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Health Effects of High Radon Environments in Central Europe: Another Test for the LNT Hypothesis?

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ABSTRACT

Among the various "natural laboratories" of high natural or technical enhanced natural radiation environments in the world such as Kerala (India), Brazil, Ramsar (Iran), *etc.*, the areas in and around the Central European Ore Mountains (Erzgebirge) in the southern parts of former East Germany, but also including parts of Thuringia, northern Bohemia (now Czech Republic), and northeastern Bavaria, are still relatively little known internationally.

Although this area played a central role in the history of radioactivity and radiation effects on humans over centuries, most of the valuable earlier results have not been published in English or quotable according to the current rules in the scientific literature and therefore are not generally known internationally. During the years 1945 to 1989, this area was one of the world's most important uranium mining areas, providing the former Soviet Union with 300,000 tons of uranium for its military programs. Most data related to health effects of radon and other carcinogenic agents on miners and residents became available only during the years after German reunification. Many of the studies are still unpublished, or more or less internal reports.

By now, substantial studies have been performed on the previously unavailable data about the miners and the population, providing valuable insights that are, to a large degree, in disagreement with the opinion of various international bodies assuming an increase of lung cancer risk in the order of 10% for each 100 Bq/m^3 (or doubling for 1000 Bq/m^3), even for small residential radon concentrations. At the same time, other studies focusing on never-smokers show little or no effects of residential radon exposures. Experiments in medical clinics using radon on a large scale as a therapeutic against various rheumatic and arthritic disease demonstrated in randomized double-blind studies the effectiveness of such treatments.

The main purpose of this review is to critically examine, including some historical references, recent results primarily in three areas, namely the possible effects of the inhalation of very high radon concentrations on miners; the effect of increased

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residential radon concentrations on the population; and the therapeutic use of radon. With many of the results still evolving and/or under intense discussion among the experts, more evidence is emerging that radon, which has been inhaled at extremely high concentrations in the multimillion Bq/m^3 range by many of older miners (however, with substantial confounders, and large uncertainties in retrospective dosimetry), was perhaps an important but not the dominating factor for an increase in lung cancer rates. Other factors such as smoking, inhalation of quartz and mineral dust, arsenic, nitrous gases, *etc.* are likely to be more serious contributors to increased miner lung cancer rates. An extrapolation of miner data to indoor radon situations is not feasible.

Concerning indoor radon studies, the by far dominating effect of smoking on the lung cancer incidence makes the results of some studies, apparently showing a positive dose-response relationship, questionable. According to recent studies in several countries, there are no, or beneficial, residential radon effects below about 600 to 1000 Bq/m^3 (the extensive studies in the U.S., in particular by B. Cohen, and the discussions about these data, will not be part of this review, because they have already been discussed in detail in the U.S. literature). As a cause of lung cancer, radon seems to rank — behind active and passive smoking, and probably also air pollution in densely populated and/or industrial areas (diesel exhaust soot, *etc.*) — as a minor contributor in cases of extremely high residential radon levels, combined with heavy smoking of the residents.

As demonstrated in an increasing number of randomized double-blind clinical studies for various painful inflammatory joint diseases such as rheumatism, arthritic problems, and Morbus Bechterew, radon treatments are beneficial, with the positive effect lasting until at least 6 months after the normally 3-week treatment by inhalation or bathes. Studies on the mechanism of these effects are progressing. In other cases of extensive use of radon treatment for a wide spectrum of various diseases, for example, in the former Soviet Union, the positive results are not so well established. However, according to a century of radon treatment experience (after millenniums of unknown radon therapy), in particular in Germany and Austria, the positive medical effects for some diseases far exceed any potential detrimental health effects.

The total amount of available data in this field is too large to be covered in a brief review. Therefore, less known — in particular recent — work from Central Europe has been analyzed in an attempt to summarize new developments and trends. This includes cost/benefit aspects of radon reduction programs. As a test case for the LNT (linear non-threshold) hypothesis and possible biopositive effects of low radiation exposures, the data support a nonlinear human response to low and medium-level radon exposures.

Key Words: radon, radiation risks, LNT hypothesis, lung cancer, radon balneology.

HISTORY OF RADON EXERIENCE AND RESEARCH IN CENTRAL EUROPE

Observations of beneficial radon effects on human health may reach back into pre-historic times, as there are archaeological indications that the radon sources in Gastein, Austria, have already been used many thousand years ago (Deetjen 1999).

The use of radon-containing springs for health reasons in such different civilizations as ancient Rome, medieval Japan, and Central Europe has been documented for hundreds or thousands of years without any knowledge of radon.

The modern history of radioactivity and radon may be traced back to the mining activities in the mountain range between Saxony and Bohemia southwest of Dresden, where in 1168 Freiberg silver ore was accidentally discovered, which became the basis for the largest silver mining activities in Europe during the 13th century, in particular after additional discoveries in 1470 in Schneeberg. In 1481, Schneeberg already had 153 mines, and the rich profits permitted relatively advanced mining technologies, reaching a depth of about 400 m. More silver was found in 1497 in the nearby city of Annaberg, and in 1516 in St. Joachimsthal on the Bohemian side of what by now was known as the "Erzgebirge" (Ore Maintains), indicated in Figure 1 in a "radon map" of Germany.

The silver minted there became known as the "Joamchimsthaler", abbreviated later into "Thaler", and anglicised into "Dollar". When the mines became exhausted and abundant silver available easier in Latin America, mining continued for cobalt (providing, the blue color for the famous Meissen porcelain), bismuth, nickel, tungsten, arsenic, as well as uranium, used, for example, in the green-yellow fluorescent uranium glasses. Therefore, this area had already a half millennium tradition of continuous mining before, in 1946, the Soviet rush for uranium made this area the "Klondike in the Ore Mountains" (Paul 1991; Becker 1992) and, with a total output of 220,000 tons of uranium until 1989 when East Germany ceased to exist and the nonprofitable production was stopped, one of the world's main uranium sources.

Several elements have been discovered in this area, including germanium and, in 1789 the Berlin chemist Klapproth discovered uranium (for a review see Schüttmann 1989). From the local mineral "Pechblende" came the uranium in which Becquerel discovered radioactivity, and Hahn and Strassmann in 1938 in Berlin nuclear fission, as well as the Curies in Paris in 1898 polonium and radium. After E. Rutherford found that thorium emitted a radioactive gas that he called "emanation", Dorn in Halle, Germany, found a similar emission from radium, and two other German scientists (J. Elster and H. Geitel, Wolfenbüttel) identified both gases as normal constituents of the atmosphere, resulting from the radium content in the Earth's crust (for further historical references see Schüttmann and Aurand 1991).

In 1902, J.J. Thompson discovered in Cambridge/England that "emanation" was also part of the local water. In Bad Gastein, Austria, the physicist Mache from the Vienna University (after whom the first unit for radon concentrations was named) tested 15 natural springs and found varying, but in some cases very substantial concentrations of "emanation". Together with his colleague Meyer, he later investigated other spas in Austria and Bohemia, and reported in 1905 also high concentrations in the waters and air in the uranium mines in Joachimsthal, which was the first reference to underground radon. In 1907, H. W. Schmidt, University of Gießen, Germany, reported high radon concentrations in residences (for further details see Schüttmann 1986, 1990, 1992, 1994, 1997a).

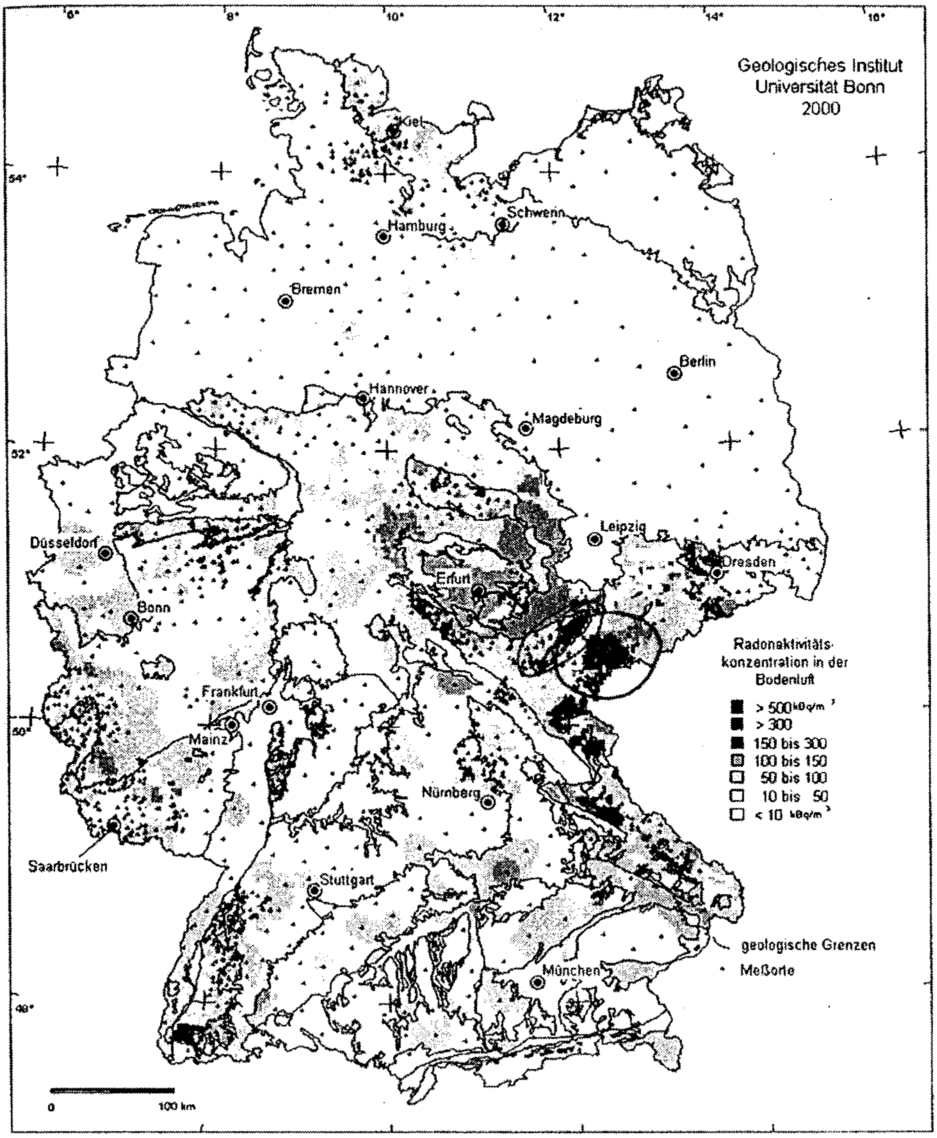

Figure 1. **Distribution of radon air in top soil in Germany.** Areas in black indicate more than 500,000 Bq/m³, in white less than 50,000 Bq/m³, and circles around the main uranium mining areas Schneeberg/Schlema (after Radon-Handbuch Germany Figure 2.1, 2001).

Preceding the discovery of what is now known as radon (usually including in this term the various daughter products that are more or less in equilibrium with radon, assuming usually an F-factor of about 0.4) and its beneficial health effects, there have also been observations of detrimental health effects among miners in this area. First indications date back to around 1485 to 1490, when A. P. Schneevogel mentioned "dangerous air in the depth of the earth". About 1530 the famous physician Theophrastus Bombastus von Hohenheim (called Paracelsus) wrote a book published after his death in 1567 (Paracelsus 1925 edition). Already in 1473, U. Ellenbog and in 1529, M. Hunt (Leipzig, Saxony University) published warnings for miners concerning what was called "Bergsucht" (mountain disease), as a summary description of all sorts of pulmonary problems affecting miners. However, it was Paracelsus who first brought this disease to wider attention.

Among his many insights in medical history are "It is the dose which makes the poison", and "I believe only in what I found myself, and was confirmed by long experience". Another famous name associated with the early history of miner's lung diseases is that of G. Agricola (latinized for Georg Bauer), also from Saxony (1494 to 1555), who wrote basic books about mining and metallurgy, and also mentioned lung diseases among the miners in various European countries due to "bad vapours" in mines caused by the lack of ventilation (Agricola 1928 edition; also see Menzel 1989; Schüttmann 1994).

RADON AND LUNG CANCER IN MINERS

The disease "Bergsucht" was, lacking modern medical diagnostics, a summary expression for pneumonia, acute and chronic bronchitis, lung emphysema, tuberculosis, silicosis, and other mineral dust-related problems. It was in the Schneeberg region of Saxony that these, at those times already world-wide common miner's diseases, were first studied. They led, after shortness of breath *etc.*, to a relatively early death. In the 19th century, it became known as "Schneeberg lung disease" or "Schneeberg mountain sickness". In 1879, two local doctors reported in detail that this disease was a malignant process that became known as "Schneeberg lung cancer" (Härtling and Hesse 1879). Originally assumed to be a lymphosarcoma, it was later identified as bronchial carcinoma. As a possible cause, the high content of arsenic, but also toxic metals such as cobalt, nickel, bismuth, and quartz dust were considered. Only after the discovery of ionizing radiation, "emanation" also became a suspect, and was in 1913 first associated with the high lung cancer rates by the mining inspector H. E. Schmidt from Zwickau, Saxony (for a historical review see Schüttmann 1988).

Later epidemiological studies on miners exposed to very high radon levels (between 7.6 Working Level Months (WLM) in Radium Hill and 580 WLM in Colorado) in various countries, including China, France, Sweden, Canada, Czechoslovakia, and the U.S., led to the "meta-analysis" of such studies (Lubin *et al.* 1994), which was the basis of the semiofficial risk assumptions in the BEIR reports (BEIR

VI 1999). It assumed radon to be the key reason for miner lung cancer despite some remarkable inconsistencies. For example, the excess relative risk (ERR) per WLM, which should have been rather uniform assuming radon as the main cause and a linear dose-response relationship, varied between 0.0016 in China and 0.051 in Port Radium, or by a factor of almost 30.

Nevertheless, data like those obtained in Bohemia, became the basis of further regulatory activities. Other investigations project a different image. For example, the "forgotten doses" among miners may have resulted in an underestimate of the actual dose (and corresponding overestimate of residential doses) by a factor of about three (Duport 2002), and other estimates of the radon to miner's lung cancer (Conrady, contribution unpublished) amount to a contribution of only around 7% of the radon to the total of additional miner lung cancers.

Very high radon concentrations have also been observed in non-uranium-mining underground activities, for example, mineral and coal mines (*e.g.*, in Poland), guides in natural caves open to visitors in various countries. There are high overground radon professional exposures, for example, in public water supply facilities. In the "clean water hall" of a plant in Hof, Bavaria, perhaps the world record of about 750,000 Bq/m^3 in air has been measured repeatedly (*e.g.*, Becker *et al.* 1992). Even values above 1 MBq/m^3 occasionally occurred. The situation is similar in the water storage facilities of hundreds of other German not only in Bavaria, using water from formations with a high natural uranium content. For example, in Eastern Bavaria the annual radon exposure of 11% of the water supply employees (assuming current ICRP values) presently exceeds the legal 20 mSv/y limit for radiation workers (Mück 2002).

According to BEIR VI, smoking increases the lung cancer risk by a factor of 10 to 20 and radon by 0.2 to 0.3, which implies a smoking risk about 50 times higher than the radon risk. Miners are known to have smoked more than the average population. In the Schneeberg area, the miner's smoking rate in the early uranium-mining period, also called the "wild years" (1946 to 1954), has been estimated to have been above 90%. Moreover, uranium miners (many of them forced laborers) received, in compensation for extremely unpleasant and dangerous work, large rations of cigarettes and cheap liquor for the normal population smoking was in the starvation situation of the Soviet occupation zone of Germany in the post-WWII years an unaffordable luxury but almost all miners were heavy smokers inside as well as outside the mines. In nearby former Czechoslovakia, the situation was similar.

The correction of epidemiological data for the by far dominating factor of smoking is complicated by the fact that smokers notoriously underestimate (even more than alcohol and drug addicts) their actual cigarette consumption, in particular after a lung disease has been diagnosed. Thus, "retrospective smoking dosimetry" with self-estimates covering several decades, or based on unreliable memories of relatives, are subject to substantial uncertainties, which may explain in part the wide fluctuations between 0.2 and 5.1% per WLM in radon risk estimates (see, for example, Suidicani and Hein 1997; Conrady *et al.* 1999). Smoking itself produces, as was first pointed out in Germany (Rajewski and Stahlhofen 1966), an alpha radiation exposure to the bronchial tract due to the polonium-210 content in tobacco, but this has not to be considered a health hazard compared with the other smoking effects (Cross 1984).

Among other complicating factors in the correct assessment of miner radon risks are

1. Large uncertainties in the retrospective estimates of radon exposures in mines at times before individual radon dosimetry, with concentrations known to be subject to high fluctuations with time and location, depending on ventilation and other factors. There is, however, sufficient evidence that the concentrations frequently exceeded 2 MBq/m^3 (or about 2 Sv/y according to ICRP). Other estimates (Kreuzer *et al.* 2002) assume in the East German uranium mining area, for example, in 1955, median exposures of 120 (upper 75% quartil 200) WLM/y. According to a recent study involving 48,000 former uranium miners, about 500 cases of lung cancer matched with 1000 controls, with only 9 never-smokers among the miners and 165 among the controls, up to at least 800 WLM no radon effects have been found (Brüske and Hohlfeld, to be published).

2. Confounding effects such as diesel exhaust fumes, nitrous gases from blasting, dust effects due to dry drilling, *etc.* It also became known that "hidden doses" due to external gamma radiation, inhaled radioactive ore dusts, very different equilibrium factors, *etc.*, contribute as much or more to the miner exposure and may increase the actual doses by a factor of up to three. Miners may also have been exposed to other carcinogens during other parts of their professional life and/or lived in high radon houses (Duport 2002).

3. Basic problems in the dose calculations, for example, because of uncertainties in the lung models (there is a difference in the effective dose estimates for radon between two consecutive ICRP reports by a factor of about three), and in the radiobiological effect (the "official" name for it continues to change) for alpha particles, assumed by ICRP to be 20. To quote from a recent EU publication: "An analysis of lung cancer deaths in uranium miners leads to an RBE for alpha particles of 5 to 10, depending on which cells are regarded as targets" (Edwards 2001). Careful animal inhalation experiments in the U.K. with differently spiked aerosols demonstrated an RBE for inhaled nuclides of 2, which is a factor of 10 less than the current ICRP recommendation of 20 (Kellington *et al.* 1997).

4. Obviously, the role of the exposure rate has been vastly underestimated. It has been shown in animal experiments at high radon levels that the time distribution of the dose is equally or even more important than the WLM dose (Monchaux

and Morlier 2000; Monchaux 2001). They found that the lung cancer rate in rats exposed at low rates was actually lower than in the controls. These experiments continue in cooperation with British and U.S. scientists.

In Germany, there are currently two studies about radon effects on miners in progress. One case-control study for the Federal Institute of Worker Protection and Medicine has been primarily completed, with more detailed follow-up studies perhaps to follow. According to such studies, only about 7% of the lung cancers among uranium miners may be related to radon (Conrady *et al.* 2000). To quote from the abstract: "Radiation exposure did not determine predominantly the lung cancer risk. In its relative significance, smoking is first, followed by quartz dust at second position. At third follows arsenic, and at fourth position radon with its daughters."

The other study by the Institute of Radiation Hygiene of the Federal Radiation Protection Office (Kreuzer *et al.* 2002) is still in progress, with a sample size of about 60,000 miners (out of a database of 130,000), and a similar number of controls. The miners have been classified into three periods of the Soviet uranium mining (also known as Wismut AG):

1. "the wild years" 1946 to 1954 (Becker 1992) with very high dust and radon exposures and essentially no protective measures. During this period, radon levels have been estimated to exceed frequently 2 million Bq/m^3 in the mines;
2. a transition period with better ventilation, introduction of dust-reducing wet drilling, *etc.*; and
3. introduction of simple radon measurements and approaches to international standards after 1971, until the end of the mining activities in 1989.

The evaluation of the data, which have been mostly kept secret until the collapse of East Germany, will probably be completed in 2003. Special efforts are being made to consider the main confounders smoking and arsenic.

There seems to be no doubt that radon contributes to some degree to the increased lung cancer rate among uranium miners, but several questions remain open in the common approach to extrapolate miner data over orders of magnitudes down to the completely different residential radon situation, in particular: how are the epidemiological miner data; how important is the role of radon compared to the confounders; and what are the consequences of the completely different working conditions of the miners? Among the many differences between miners and home residents, as already pointed out years ago (*e.g.*, Schüttmann 1997), many factors have to be considered, such as:

1. the very different dose levels and dose rates;

2. the underestimation of the miner exposures, *e.g.*, due to radioactive dust, external gamma exposures, and sometimes unusually high additional residential exposures (*e.g.*, Duport 2002);
3. neglecting the above-mentioned confounders, and the so far little known synergistic interactions;
4. differences in the lung characteristics between miners and residential populations depending on age and sex, the structure of the bronchial system, localization of the target cells, and condition of the mucocilear clearance;
5. differences in the breathing function (*e.g.*, frequency, volume, ratio mouth to nose breathing); and
6. breathing air characteristics (aerosol properties and size distribution, radon to daughters equilibrium, contribution of unattached daughter products, *etc.*).

Another factor that has widely been neglected in considering miner lung diseases is the occurrence of lung fibrosis, which should not be confused with cancer, emphysema, and other lung problems. This complex topic has been well described (Arndt 1994) with numerous references to human and animal data. They show the synergistic effect between the inhalation of uranium containing and other mineral dusts as well as other dangerous gases and aerosols and radon exposures. There are various parameters besides radon exposures, including increased uranium and thorium excretion in urine, and autoradiographic or body-counter determination of long-lived radon daughter products such as polonium-210 in the skeleton, which could lead to additional information beyond the limited dosimetric relevance of radon lung exposures.

Also to be considered is the actual hit probability for stem cell nuclei in the bronchial epithelia for alpha exposures. Obviously, even within the dose limit for miners, the probability of a nucleus being hit is extremely small, and most of the cells experience no hit during the human lifetime. More information on the radiation response of the lung can be found in the proceedings of a symposium in Germany (Herrmann *et al.* 1994). Further interesting evidence regarding radiation-induced carcinoma in the human lung have been provided, for external X and gamma exposures with a threshold of ca. 2 Gy (Rossi and Zaider 1997), for inhaled plutonium oxide (Tokarskaya *et al.* 1997) of 0.8 Gy (16 Sv according to ICRP), and for radium incorporation by dial painters of 10 Gy, corresponding to 200 Sv (!) according to ICRP (Rowland 1995).

It is obvious that, for the reasons outlined above, a linear transfer from the conditions in mines over orders of magnitude down to normal residential levels is not feasible. Concerning miner exposures, the informal consensus among the experts currently is that there is no lung cancer hazard below 500 to 1000 WLM. However, the important question of a possible extrapolation from miner data to indoor radon effects is still a subject of studies and controversies in Central Europe, as some epidemiologists continue to claim consistency between miner and indoor data.

INDOOR RADON AND LUNG CANCER

The first measurements of increased indoor radon levels were carried out in Joachimsthal at the German/Czech border by H. W. Schmidt from Giessen in 1907, followed by many other measurements in other locations in and around Germany. In 1948 measurements of the radon concentration in the Bad Schlema outdoor atmosphere (about 365 Bq/m^3), houses (3,200 Bq/m^3), and soil air (150,000 Bq/m^3), which had been obtained since 1944, were published together with a map showing the radon distribution in this city (Krebs and Lamper 1948). In 1956, in Sweden very high values were measured in buildings for which alum shale with a high natural uranium content had been used as a construction material (Hultquist 1956). In the U.S., health officials found out in 1966 that in and around Grand Junction, Colorado, around 1950 to 1965 large amounts of sand-like tailings from uranium extraction had been used for the construction of homes, schools, and other public buildings, leading to elevated indoor radon levels. The practice was stopped and an extensive remediation program initiated.

This triggered a surge of scientific and public interest in the residential radon issue, spilling over from the U.S. and Sweden to other countries, as described in detail in "Element of Risk: The Politics of Radon" (Cole 1993). For example, in the New York Times, in the peak year of 1987, articles about radon appeared, and one specialist, J. Harley, accumulated a total of 2500 articles on this subject (by now, this number probably exceeds 5000, making it impossible to cover them comprehensively in a review like this). V. J. Houk, Asst. Surgeon General of the U.S. Public Health Services, declared in 1988 that "radon-induced lung cancer is one of today's most serious public health issues", and a commercial Advertising Council, Inc., was hired by EPA to promote, at great expenses to the taxpayer, the "EPA Radon Awareness Program". Such EPA efforts still continue in the U.S., as well as in other countries; however, with only limited success (Marcinowski 2002).

E. Letourneau, then Director of the Canadian Radiation Protection Bureau, statedthat in 1991 seven countries had adopted or proposed indoor radon standards, namely, Canada, Finland, Germany, Norway, Sweden, the U.K., and the U.S., and noted that "radon is a disease which spreads from the north.... The geographic configuration is related to the luxury of worrying about risk that most countries do not feel is worth to worry about." He also remarked that "radon is an artificial disease, created by the multiplication of a very small risk with large populations, in order to create frightening numbers" (Letourneau 1987).

Many similar statements could be added. SCIENCE wrote in an Editorial (Abelson 1991), that "EPA continues to assert that radon is a major cause of lung cancer fostering a radon program that could entail huge financial and emotional losses while yielding negligible benefits to public health." W.G. Mills, then president of the Health Physics Society, wrote to the author in 1993: "Fortunately, the general public is not buying EPA's activist efforts, and only the U.S. Congress and those in the radon business keep the "hazard" alive". This statement is still true, in particular if personal expenses are involved. In many high-radon areas in Western Europe despite expensive radon-warning campaigns, an increasing number of people refuse even free-of-charge governmental radon measurements as an unwanted and unnecessary intrusion into the privacy of their homes.

Already about a decade ago the U.S. Health Physics Society criticized the EPA assumption that indoor radon causes about 20,000 lung cancer deaths annually in the U.S., promoting remediation measures that would cost the U.S. citizens $8 to 20 billion, with a 1988 Indoor Radon Abatement Act requiring the long-term national goal that all buildings "should be as free of radon as the ambient air outside the buildings". Some scientists pointed out that, if technically feasible at all, the cost could be $1 trillion (unless, of course, all U.S. citizens would decide to live in tents, tree houses, or on rafts). Such intensely promoted programs in the U.S. also influenced the recommendations of international organizations, and expensive radon survey and reduction policies in Europe (Becker 2001).

According to the latest, yet unpublished reports, the currently recommended EU limits of 200 Bq/m^3 for new and 400 Bq/m^3 for new houses, are substantially exceeded in many countries. For example, in Sweden, about 150,000 dwellings (4% of the total) exceed the 400 Bq/m^3 limit, in Southern Tyrol/Italy 10%, and in the Czech Republic 2 to 3% of all buildings (in some areas more than 20%). Switzerland established legal limits of 400 for new and 1000 Bq/m^3 for old buildings. This is close to recent suggestions of ICRP, namely, 500 Bq/m^3 at home and 1000 at the working place, but in conflict with the regulations in the EU.

It has been estimated in various official and semiofficial reports and recommendations that residential radon probably is, far behind smoking, the second most important cause of lung cancer. There is, however, increasing evidence that this may not be true because most of the so-called "radon effects" are actually directly related to smoking. Even passive smoking and the inhalation of polluted air in industrialized areas, soot from diesel engines (big cities, heavy construction vehicles, truck drivers, *etc.*) create a higher risk, also regarding other types of cancer.

In essentially all industrialized countries, in particular in Western Europe, more or less comprehensive residential radon screening programs have been carried out by governmental agencies. Hundreds of publications are by now available on this subject, involving even such unlikely locations as kindergartens in Slovenia, hospitals in England, Greek Caves and wine cellars in Germany. This avalanche of data is closely related to the fact that radon in buildings is relatively easy (but not always accurately) measurable by the method of alpha particle track etching in organic polymers. Many areas in various countries have, by expensive screening programs, been identified with high and low concentrations. The average radon levels in Finland far exceed those in the Netherlands, and there are areas such as Cornwall in the U.K., or (former) uranium mining areas in Germany and Czechia well above the country average.

In earlier years, activated carbon detectors and electronic nonintegrating devices have been used, but turned out to be not sufficiently accurate due to the well-known very substantial fluctuations orders of magnitude, depending on the daily ventilation cycles, annual seasons, exact location in a house, wind direction, *etc.* (see, for example, Miles 2001). Therefore, long-term radon integrating detectors, based on the method developed by the author decades ago (Becker *et al.* 1968; Becker 1969), are, usually for a 3 to 12 month period, most widely used in differently designed devices with different polymers and evaluating techniques.

In Europe, small chambers containing the polymer that have been refined by the NRPB in the U. K., the SSI in Sweden, the Karlsruhe Research Center in Germany, and by several private companies in Sweden, Germany, and Hungary, are particularly popular. They undergo frequent quality control tests under carefully controlled laboratory conditions. However, they do not reflect the actual *in situ* precision. Nevertheless, results are frequently reported as three- to four-digit numbers, thus suggesting high accuracy when even the first digit may be rather questionable. Current costs for a reasonably reliable 3-month test are around $10 to 20 U.S., and for the currently popular tests in schools and kindergartens, about $100 U.S. are assumed.

More recently, electronic integrating devices as well as "retrospective" methods, *e.g.*, based on the measurements of alpha tracks in CR 39 of eye glasses, or of lead-210 with polymers on the surface of glass of known age (such as the inside of house window and picture glasses) are also being used. The results are reliable within about 30% under controlled conditions, but may vary more in practical situations involving wider fluctuations in the equilibrium between radon and daughters, and changes made in the house. Long-term residential radon exposure estimates remain subject to substantial errors.

As a typical result of one of the many comprehensive radon surveys, a map of Germany in Figure 1 shows the radon activity in ground air with a high resolution. Obviously, it varies between as much as over 500,000 Bq/m^3 in some areas of Saxony and Bavaria, and less than 10,000 Bq/m^3 in other parts (Kemski *et al.* 1999). Those data may to a large degree (but not completely) be correlated to the radon concentrations in ground-floor living rooms (Figure 2).

During the last decade, a well-known worldwide discussion about the lung cancer risk due to radon in homes as well as in other overground facilities such as working places in water supply facilities, schools, and other public buildings took place. Only a few relevant points can be mentioned within the limited scope of this review. An ongoing argument concerns the relative merits of different epidemiological meth-

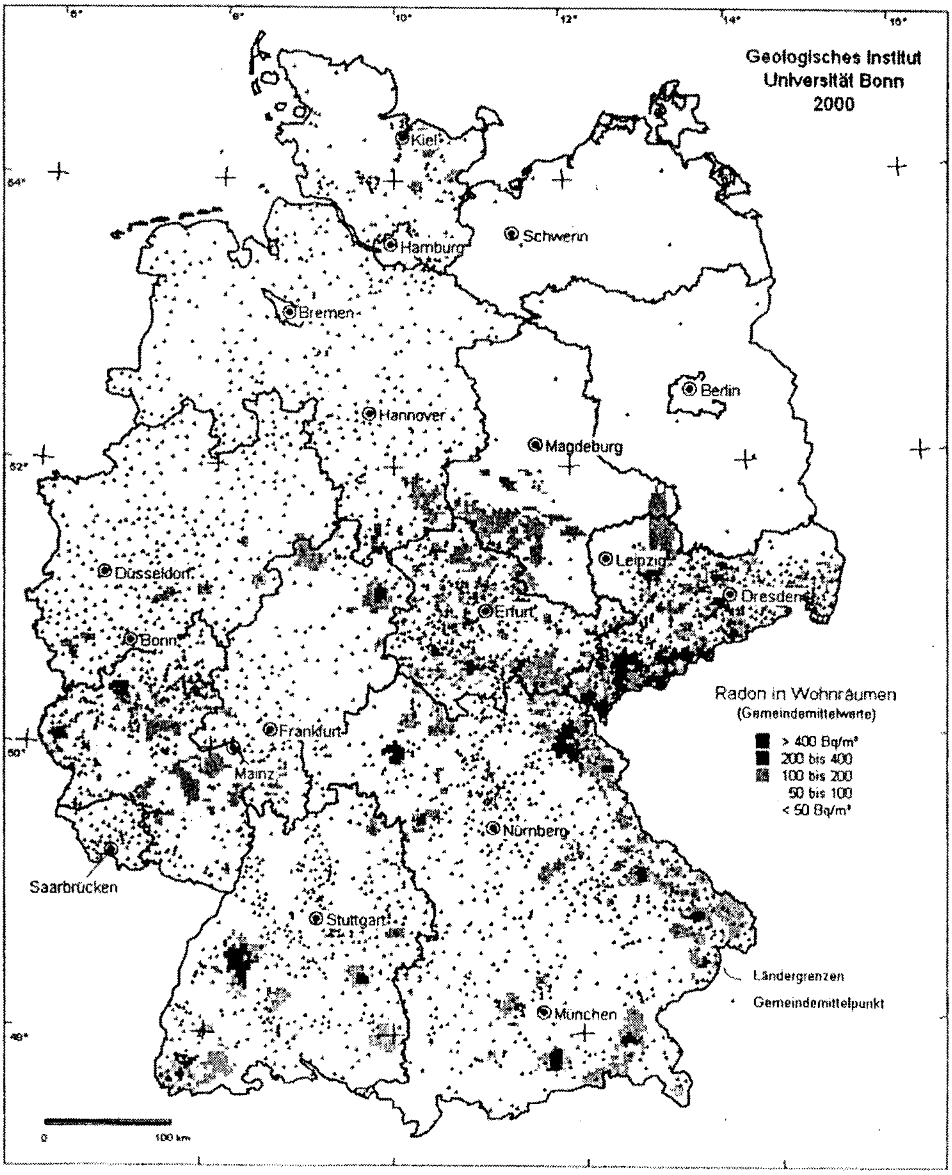

Figure 2. **Average of the radon in the ground floor of living rooms of communities in Germany (black above 400 Bq/m³, white less than 100 Bq/m³) (Siehl 2000).**

ods to assess residential lung cancer incidence, in particular the "ecological", the case-control, and the cohort studies, which all have advantages (such as large numbers of cases) as well as disadvantages (time, costs, role of confounders, statistical power).

In a recent review, it is concluded that current controversies about radiation risk estimates based on epidemiological studies are due to diverging data interpretation, with over- and underestimates of the significance (power) of the studies frequently leaving the scientific basis, with a detection limit for relative additional risks around 20% (Breckow 2002). A comparative analysis of 18 case-control studies in Russia (Yarmoshenko 2002), with "weighting factors" given to their reliability, resulted in a U-shaped response curve, and there is evidence from studies in Germany that moderately increased radon levels also reduce other types of cancer, including leukemia.

The well-known and much-discussed comprehensive studies by B. Cohen in the U.S., which have been confirmed by several other studies there, have also been confirmed in Central Europe. According to the ICRP estimates, lung cancer among the (largely never-smoking) females in the former Soviet uranium mining areas in East Germany should have been much higher than the actual cancer register shows. In one of the highest radon areas (district of Gera), the observed values were among the lowest the whole country. Comprehensive measurements in the high radon areas, combined with remediation measures, amounted to total costs to the German government of about $2000 million U.S. (Becker 1996). For example, in the old mining town of Schneeberg near Schlema, the average radon concentration in homes was 290 Bq/m^3, or twice the limit of the U.S. EPA; 13% exceeded 1000 and over 1% 15,000 Bq/m^3 (with a maximum of 115,000 Bq/m^3). Those were essentially the same houses in which no lung cancers had been detected in careful studies decades earlier (Saupe 1928).

In fact, the expected: on the basis of the country average, not the ICRP assumptions, cancer cases among the females in the high radon areas between 1983 and 1987 are lower and not higher than the country average (Table 1 and 1c). Obviously, the residential lung cancer rate is *inversely* proportional to the radon concentrations. With increasing radon values, the number of observed cases actually appears to decrease and not increase, as predicted by ICRP, with increasing radon levels (Table 1c). A study involving the lung cancer registry of East Germany between 1960 and 1988 (Conrady *et al.* 1996) has been summarized by the authors as follows: "No relation between residential radon exposure and the cancer risk in general, or lung cancer risk in particular, could be detected in the ecological analysis of regions, counties, and communities."

Similar results have also been reported from other countries such as Austria (Friedmann 2002). In different states with annual average population exposures between 47 and 136 Bq/m^3, according to ICRP 65 there should have been annual lung cancer casualities between 5.7 and 16.5 per 100,000 (a factor of about 3), but it was in fact lower in the highest than in the lowest radon regions. Looking just at the female cases, in one region (Oberösterreich) there should have been 60% more "ICRP estimated radon cases" than were totally observed.

Table 1. **(a) Observed cases of female lung cancer in high residential radon areas in Saxony compared to expected values on the basis of the East German average (data from Arndt 1992). (b) Observed and expected cases among nonsmoking females in high and low residential radon areas in Saxony, all age categories 1961–1989 (data from Conrady *et al.* 1996). (c) Percentage of observed cases according to the population average, and to the ICRP model (data from Schüttmann and Becker, unpublished).**

Table 1a

County	*Observed*	*Expected*
Aue (including Schneeberg)	37	45
Annaberg-Buchholz	11	31
Schwarzenberg	10	20
Klingenthal	9	15
Total	67	111

Table 1b

Indoor radon level (Bqm^{-3})	*Observed cases*	*Expected cases (population average)*	*Expected cases (ICRP model)*
< 100	1251	1202	1477
100 - < 250	374	400	492
150 - < 500	152	157	255
> 500	378	443	975
Total	2155	2202	3199

Table 1c

Radon range (Bq/m^3)	*Percentage of population average*	*Percentage of ICRP model*
< 100	104	85
100 to < 250	94	76
250 to < 500	97	60
> 500	85	39
Average	98	67

It is believed among epidemiologists that case-control studies are less subject to confounding factors and thus more reliable. The most widely quoted "meta-analysis" of eight such studies in several countries in Europe, the U.S., and China show about 30 data points with very large vertical and no horizontal error bars (Figure 3), with only one or two slightly above the zero line. Even for the 450 Bq/m^3 Swedish data point, the same group has recently shown that, with a different evaluation method, this "positive" result can be transformed into a "negative" one (Legarde *et al.* 1997).

A recent study from the Swedish Radiation Protection Authority (formerly SSI) (Mjönes and Folk 2002) finds that the lifetime lung cancer risk for smokers at 1000 Bq/m^3 (seven times the EPA limit) is 25%, but less than 10% (with a background level of about 3%) for never-smokers. The authors conclude that "most of the radon-related lung cancers, perhaps as much as 90%, occur among smokers". This appears to confirm the observation of Schüttmann (1999) that residential lung cancer was essentially nonexistent before large-scale cigarette smoking commenced in Central Europe during the second half of the 19th century.

In a detailed review summarizing the results of 12 different studies) the residential radon risk among non-smokers (Neuberger and Gesell 2002) came, even without considering the above new data, to a very similar conclusion, namely, that "most of the studies did not find any significant association between radon and lung cancer in non-smokers... Based on the most recent findings, there is some evidence that radon may contribute to lung cancer risk in current smokers in high residential radon environments". Obviously, the evidence converges into a simple conclusion: Better not to smoke if one happens to live in a house at more than 1000 Bq/m^3.

The intense efforts in the accumulation of more data in case-control studies continue (Kreienbrock 2002). So far, a total of 17 studies have been completed, and 10 more are under evaluation. Some of them seem to indicate a slight increase in the odds ratio with increasing radon levels (Figure 4), in reasonable agreement with ICRP and BEIR VI estimates of the lung cancer risk doubling with an increase of 1000 Bq/m^3, but others show quite different results. However, even the authors of

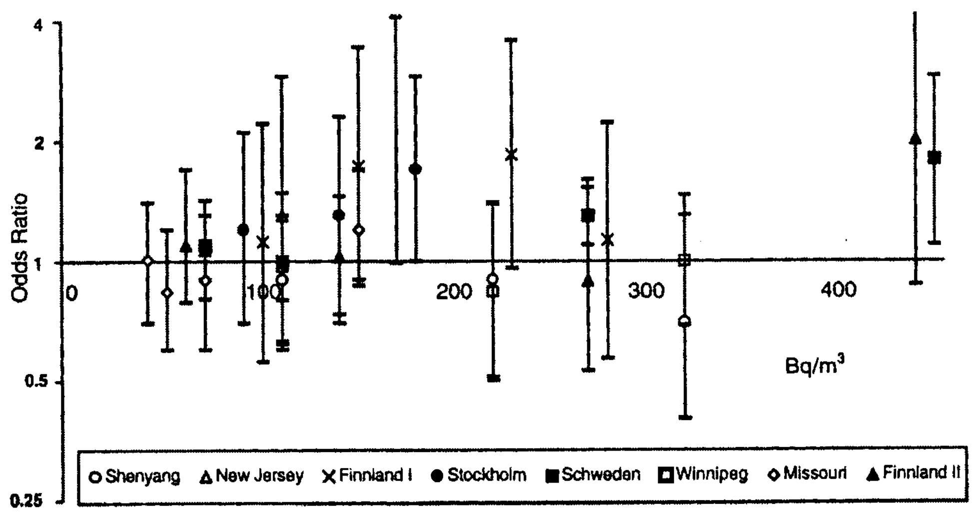

Figure 3. **Relative lung cancer risk as a function of residential radon according to a meta-analysis of case-control studies in various countries (modification of Figure 1, p. 52, Lubin and Boice 1997).**

this study state in another publication (Kreuzer *et al.* 1998) on lung cancer in young adults that "radon was not considered a risk factor, because it is a weak risk factor. To detect a risk, big sample sizes and a high prevalence of radon are needed."

An EU-supported international study (Conrady *et al.* 1999) clearly shows, contrary to the above study and in clear disagreement with the ICRP/BEIR VI LNT model, among nonsmoking women a threshold for residential lung cancer around 1000 Bq/m³ (Figure 5). These and further results (Conrady *et al.* 2001) are in good agreement with the data for nonsmoking women in the Chinese Sheniang study, indicating an initial decrease with increasing radon concentration, followed by an increase above approximately 1000 Bq/m³ (Figure 6).

The most likely explanation of such different results in an area of high statistical uncertainties appears to be the underestimated effect of the dominating role of cigarette smoking in human lung carcinogenesis. It is not only of historical interest that, at a time when this type of cancer was already well known in Saxony due to the miner diseases, lung cancer was extremely rare in the population, with essentially every single case reported in a scientific publication or an M.D. thesis. Approxi-

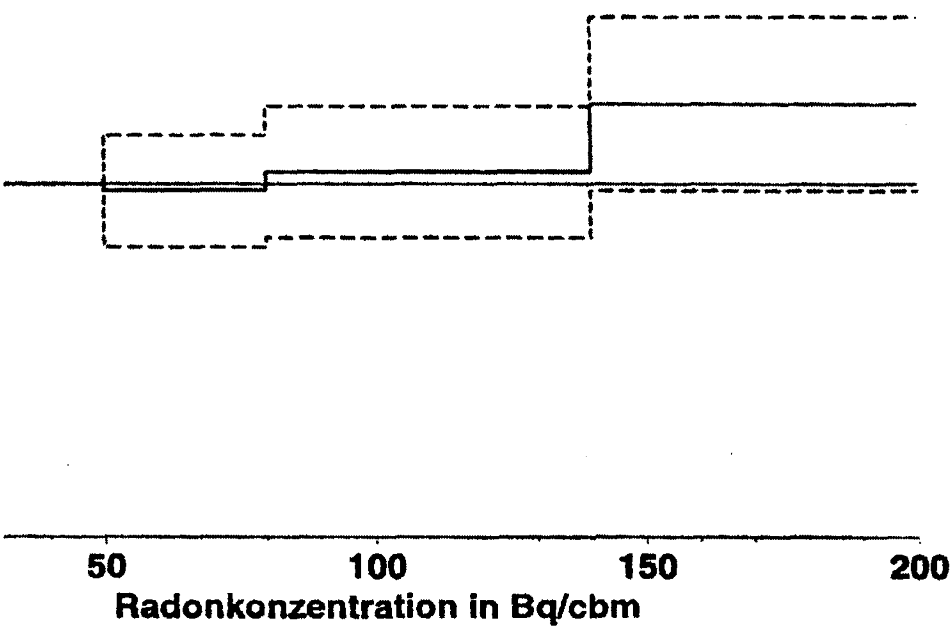

Figure 4. Lung cancer risk as a function of residential radon levels (Bq/m³): estimated odds ratio and 95 % confidence intervals according to the "East German Radon Study". (Reproduced from Wichmann *et al.* 1999, used with permission of Ecomed and the editor.)

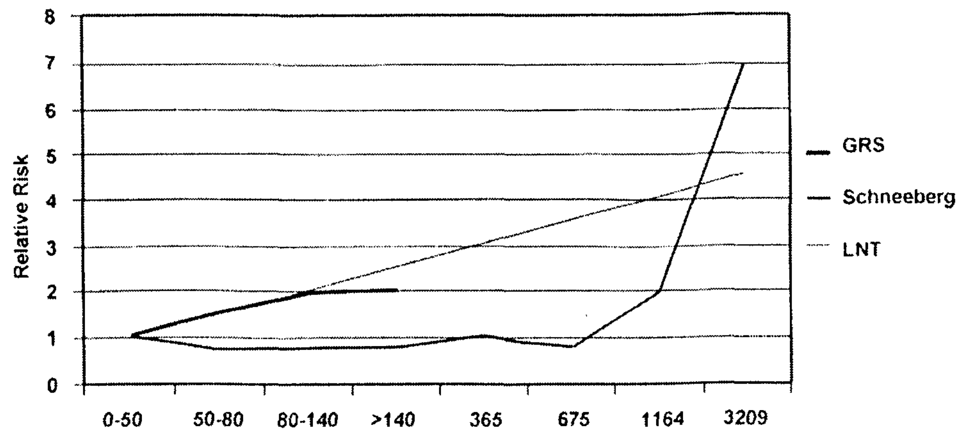

Figure 5. The relative lung cancer risk as a function of residential radon levels (Bq/m³) according to ICRP (LNT hypothesis — straight line), the "German radon study" by Wichmann *et al.* (1998, 1999), and the "Schneeberg study" (lower line) by Conrady *et al.* (1999).

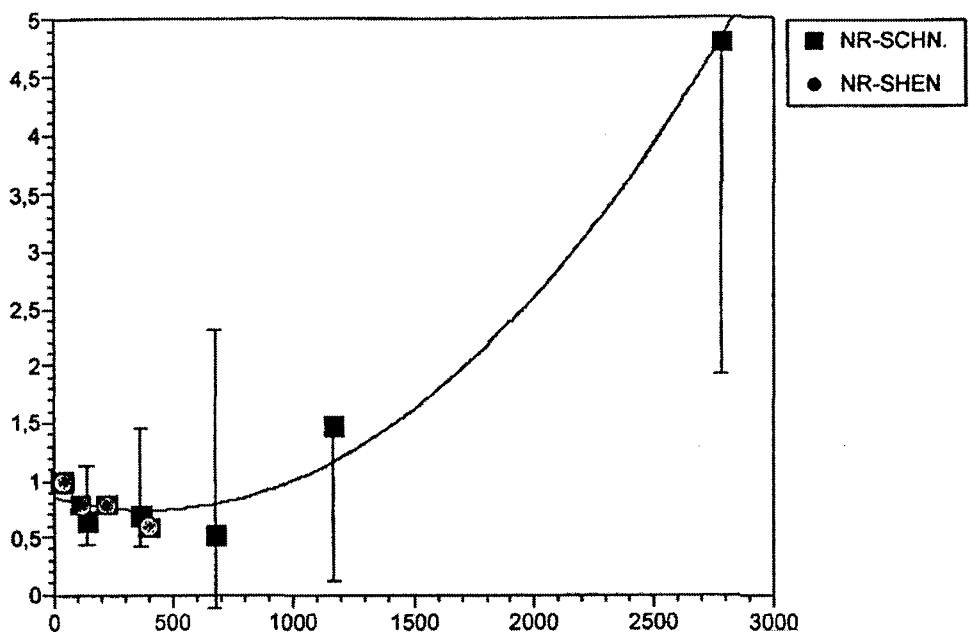

Figure 6. Odds ratio for lung cancer as a function of residential radon concentration (Bq/m³) among nonsmoking females in the Schneeberg Study, compared to the also nonsmoking females in the Sheniang study. (Reproduced from Conrady *et al.* 2003, Proceed. 3. Biophysikal. Arbeitstagung Schlema 2001, registered with the German Library in Frankfurt, ISSN 1610-5079, used with permission of RADIZ.)

mately 20,000 autopsies have been performed since 1852 in Saxony's largest hospital in the capital of Dresden. The lung cancer rate rose from only 0.06% between 1852 and 1876 to 0.21% from 1877 to 1884. Between 1885 and 1894, it increased to 0.43%, and currently is almost 10 times higher. It is probably no coincidence that Germany's first cigarette factory had started production in Dresden in 1862 (Schüttmann 1999).

The overwhelming effect of the confounder smoking on radon epidemiology has been summarized recently in a paper *"The true size of lung cancer risk from indoor radon: Hidden behind a smoke screen?"* (Conrady *et al.* 2003; see also Becker and Field 2001; Becker and Schüttmann 1998; and Becker and Wichmann 2002). It is not likely that further meta-analysis work, including new case-control studies, as they are currently in progress in Canada and the U.K., will be able to overcome this problem. The main reason is the retrospective assessment of smoking habits, in particular after lung cancer has been found.

Even more than in alcohol and drug abuse, it has been shown that smokers — especially after diagnosis of a lung disease — vastly "underestimate" their past and present smoking behaviour, thus making it de facto impossible to establish radon effects by epidemiology in populations with a high percentage of smokers. It has been shown that an underestimate of only one cigarette/day could falsify some of the case-control radon studies on which "official" risk estimates are currently based. Because of its great fundamental and economic importance, the discussion about the relative merits of different epidemiological studies continues (see, for example, Mossmann 1998; Breckow 2002).

THERAPEUTIC USES OF RADON

Sources now known to have a high radon content have been used for therapeutic bathes for many centuries, *e.g.*, in Ischia, Italy, over 2000 years ago, in Misasa, Japan, for 800 years, and in several places in medieval Europe. After the discovery of radon, its known balneological (bathing in water with high radon content) or speliotherapeutic (inhalation of high-radon air — both summarized as balneology here) applications started 1904 in Bad Kreuznach, Germany, and Bad Gastein, Austria. The radon concentration in the waters varies widely. The strongest water source ever was probably the "Bismarckquelle" in Schlema with about 40,000 Bq/l, and currently is the "Wettinerquelle" in Bad Brambach with 26,000 Bq/l (for Misasa, Japan, a value of 160,000 Bq/l, has been mentioned).

A typical inhalation source (Bad Gastein "Heilstollen") in which patients spend six times half an hour during a 3-week treatment period (at a total cost of about $500, usually paid by the public health service) has approximately 40,000 Bq/m^3 in air. The radon is delivered to the patients primarily by inhalation for a prescribed time in former mine shafts, or by bathing in radon water (with some of the radon being lost between source and application). Obviously, modern radon balneology, as it developed during the last century primarily in Europe, has very little or nothing to do with the popular fashion between approximately 1920 and 1940, also mainly in Europe, of adding radium to many "healthy" food items, including drinking water, crackers, chocolate (there is, for example, a German patent of 1934 for adding radium bromide solution during the chocolate manufacturing process), and even bed blankets in the U.K.

An interesting compilation of the earlier medical experience with low-dose radium and radon ("emanation") treatments has been provided by Czech authors around 1930 (Radium..., ca.1930). This booklet contains quotations from medical journals as well as testimonies by individual physicians about positive health effects due to external and internal radium/radon therapy for a multitude of diseases. One of the authors of this booklet, P. Parchomenko, states that "it was found out that the weak rays bring about characteristic biological effects, which as we know now are one of the most important benefactors of nature... The effect of weak irradiation differs greatly from that of the high activity of strong radon preparations."

There have also been many publications about modern radon balneology in European journals (*e.g.*, Falkenbach 1996), but only very few have been published in English (*e.g.*, Franke *et al.* 2000). Today, therapeutic radon centers (spas with medical supervision of the treatment) are located (for further reviews see Pratzel and Deetjen 1997; Deetjen and Falkenbach 1999; Jöckel 2001) in many countries including

- Germany (Bad Brambach, Bad Kreuznach, Bad Münster am Stein-Ebernburg, Schlema, Sibyllenbad, Bad Steben)
- Austria (Bad Gastein, Bad Hofgastein, Bad Zell)
- Chechia (Jachimov/formerly Joachimsthal, Karlsbad)
- France (Plombieres)
- Italy (Ischia, Meran)
- Ukraine (Chmelnk, Deneschi)
- Russia (Pjatigorsk)
- Japan (Misasa).

There are many other places that people visit for radon treatment, *e.g.*, about 2000 people annually coming to several old uranium mines in a small town such as the "Free Enterprise Health Mine" in Boulder, Colorado, U.S. (Singer 2001), where even cats and dogs have been treated for age-related ailments, and some patients returned for decades.

An interesting topic is radon therapy in the former Soviet Union, where such treatments for a very wide spectrum of diseases was not restricted to natural radon sources. Many hospitals produced radon from radium solutions. There has been some cooperation with German therapists (Andrejew 1992). A summary of the Russian experiences is available in German (Legler 1993). Russian research on radon balneology can be traced back to 1902, with a special role played by the Governmental Balneological Institute in Pjatigorsk founded in 1920. There are thousands of publications on radon therapy in the Russian literature, also dealing with the dose-effect relationship, because the "artificial" radon dose could easily be quantified and modified (K. Becker 2003, in press).

For example, in experiments with 148 patients, and radon concentrations between 1500 and 15,000 Bq/l in the 12 radon water bathes of 10 to 15 min each, very good or good improvement in cervical pain syndrome have been observed among 55% of the patients (control group 25%), but with side effects ("bathing reactions") above 7500 Bq/l. Also with other painful diseases, optimal results have been obtained in the 1500 to 4500 Bq/l range (Strelkova *et al.* 1980). Various other Russian authors confirmed this and similar observations. The techniques included injections and various local applications, and the indications ranged from heart and neurological, gynecological, and skin diseases to gastritis and ulcers. Contraindications were acute infections, psychic problems, pregnancy, malignant tumors, and tuberculosis.

Most of these indications are not considered for radon therapy nowadays in Western Europe. Currently, about 75,000 patients are treated annually in German and Austrian radon spas, mostly during a medically supervised 3-week period, for which the public health system pays the costs (normally not only involving the medical treatment, but also travel and accommodation). There are, however, also many patients who take the treatments on their own expense, often repeatedly because of the observed positive results.

Such effects have been categorized frequently as a variety of "traditional" medicine, similar to homeopathy, some herbal treatments, oriental practices, including acupuncture and so on, with the benefits likely to be only or largely based on psychological placebo effects without scientific basis. This situation changed substantially in recent years due to:

1. several randomized chemical double-blind studies (known as the "gold standard of demonstrating medical effects"); and
2. accumulating experimental evidence that even the low total doses of radon treatments (in the order of 1 to 5 mGy) have scientifically demonstrable positive effects on the cellular and organism level.

The status has been summarized in two booklets (Schüttmann 1994, 1996) published by the non-profit organization RADIZ (Radon Documentation and Information Center), Curiestr. 3, D-08301 Schlema, Germany. From this organization, which was founded in 1992 by K. Aurand, also further radon-related booklets and conference reports (in German) are available.

A problem in the quantification of the pain-reducing effects is the fact that there exists apparently no method yet for objectively measuring chronic pain. There are, however, well-established methods such as the application of a defined pressure (in kg/cm^2) to pain-sensitive "tender points" (Figure 7), to which the patients respond on a 0 to 10 scale between no and intolerable pain, or by measuring the backbone flexibility in Morbus Bechterew patients from the distance between the back of the head and a wall on which the patient is leaning. With a sufficient number of patients, the reproducibility of such tests is rather good.

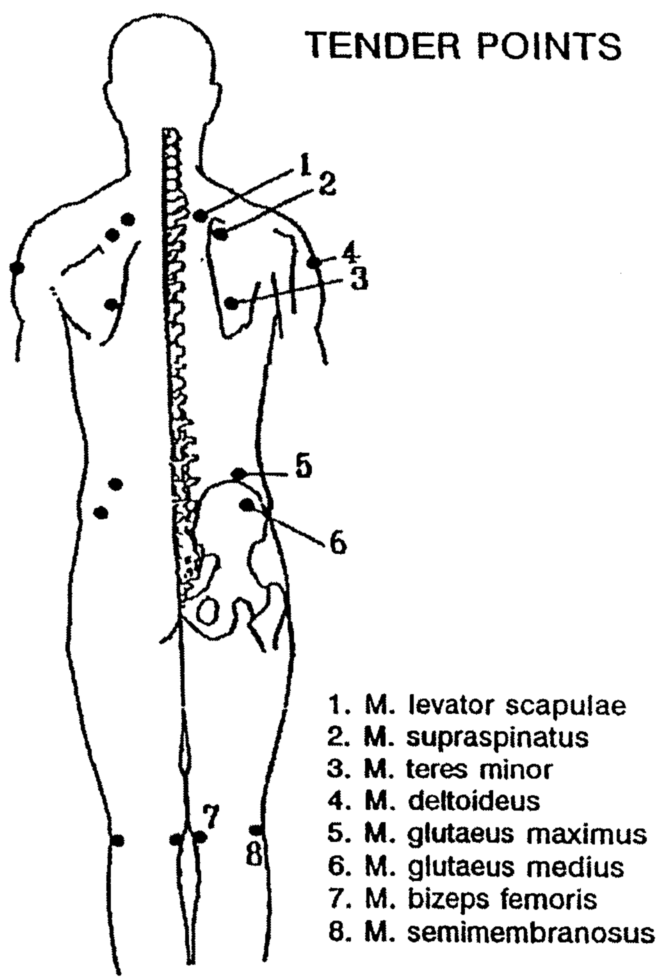

Figure 7. **Tender points used for testing the pressure pain sensitivity of patients with rheumatic/arthritic problems.** (Baumann 2003, Proceed. 3. Biophysikal. Arbeitstagung Schlema 2001, registered with the German Library in Frankfurt, ISSN 1610-5079, used with permission of RADIZ.)

With a bar code key, unknown to the patient and the medical staff, either radon-containing or radon-free water of the same temperature, carbon dioxide content, *etc.*, is applied. While up to the end of the 3-week treatment the improvement, as expressed in the pain threshold at pressure points, improves in both groups, the positive long-term effect further increases during the 4-month investigation period in the radon group, but begins to disappear in the non-radon group (Figure 8). There are, of course, many different methods to express such and similar other results (for a review representing the status of about 1996 regarding radon treatment of degenerative diseases of spine and joints, with 72 references, see Pratzel *et al.* 1997).

A more current compilation of by now four completed radon double-blind studies has been presented recently (Reiner 2001). It adds to the above study in Schlema further results by Lind-Albrecht 1994; Reiner in Bad Brambach 1997; Heisig in Bad Steben 1997; and Skorepa, also in Bad Steben, 1999. A typical result is given in Figure 9 in which the beneficial effect (expressed as a "complex parameter") is given for rheumatic arthritis patients at the end of the treatment, 3 and 6 months after treatment. The results of these and other studies are in progress. In Figure 10, a summary of all studies is presented, with the 95 % confidence limits for short-term, middle-term, and long-term effects (values below zero indicate positive effects). Further studies are in progress, including radon inhalation in Bad Gastein

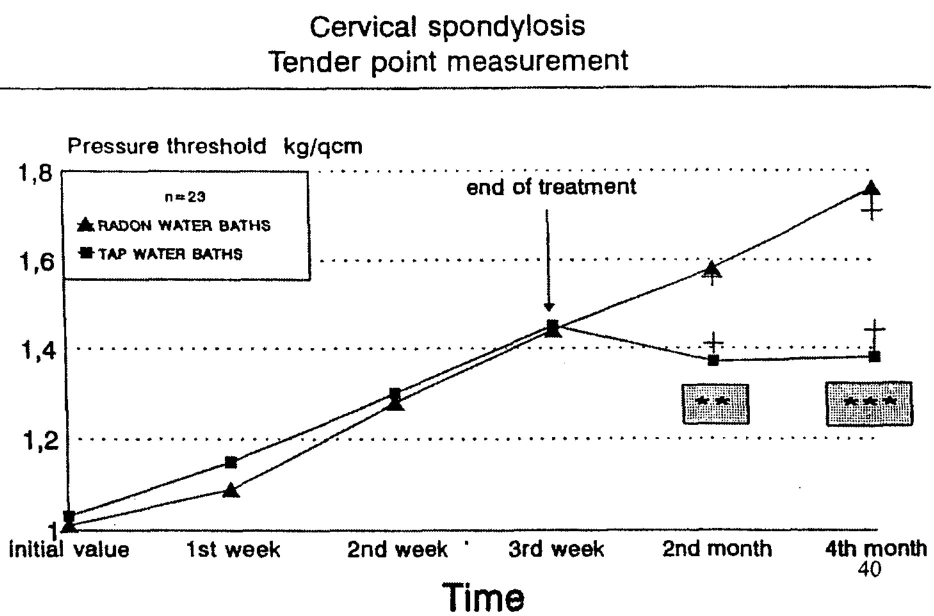

Figure 8. **Tender point measurements of pain threshold with cervical spondylosis patients during, and after the end of the treatment with Rn and placebo tap water (note change of time scale at end of treatment).** (Reproduced from Pratzel *et al.* 1997, used with permission of ISMH.)

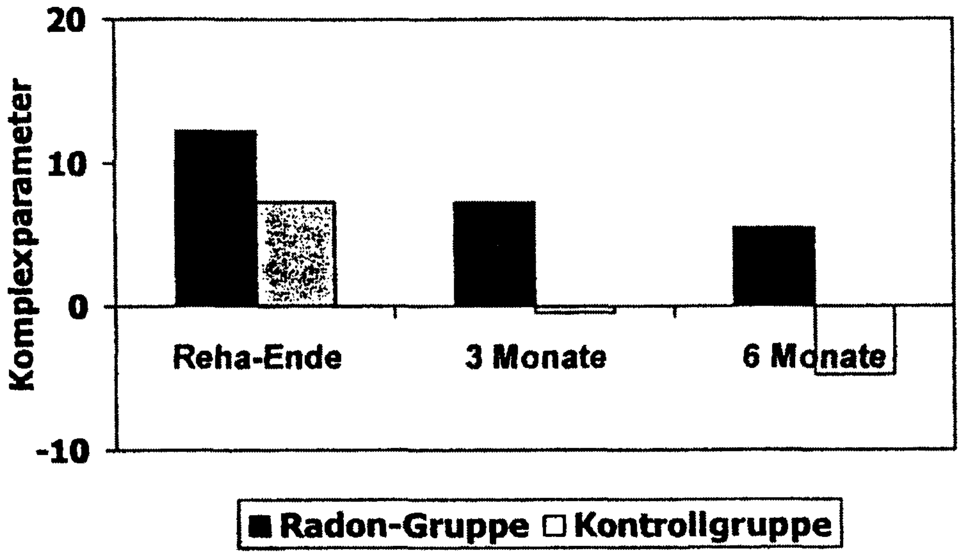

Figure 9. **A complex "painless parameter" comparing in a study the radon and the control group at the end of the treatment period (left) with the effects 3 months (middle) and 6 months (right) after the treatment; radon group black, controls light.** (Reiner 2003, Proceed. 3. Biophysikal. Arbeitstagung Schlema 2001, registered with the German Library in Frankfurt, ISSN 1610-5079, used with permission of RADIZ.)

in which the results, with Dutch patients, look promising (Falkenbach 2001). It seems that approx. 40,000 Bq/m^3 represent the lower limit for successful inhalation treatments.

The mechanism of the biopositive radon effects is still not clear and subject to intense research. More general explanations such as stimulation of the immune system (*e.g.*, Soto 1997) have been replaced by detailed investigations such as the influence on the Langerhans cells, an increase in the encephalin level, reduction of oxygen radicals in the neutrophiles and macrophages, influences on homoeostasis, factors influencing the attachment of leukocytes at joint tissues, and so on. One of the most recent publications deals with the long-lasting radon progeny activity on skin and hair after speliotherapeutic radon exposures in Bad Gastein (Falkenbach *et al.* 2002). They found surprisingly high adhesive properties of radon daughters, thus extending the period of possible biopositive effects on Langerhans cells, and perhaps systemic effects mediated by their alteration.

Unlike the successful treatment of non-malignant inflammatory diseases with local external X or gamma radiation in a fractionated 3 to 6 Gy treatment, which is currently used on about 20,000 patients annually just in Germany, the doses due to

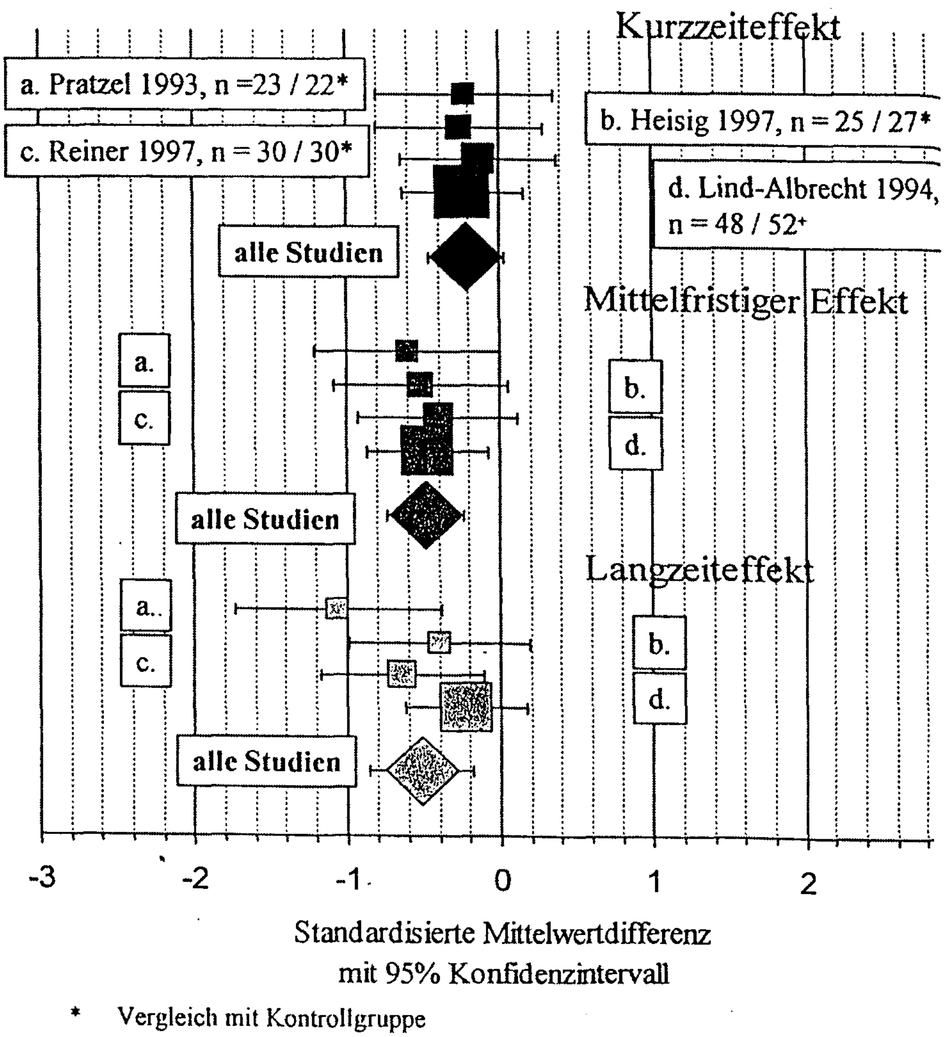

Figure 10. **Summary of the pain-reducing effects of four randomized double-blind radon studies between 1993 and 1997, showing in comparison with the control groups (bars indicating the 95 % confidence limits) the short-term effects (upper third), mid-term (middle), and long-term (lower part) effects; summary of all studies bottom line.** (Reiner 2003, Proceed. 3. Biophysikal. Arbeitstagung Schlema 2001, registered with the German Library in Frankfurt, ISSN 1610-5079, used with permission of RADIZ.)

radon inhalation or through the skin by bathing in radon water are very low. As demonstrated in measurements of the radon exhalation rate of persons submersed in radon water and other studies, the half-life of radon in the body is short (in the order of a few hours). It accumulates in certain fatty tissues, and the effective whole-body dose is only in the range of a few mGy (see, for example, Tempfer *et al.* 2002).

It should be noted that the conventional treatment of arthritic and rheumatic diseases with nonsteroid antirheumatics (such as aspirin and diclophenac) have serious side effects, leading to the estimated death of about 2000 persons annually in Germany, and 12,400 in the U.S. On the other hand, no lethal side effect of radon balneology has ever been reported (Jöckel 2001). Despite large-scale and expensive efforts by the German authorities (ca. $2000 million) to measure and reduce the population exposure to radon (Becker 1996), the Federal Institute of Radiation Protection now "tolerates" therapeutic radon treatments, with a few exceptions such as children and pregnant women. In the German media, there have been various TV and radio specials as well as articles discussing radon therapy (Test 1999).

The persons professionally active in the treatment facilities are classified as radiation workers and subject to personnel monitoring. They receive a dose of about 8 to 15 mSv/y, based on the current ICRP models assuming a biological effectiveness (RBE) of 20 for alpha and other high-LET (*e.g.*, neutron) radiation. There is by now general agreement among the experts that the RBE should be reduced to about 5 to 10, with some careful inhalation studies for lung cancer induction in animals in England, indicating values as low as 2 (Kellington 1997).

TRENDS AND CONCLUSIONS

Most research on radon effects in Western Europe suffers from a biased anti-radon attitude, essentially equating residential radon concentrations with a health risk based on the ICRP, BEIR VI, and other "official" statements. They are strongly influenced by the situation in the U.S., and the studies and recommendations of international, regional, and national governmental and nongovernmental bodies that are closely interconnected. The more important ones are ICRP, UNSCEAR, IAEA, EU, as well as NCRP and EPA in the U.S. This is reflected in governmental support for "anti-radon" research and epidemiological studies of controversial quality. The situation has been described by many authors (for example, Proctor 1995):

"If the politics of science consist in the structure of priorities, then it is important what gets studied and why, and what *not* gets studied and why not. One has... to study the social construction of ignorance. The persistence of controversy is often not a natural consequence of imperfect knowledge but a political consequence of conflicting interests and structural apathies. Controversy can be engineered; ignorance and uncertainty can be manufactured, maintained, and disseminated." This describes what happened in many countries in Central Europe. For example, a "German Radon Study" on residential radon epidemiology has been supported at the level of about $8 million by the Ministry of Environment (Wichmann *et al.* 1998, 1999), but other studies questioning the official LNT radon hypothesis (such as Conrady *et al.* 2000), as well as those on radon balneology research, did not receive any governmental support.

It is interesting to note that in all countries, despite substantial "educational" efforts to promote residential radon remediation, there has been a remarkable reluctance of people to react to governmental warnings and advice, in particular when private funding of such activities is involved. An increasing number of people in high-radon areas even refuse the free-of-charge radon monitoring of their homes. Assuming an EU limit of 200 Bq/m^3 in homes, in Germany 200,000 residences involving about 800,000 persons would require remedial action. Radon reduction costs currently vary between $2,500 and $25,000, with up to $130,000 for an old house in Austria. There are lower predictions for the future, but new radon-reducing regulations would certainly increase construction costs, in particular because new energy-preservation regulations require better thermal insulation that imply less ventilation of homes, known to increase residential radon levels.

Obviously, miner's data cannot be extrapolated to residential radon situations, the dose-rate effect is substantial, and the uncertainties of retrospective smoking dosimetry dominate by far those of retrospective radon dosimetry, as — with a risk rate of 10 to 20 — the "error" in the number of cigarettes smoked in the past far exceeds the risk attributed to radon. Serious cost/benefit assessment of the radon issue would lead to a number of basic ethical questions, for example, How much of the limited funds should a society devote to the further reduction of hypothetical risks such as residential radon? If they exist at all, they are certainly minor compared to other, real and demonstrable environmental and health risks in affluent, and even more so in less affluent, societies — keeping in mind that the daily income of about half of mankind amounts to <$2.

Because of the omnipresence of radon, its (officially claimed) large contribution to total population dose, and the wide fluctuation in concentration in different areas of the world depending on soil composition, construction materials, and other factors, it should be considered an important test for the validity of the LNT hypothesis, and the regulatory measures related to it. This topic thus also relates to areas such as waste management, decommissioning of nuclear facilities, public acceptance of nuclear energy, and other issues. So far, most of the more recent data indicate (despite the well-known difficulties with low-dose epidemiology) that for radon, delivering relatively large local doses at high-LET and low dose rate, the same basic dose-response diagram applies as for other radiation effects on organisms (Figure 11). Radon thus provides important further evidence against the LNT hypothesis, and if a threshold is needed at all, it should be around 500 to 1000 Bq/m^3 (Becker 2002), and not 148 to 400 Bq/m^3 as currently suggested by various national and international bodies.

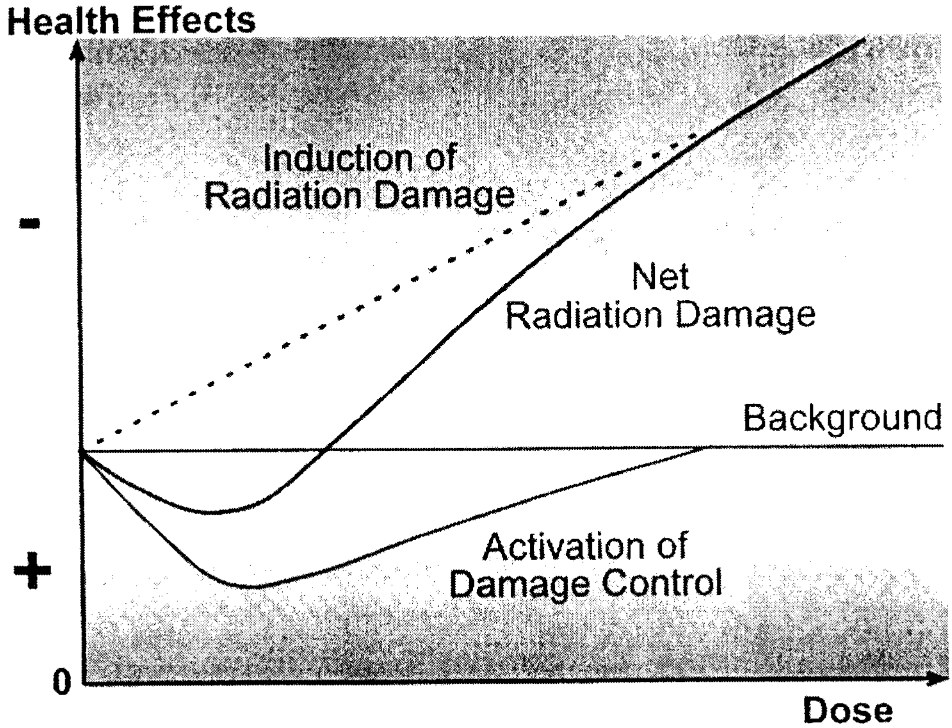

Figure 9. Schematical diagram of the biopositive and bionegative radiation effects as a function of dose, with the damage induction superimposed by the biological defense mechanism, with a de facto threshold generally in the area between 0.2 and 2 Gy (Becker 2002, after Feinendegen).

ACKNOWLEDGMENTS

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* Note: Because of the abundance of relevant literature, the references of this relatively short report concentrate on more recent publications, reviews and books, in which many more references can be found.

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