 148 Bq/m^3.

In Norway. The radiation authorities have decided to follow WHOs handbook. The radon level should be below 200 Bq/m^3, and it should be possible to introduce remedial action for the site of the building, if and when the radon concentrations in the inside air is above 100 Bq/m^3.

In most other European countries the remedial action level is suggested to be 400 Bq/m^3 for old houses and 200 Bq/m^3 for new houses. In general, it is possible to reach a set level, but the cost may be very large.

In the **LNT-model** collective doses can be used. It is therefore possible to make cost-effectiveness analyses and thus provide useful information for policy makers when evaluating policies and alternatives, The results of such analyses have created a number of jobs for measurements and a whole industry for prevention and mitigation of a large number of houses in some areas. We consider this to be waste of money.

Comment

In the particular case of lung cancer it is more wise to give the money to actions against smoking – and in particular to stop young people from beginning.

The costs for remedial actions for existing dwellings within OECD countries above the action level of 400 Bq/m^3 have to be more than 10 Billion ECU. As long as Public Health effects are dubious, no new regulations should be imposed on the public causing billions of ECU without a certain Public Health effect.

Summary – discussion
The LNT is out and hormesis is in

How would the world be without the frightening LNT hypothesis and we instead would experience that small doses of ionizing radiation, given at a low dose-rate, is positive for the mankind?

We would like to mention a few things that would change our daily life

1. Radon in homes

It is evident from this long paper that we can forget about most of the remedial actions for reducing the average radon level. This would save a lot of money for those involved.

2. Nuclear power

In the fight for reducing the CO_2 release to the atmosphere, nuclear power could be a considerable contributer to the worlds energy supply.

The world energy consumption increases annually by approximately 2 %. Also the use of fossil fuel with CO_2 release increases. A significant contribution to halt and even reduce the CO_2 release would be to increase the contribution from nuclear energy. It is a surprise to us that environmental organizations that worry about global warming - **are not pro nuclear.**

Some individuals like the well known environmentalist James Lovelock expressed the following in 2004; “only nuclear power can halt global warming”. The well known climate scientist James Hansen (leader of NASA Goddard Institute for Space Studies from 1981 to 2013) suggests efficient energy use, renewable energy, a smart grid and generation IV nuclear reactors. He suggests to develop fast reactors that consume nuclear waste, and thorium reactors to prevent the creation of new long-lived nuclear waste.”

The conclusion in this paper that LNT is not working and that small doses given at a low doserate have an hormetic effect, strongly suggest a ”go ahead” for modern molten salt reactors with thorium. In the middle of this century these reactors could be a significant contributer to the world energy production.

3. Reactor accidents

We have had two major breakdowns of nuclear reactors which both have been treated according to the LNT-theory. For both Chernobyl and Fukushima consequences have been calculated using **collective doses and LNT**.

In Chernobyl a number of people were hospitalized with acute radiation syndrome and 28 died within 3 months. There has also been recorded thyroid cancer to children that was drinking contaminated milk (I-131). Altogether 11 deaths have been recorded. Whether these cancers have been caused by the Chernobyl accident is rather douptful since similar changes in the thyroid have been observed without radiation. Furthermore, the thyroid doses from I-131 after the Chernobyl accident have not been measured and they are very poorly determined.

Cancer deaths in combination with the reactor accidents are based on LNT. No threshold and no hormetic region has been considered. However, the most significant and serious decision taken after the reactor accidents in Chernobyl and Fukushima was to evacuate several hundred thousands of people. The decision was taken based on the LNT-theory and the use of collective doses. No attempts were made to compare the **radiation level in the contaminated areas with the level found in the HBR (High Background Radiation) regions.** If such a comparison had been made, the most negative of the reactor accidents could have been avoided.