

Health and Environmental Issues Linked to the Nuclear Fuel Chain

Section B : HEALTH EFFECTS

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prepared under contract to the
Canadian Environmental Advisory Council

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B. Biological Effects of Ionizing Radiation

B.1. Radiation Burns and Cancer Therapy

Some of the harmful effects of ionizing radiation were apparent from the outset. Too much x-radiation caused recurrent reddening of the skin or loss of hair, hours or days later, often followed by painful radiation burns. By 1897, 69 cases of skin damage were reported. By 1902, hundreds of cases of x-ray injuries were documented. Surgery was often needed to repair the damage.

In 1896, in Chicago, after painfully injuring his hand with x-rays, W. Grubbe [24] decided to focus those same rays on a cancerous tumor, using lead to shield himself from unwanted exposure. His was the first recorded therapeutic use of such rays to shrink tumours. That same year, scientists in several other countries began using x-rays to treat cancer and to relieve arthritic pain.

Gamma rays were found to be equally potent. In 1898, Becquerel carried a sealed tube of radium in his vest pocket. As a result, he got a nasty burn on his chest which ulcerated and left a scar. At about the same time, Marie Curie's hands suffered painful radiation burns after she handled a thin metal box containing a small tube of radium.

Before long, radium-filled "needles" were being used to treat solid tumours. Such a needle, inserted into an unwanted growth, would deliver most of its harmful gamma energy [25] to the diseased tissue, while minimizing the dose to healthy tissue. Workers preparing the needles, surgeons implanting them, and nurses attending the patients, often received substantial gamma doses.

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B.2. Early Suggestions for Exposure Standards

In 1902, Rollins suggested using a photographic plate to measure x-ray or gamma ray doses, anticipating the "film badges" worn by atomic workers today. If the plate wasn't fogged after seven minutes, he asserted, then the radiation wasn't harmful. If that criterion were followed today, doses would be allowed which are more than 700 times larger than the maximum permissible exposures set for atomic workers in Canada in 1990.

In 1916, the British Roentgen Society unanimously declared that medical and dental x-ray examinations are hazardous, and recommended a number of precautions. In 1921 the same body published a set of recommendations for radiological protection from x-rays and radium. Unfortunately, these recommendations never became widely known and were largely ignored.

It was generally assumed by practitioners that any dose well below that which produced reddening of the skin (the "erythema dose") was safe. This idea was formalized in a 1925 recommendation (advanced independently by Sievert and Mutscheller) that no more than 1/100 of an erythema dose should be allowed in any 30-day period. Such a "tolerance dose", although 50 times lower than that suggested by Rollins, is still 15 times higher than the maximum permissible exposure for an atomic worker in Canada in 1990.

Throughout this period, there were no units of measurement to allow for quantitative comparisons of dose. The x-ray film at that time was highly variable in sensitivity, and reddening of skin depended on a great many factors. More importantly, the concept of radiation safety had not yet been extended to include the more subtle effects of exposure to ionizing radiation.

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B.3. Sterility and Cataracts

There were, indeed, other less immediately obvious medical effects resulting from exposure to ionizing radiation.

By 1903, x-rays had been used to permanently sterilize rabbits and guinea pigs of both sexes. Somewhat lower doses caused temporary sterility in males or a permanent reduction in fertility in females. Below a certain threshold dose, however, there seemed to be no noticeable impairment of fertility, perhaps because nature is so prolific in producing sperm and eggs.

By 1904, it was learned that exposing the lens of an animal's eyes to ionizing radiation could produce cataracts. By 1940, there were over 100 documented cases of radiation-induced cataracts in humans.

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B.4. Blood Disorders

It had been demonstrated by 1904 that immature cells and rapidly dividing cells are more sensitive to ionizing radiation than mature cells. In particular, cancerous growths in which cells are proliferating rapidly are more radiosensitive than healthy tissue -- a fact which contributes to the effectiveness of radiation therapy.

The blood-forming cells, located mainly in the bone marrow, are both immature and rapidly-dividing.

They are highly susceptible to radiation injury. By contrast, most mature blood cells are relatively radioresistant. A curious exception to this rule is the lymphocyte, a particular kind of mature white blood cell which is extremely radiosensitive. The reason is unknown.

A dose of ionizing radiation causing an immediate decrease in lymphocytes may not affect the other mature blood cells right away. However, all blood cells are constantly being replaced by new ones. If those replacements are not forthcoming because of damage to the bone marrow, the population of white blood cells will drop a few days after exposure, sometimes followed by a rather slow decrease in red cells. Red cells live longer than white cells, so they are replaced more gradually; hence the effect is seen somewhat later.

As early as 1903, x-rays had been used to produce leukemia in mice. It was soon common knowledge that those who worked with x-rays and/or radium often exhibited significant blood changes themselves, sometimes mild, sometimes fatal, ranging from leukopenia or anemia (reduction in white or red blood cells respectively) to leukemia (cancer of the bone marrow, characterized by an unregulated proliferation of white blood cells).

Marie Curie and her daughter Irène both died from leukemia brought about by many years of radium exposure.

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B.5. Cancer and Life-Shortening

Radiation burns which had apparently healed often developed into cancers later on. As early as 1922, Ledoux and Lebard estimated that more than 100 early radiologists had died of occupationally produced cancers. In the 20-year period before 1949, radiologists also suffered an incidence of leukemia nine times the normal rate.

A number of studies then and since have shown that the average life-span of early radiologists was significantly shorter than that of unirradiated medical practitioners -- not only due to increased cancer and leukemia, but also because of increased diseases of the circulatory and renal systems.

Laboratory studies have consistently shown a shorter life expectancy among animals exposed to ionizing radiation than among unirradiated animals. This fact has been subject to different interpretations. Does it indicate premature aging brought on by exposure to ionizing radiation? Is it due entirely to the excess cancer and leukemia deaths among the exposed animals, reducing the average life span? Or is there a non-specific life-shortening effect associated with ionizing radiation? No definitive answers are yet available.

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B.6. Radium Jaw, Anemia and Septic Infections

In the mid 1920's, a number of dentists reported a phenomenon called "radium jaw" among some of the hundreds of young women workers in radium dial-painting factories. Their jaw bones were quickly deteriorating, becoming soft and porous, often suffering spontaneous fractures. Teeth were breaking and falling out. Gums were sore and septic with virulent bacterial infections. These symptoms were often accompanied by a profound anemia.

In 1925, Harrison Martland, a forensic pathologist, concluded that radium jaw was caused by minute amounts of radium which the women swallowed by "pointing their brushes" with their lips (a practice soon discontinued). He cited, in evidence, the faint but detectable gamma radiation emitted from their living bodies and the radon gas detected in their exhaled breath.

Several of these women died in their 20s or 30s from anemia or from septic infections which were resistant to treatment. Autopsies clearly revealed alpha activity concentrated in the bones, spleen and liver. Radium, being chemically similar to calcium, had followed the same biological pathways as calcium and ended up mainly in the skeleton. The women's bones were sufficiently radioactive that images of them could be made simply by resting the bones on photographic paper in a dark room.

Martland attributed the young women's fatal anemias to radiation damage done to the bone marrow, exhausting its ability to produce red cells. A marked impairment of the body's natural resistance to bacterial infection was evidently a side-effect. It was linked to the drastic reduction in white blood cells, whose primary function is to fight infection.

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B.7. Cancer of the Bones and Head

Some of the affected dial painters seemed to recover from their initial illnesses. Others displayed no noticeable ill effects, despite significant radium contamination. However, in later years, many of these same women developed crippling inflammations of the skeleton degenerating into bone cancer at a multitude of different sites, such as knee, arm, foot, mandible, rib-cage, pelvis, and eye socket. Spontaneous fractures and deformities of the spine were not uncommon. Such effects were generally experienced years, or even decades, after the women had quit their jobs as dial painters.

Bone cancer is an exceedingly rare disease, yet it was epidemic among the dial painters. There was no doubt that radium was the cause.

Autopsies revealed that the fatal dose was between 10 and 180 micrograms of radium. [26] This amount -- invisible to the naked eye, too small even to be detected by chemical means -- had been metabolized by the digestive tract and distributed throughout the skeleton. It was impossible to discover exactly how much radium had been ingested; most of it would have been excreted in the feces. Subsequent bone cancer victims have shown amounts of radium as small as 1.5 micrograms in their skeletons.

Over 90 percent of the ionizing energy emanating from the deposits in the bone was alpha radiation. By comparison, the tiny amounts of beta and gamma radiation were negligible. [27]

Martland summed it up by writing: "Alpha particles are probably the most potent and destructive agent known to science." He noted that 10 micrograms of radium in a skeleton today will still be releasing 160,000 alpha particles per second 2,000 years from now.

Although Martland couldn't know it, a substantial number of the dial painters (about half as many as those who eventually contracted bone cancer) would later die from cancers of the soft tissues in the head. Radon gas, generated inside their bodies by the decay of radium, collected in their sinus and mastoid cavities. There the radioactive gas and its short-lived progeny bombarded the surrounding soft tissue with alpha particles, causing cancer.

Many other radium workers suffered from ailments similar to those of the dial painters, but their cases received far less publicity.

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B.8. Radium Novelties

Faced with the evidence of the dial painters, Martland urged an end to the marketing of fraudulent tonics, quack nostrums and confections containing radium which were being consumed regularly by thousands of people. "I am now of the opinion that the normal radioactivity of the human body should not be increased," he wrote.

In 1927, Eben Byers, a prominent steel tycoon from Pittsburgh, died of radium poisoning after having consumed four half-ounce bottles of radium water each day for over two years. The press coverage of this sensational case did much to alert the public to the dangers, but it was still some time before food and beverages containing added radium were no longer sold.

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B.9. Radium Injections

Martland also warned against intravenous injections of radium salts (then a fad practiced by thousands of physicians) noting that radium injections had no proven medicinal or curative effect. His warning went largely unheeded.

Beginning in 1944, German doctors injected over 2000 patients, including hundreds of children, with a short-lived isotope of radium, radium-224 (half-life 2.64 days). [28] This treatment was intended to be of therapeutic value for tuberculosis of the bone, and, in some older patients, for "ankylosing spondylitis" (a painful arthritis of the spine).

In the case of the children and other tuberculous patients, the injections were discontinued in 1951 when they were found to be of no therapeutic value. Among the younger patients, broken teeth, stunted growth, and cataracts were some of the non-cancerous effects attributed to radium poisoning. The treatment was continued for spondylitic patients, as the radiation therapy offered some relief from arthritic pain.

Excess bone cancers occurred among these patients, as with the radium dial painters. There were two new findings: first, children are more susceptible to radiation-induced bone cancer than adults; and second, protracting a given dose of radium-224 (i.e. spreading it out over a longer time) actually makes it more effective in causing bone cancer, not less. These findings have been confirmed and extended in experiments with animals.

No head cancers were found in these patients. When radium-224 decays, it yields radon-220, having a half-life of only 56 seconds. Apparently this is too short a time to allow the radioactive gas to collect in the head.

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B.10. Cancer of the Lung

In the 1930s, a mysterious, ancient epidemic of lung cancer was also linked to alpha radiation. Beginning in the 16th century, it had been reported regularly that generations of underground miners near Schneeberg, Germany, suffered from an extraordinarily high incidence of fatal lung disease.

By 1897, it had been demonstrated both anatomically and clinically that from half to three-quarters of these miners were dying of lung cancer, while most of the rest were dying of other lung diseases. This level of lung cancer incidence was much higher than among the surrounding population, where it was virtually unknown. The ores were particularly rich in uranium.

By the late 1930s, a similar statistic -- fifty percent mortality from lung cancer -- was found among the miners in Joachimsthal, Czechoslovakia, whence Marie Curie and Henri Becquerel had obtained their first supplies of uranium-bearing ore. The German and Czechoslovakian mines are located on opposite sides of the Erz Mountains ("Ore Mountains").

Several scientific papers published before 1940 clearly indicated that airborne radioactivity in the mines was the cause of these lung cancer epidemics. The principal culprit was thought to be radon-222, an

alpha-emitting gas, rather than radioactive dust, because other kinds of workers chronically exposed to radium dust showed no such increases in lung cancer.

Animal experiments confirmed the extraordinary effectiveness of radon in causing lung cancer, compared with inhalation of radioactive dust. However, scientists found it difficult to understand how radon-222 could deliver a radiation dose sufficient to account for such a large increase in lung cancer.

Being a gas, radon behaves predictably. It mixes easily with air. It is exhaled as easily as inhaled. Although the concentration of radon gas in the mines was highly variable, there was a well-defined range of measured values, so the dose to the lungs could be roughly estimated. Yet many other people had received much larger doses of x-rays to the chest, without experiencing any noticeable increase in lung cancer. Why were the lungs of the miners suffering so much damage from this alpha-emitting gas?

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B.11. Radon Progeny

The answer was a long time in coming. In the early 1950s, two American scientists [29] made the elementary observation that the miners were inhaling, not just radon gas, but its short-lived progeny as well. It is surprising that no one thought of this before, since the decay chain for radon-222 was worked out shortly after the discovery of radium-226, and was well known.

As radon-222 accumulates in the mine atmosphere, there is a gradual build-up of short-lived radon progeny. Charged atoms of radioactive bismuth, lead and polonium hang suspended in the air. By electrostatic attraction, many of these charged atoms attach themselves to airborne dust particles and to droplets of respirable size. The others remain unattached, but airborne. Once the radon progeny were taken into account, the estimated dose turned out to be hundreds or even thousands of times larger than earlier calculations had indicated. The size of the final estimate depends on several assumptions.

The largest dose results when the radon is in equilibrium with its short-lived progeny; this occurs if the gas is allowed to stagnate in an unventilated space for several hours (see A.20). Under such circumstances, the gas contributes only slightly to the total dose; most of the damage is done by the attached and unattached decay products [30], especially the alpha-emitting polonium isotopes. They all lodge in the respiratory tract, and some end up delivering high doses of radiation to the bronchi, where most lung cancers originate.

Complete equilibrium between radon and its short-lived progeny is seldom achieved, but in poorly ventilated spaces it is often a good approximation.

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B.12. Radon Seeds

Meanwhile, radon began to replace radium as a therapeutic agent. Since the most intense gamma rays associated with radium needles come from the short-lived radon progeny anyway, why not use radon from the outset?

Medical practitioners learned how to cull the radon from a sample of radium, enclose it in a special golden capsule called a "seed", and implant the seed in or near a solid tumour. The same quantity of radium-226 could be used over and over again to generate more radon-222.

Since radon has a half-life of only 3.8 days (versus the 1620-year half-life of radium), its activity is largely spent after a month or two. Thus the total accumulated dose is automatically limited, even if the seed is left implanted for a long time. The maximum possible dose can be calculated beforehand, thereby reducing the chances of accidentally overexposing a patient. Removing the implant is also safer for the

medical staff.

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B.13. Genes and Chromosomes

In the late 1920s, researchers discovered another kind of biological effect from ionizing radiation: damage to genes and chromosomes. Some of this damaged genetic material may be transmitted to future generations. In this section and the next, some rudimentary facts about genes and chromosomes are summarized.

Every cell contains thousands of genes. They are housed in a small number of thread-like bodies called chromosomes, usually located in the nucleus of the cell. [31] Chromosomes are visible under a microscope, but genes are not. Each gene is sited at a precise location along its thread-like chromosome.

A cell having no direct role in sexual reproduction is called a "somatic" cell. It normally contains twice as many chromosomes as a reproductive cell. In humans, for instance, a somatic cell typically has 46 chromosomes, whereas a sperm or egg has only 23. When sperm meets egg, the fertilized egg gets two sets of 23 chromosomes for a total of 46. This is the first somatic cell of a new human being. It has its own unique combination of genes, which will determine the inherited physical characteristics of the developing offspring.

All the genetic material in a somatic cell is meticulously duplicated just before it undergoes normal cell division. Then, when the cell cleaves in two, a complete duplicate set of 46 chromosomes is given to each of the two daughter cells. This process is known as "mitosis". As the foetus grows, every somatic cell in its body gets an identical copy of the original 46 chromosomes inherited from its parents -- if nothing goes wrong.

Reproductive cells are formed by a different sort of cell division called "meiosis", occurring only in the gonads. In meiosis, the 46 chromosomes of a somatic cell are not duplicated but segregated into two equal sets of 23 chromosomes shortly before cell cleavage. Then each daughter cell receives only 23 chromosomes, becoming either a sperm or an egg, able to participate in sexual reproduction to produce further offspring. In this way, half of the genetic material originally inherited from one's parents may be passed on to one's own child, who can in turn pass some of it on to his or her descendents.

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B.14. The Nature of Genetic Damage

A mutagen is any agent causing damage to genetic material. Genetic damage falls into two main categories:

1. chromosome aberrations, involving changes in the number or structure of chromosomes;
2. alterations of the genes themselves, called "gene mutations".

Most chromosome damage is visible, often involving some form of breakage. A "deletion" occurs when a segment of a chromosome is broken off and lost. An "inversion" occurs when the broken segment reattaches, but in the reverse order. A "translocation" occurs when a broken segment from one chromosome attaches itself to a different chromosome. A "reciprocal translocation" occurs when two broken segments from two chromosomes reattach, but each to the wrong chromosome. Ring chromosomes, dicentric chromosomes and other abnormal chromosomes may be formed in a similar fashion.

Chromosome damage can have serious medical consequences. In the 1960s, it was discovered that

specific chromosome deletions give rise to the "cri-du-chat" syndrome and the "Wolf-Hirschhorn syndrome" in humans -- two hereditary disorders involving severe mental retardation, stunted growth and a delay in psychomotor development. [32]

A loss of genetic material, such as the deletion of part of a chromosome, might be expected to cause problems. But too much genetic material can be just as damaging as too little. If either the sperm or egg happens to contain an extra chromosome (24 instead of 23), the fertilized egg ends up with 47 chromosomes rather than 46. Instead of 23 pairs of matched chromosomes -- one of each type from each parent -- there are 22 pairs and a triplet. This condition is called a "trisomy". Since 1959, four hereditary human diseases have been linked to specific trisomies. [33] They are "Down's syndrome", "Edwards' syndrome", "Patau's syndrome" and the "Cat-Eye syndrome". [34]

Even chromosome aberrations involving no excess or deficiency of genetic material can have debilitating consequences. Some children displaying full-blown symptoms of Down's or Edwards' or Patau's syndrome do not exhibit any trisomies in their somatic cells. Instead they show translocations affecting the very same chromosomes which are trisomic in most other cases of these genetic diseases.

By contrast, a gene mutation causes no visible damage to the chromosome. There are two types of gene mutations: dominant and recessive. The effect of a dominant mutation can be seen in any offspring inheriting the mutant gene from either parent. The effect of a recessive mutation is not fully expressed in the offspring unless the same mutant gene is inherited from both parents.

Thus a dominant mutation carried in sperm or egg will be expressed in the first generation offspring, whereas a recessive mutation may not become apparent for many generations. It may take a long time indeed before a sperm and an egg, both carrying the same mutant gene, happen to meet.

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B.15. Genetic Damage in Fruit Flies and Mice

In 1926, the geneticist H. G. Muller began irradiating the reproductive cells of fruit flies before allowing them to mate. Following several thousand such irradiated fly populations past the second generation, he found a frequency of gene mutations up to 150 times greater than in the unirradiated control populations. Reduction of dosage led to a corresponding reduction in the frequency of mutations. Male and female reproductive cells in all stages of development were found to be susceptible to these mutagenic effects.

Muller reported (1928) that the vast majority of radiation-induced mutations were fatal, leading to the production of unviable organisms. These are called "dominant lethal mutations". Of the remainder, most (but not all) reduced the viability or fertility of offspring.

While "new" mutations were by far the most frequent, he also found some repetitions of familiar spontaneous mutations. He noted that the visible effects of mutations were often relatively inconspicuous, and that recessive mutations greatly outnumbered the dominant ones.

Muller found that most of the radiation-induced effects he observed were due to "point-mutations" affecting a single gene, although there was an occasional "line-mutation" involving a whole row of neighbouring genes, as if an ionizing particle had passed parallel to a chromosome segment containing these genes. Point-mutations and line-mutations both leave the chromosomes unchanged in physical appearance.

In his irradiated fruit fly populations, Muller also noted frequent chromosomal abnormalities, involving inversions, translocations, and duplications leading to extra chromosomes, as well as other irregularities. Within a few years, researchers found evidence of similar mutagenic effects in mice, rabbits and other small mammals, as well as plants. Only much later were such chromosomal abnormalities observed in irradiated human cells.

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B.16. Genetic Damage in Human Populations

In Muller's time, there was no direct evidence of observable genetic effects in humans, nor was there much concern. No one anticipated that large populations of human beings would ever be irradiated beyond the unavoidable background levels found in nature. The power of ionizing radiation to effect genetic change was regarded as a boon to researchers rather than a threat to people.

With the advent of nuclear fission, these perceptions changed. It became evident that large numbers of people could become irradiated as a result of nuclear weapons fallout or accidental emissions from nuclear reactors. The initial motivation which first led to the setting of exposure standards for members of the general public (as opposed to radiation workers) was to limit the genetic damage to the human species.

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B.17. Teratogenic Effects

In 1929, one year after Muller announced his results, two doctors, L. Goldstein and D. Murphy, published a study of children born after their mothers had received pelvic x-rays. While the numbers are small (650 pregnancies in all), the results are of interest because of the ramifications.

Over half of the children born to women irradiated during pregnancy were unhealthy, while the corresponding figure for women irradiated before conception was only 11 percent. That discrepancy suggests that in utero irradiation of the developing foetus, with its rapidly-developing cells, may be a more effective cause of ill health in the immediate offspring than genetic damage caused by irradiating the eggs of the mother before conception. Subsequent research has tended to support these initial tentative findings.

Goldstein and Murphy reported a marked increase in congenital malformations among the children exposed before birth. Such developmental defects, caused by in utero exposure, are called "teratogenic effects" to distinguish them from genetic effects.

The distinction is an important one. Defective genetic material inherited from the parents will be displayed in every cell of the offspring's body, including the reproductive cells. On the other hand, damage done to the developing foetus after conception will affect only some of the child's cells, and may indeed be limited to one or more organs. In the majority of cases, such damage will not extend to the reproductive cells. Thus the damage will not be transmissible to future generations.

For example, Goldstein and Murphy noted that an unusually high number of the children exposed in utero were born as "microcephalic idiots": mentally retarded children with smaller than usual heads.

The same condition, caused by a failure of the brain to grow to its proper size, was later observed among children born to mothers who were pregnant at the time of the atomic bombings at Hiroshima and Nagasaki. It is a condition clearly caused by ionizing radiation that adversely affects the unborn children; but it is a teratogenic rather than a genetic effect.

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B.18. Units of Exposure and Dose

The need to quantify radiation damage became increasingly evident, despite obvious difficulties in doing so. The first two units introduced dealt with radiation as it flies through the air, and as it is absorbed in living tissue. The two corresponding quantities are called "exposure" and "absorbed dose".

The unit of radiation "exposure", adopted by the International Congress on Radiology in 1931, was the ROENTGEN. A roentgen is a quantity of x-rays or gamma rays which will cause a precisely defined degree of ionization [35] in one kg of dry air.

The roentgen unit does not apply to particulate radiation (such as alpha, beta, neutron or high-speed ions), nor does it involve biological tissue. To rectify these shortcomings, the concept of "absorbed dose" was introduced. The unit of absorbed dose is called a RAD (an acronym for Radiation Absorbed Dose).

One rad is that quantity of ionizing radiation of any type that will deposit 100 ergs of energy in each gram of absorbing tissue.

The relation between "exposure" and "absorbed dose" depends on the tissue involved. An x-ray "exposure" of one roentgen will deliver a "dose" of very nearly one rad in soft tissue (e.g. muscle). Here, the units are almost interchangeable. In bone, however, an exposure of one roentgen corresponds to a dose of considerably more than one rad. Here, the units are not interchangeable. The difference in dose results from the fact that bones are opaque to x-rays, so they absorb most of the x-ray's energy, while flesh is transparent, allowing much of the x-ray energy to pass through without being absorbed.

The rad has now been superseded by the GRAY (Gy) which equals 100 rads. [36]

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B.19. Biological Effectiveness of Ionizing Energy

Ionizing radiation is remarkably effective in causing biological damage. In this section we will make a quantitative comparison with another, more familiar form of energy, to illustrate the point.

Based on data from the Japanese atomic bombings and from animal experiments, the best estimates are that a dose of 400 rads of whole-body radiation, delivered quickly, is enough to kill about half of the humans so exposed in a period of days to weeks (from acute radiation sickness). [37]

How much physical energy does this large dose of ionizing radiation represent? Since all forms of energy are interconvertible, we can use heat units as a basis of comparison.

A CALORIE is (by definition) the amount of heat needed to raise the temperature of one gram of water by one degree Celsius. The conversion from ergs to calories is:

$$1 \text{ erg} = 2.39 \times 10^{-8} \text{ calories.}$$

Now since 1 rad (of ionizing radiation) deposits 100 ergs of energy per gram, 400 rads will deposit

$$40,000 = 4 \times 10^4 \text{ ergs per gram,}$$

which is equivalent to

$$(4 \times 10^4) \times (2.39 \times 10^{-8}) = 9.56 \times 10^{-4} \text{ calories per gram.}$$

But this amount of energy would raise the temperature of one gram of water by less than 0.001°C ! (That is, less than one one-thousandth of a degree Celsius!) It is an imperceptible amount of heat.

This calculation highlights the enormous difference between energy in the form of heat and energy in the form of ionizing radiation. An amount of energy which is absolutely inconspicuous in one form can be lethal in another. When a radioactive material gives off any degree of perceptible heat, it is capable of killing thousands of people.

What is the reason for the difference? It is because the energy of ionizing radiation is not uniformly distributed among all the molecules of a gram of tissue, the way thermal energy is. Instead, ionizing energy is transferred to just a few electrons in a relatively few molecules, thereby disrupting the molecular basis of living cells. That cellular damage is then multiplied and amplified by normal -- and abnormal -- biological processes.

In short, the energy transfer resulting from exposure to ionizing radiation occurs in an extremely concentrated and biologically effective fashion compared with the even diffusion of heat energy.

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B.20. Prompt Effects

Radiation damage can be classified in various ways. One of the simplest and most important has to do with the time it takes for the damage to be felt. This leads to a distinction between "prompt effects" and "delayed effects".

Prompt effects are, by convention, those which become manifest within a year (usually within days or weeks) following exposure. All of the immediately obvious effects of exposure to ionizing radiation fall into this category. It includes such things as visible skin damage and loss of hair, as well as the classic symptoms of acute radiation poisoning (nausea, vomiting, epuration...).

Most of the non-cancerous blood changes caused by ionizing radiation are prompt effects. Teratogenic effects, whereby malformed embryos are produced following in utero exposure of the foetus, are also prompt effects.

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B.21. Dose Dependency and the Concept of a Threshold

The severity of a prompt effect generally depends on the dose received: the higher the dose, the more severe the effect. This is evidently so in the case of skin damage. The same can be said for loss of fertility: doses of ionizing radiation within a certain range may reduce one's fertility without causing total sterility, and the level of impairment is dose dependent. Similarly, the degree of hair loss depends on dose, up to and including total baldness.

The severity of microcephalic damage to infants born within a few months of the Japanese atomic bombings depended on the absorbed dose delivered to the mother's wombs between 8 and 25 weeks after conception. In such cases, the circumference of the baby's head was directly dependent on the distance of the mother from the bomb's epicentre at the time of the explosion: the closer to the bomb, the smaller the baby's head. The degree of mental retardation was, in turn, closely related to the size of the baby's head.

Many prompt effects, such as visible skin damage, loss of hair, nausea and the other symptoms of radiation sickness, can be prevented altogether by lowering the dose sufficiently or by spreading the dose out over a longer time period. In such cases, there is a "threshold" of exposure below which that particular effect will not occur.

In other cases, such as mental retardation following in utero exposure, it is by no means clear whether there is such a threshold. Among children exposed in utero during the Japanese atomic bombings between 8 and 25 weeks after conception, the degree of microcephaly was strikingly dose-dependent. But even those showing no apparent microcephaly consistently scored lower on intelligence tests than children who were not so exposed, and the degree of under-achievement was demonstrably dose-dependent. The school performance of such children was also significantly degraded in a manner directly related to their

absorbed dose. These data offer no clear evidence of a "safe threshold" below which such effects will not occur.

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B.22. Relative Biological Effectiveness (RBE)

Equal doses of ionizing radiation are not always equally effective in causing biological damage.

For example, children who experienced in utero irradiation at Hiroshima and Nagasaki less than 8 weeks after conception, or more than 25 weeks after conception, showed no evidence of microcephaly or mental retardation. This is in sharp contrast to those who were irradiated between 8 and 25 weeks following conception. Moreover, those who were irradiated in the period between 8 and 15 weeks following conception were at least four times as sensitive to this type of cerebral radiation damage than those irradiated in the period between 16 and 25 weeks following conception.

Another example is provided by the radium dial painters. As Martland observed in connection with radium-226 deposited in the bones, alpha radiation is considerably more potent than x-rays, beta rays or gamma rays in causing cancer. Quantitatively, a dose of 1 rad of alpha energy seems to be equivalent to a dose of about 10 or 20 rads (and sometimes, as in the case of protracted doses of radium-224, up to 100 rads) of x-ray or gamma ray energy.

Similar considerations apply to radon. When it was realized that the radon progeny play such a vital role in lung cancer induction, scientific estimates of doses to the lungs of the German and Czech miners increased dramatically. Nevertheless, there still remained a sizable gap (another factor of 20 or so) between the dose of radon-and-its-progeny required to provoke a certain amount of lung cancer, and the corresponding dose of x-rays or gamma rays needed to achieve the same result.

Such observations have led to the concept of Relative Biological Effectiveness (RBE). In any given situation, when two different doses of ionizing radiation produce the same measurable biological result (e.g. number of mutations, reduction in lymphocytes, incidence of cancer, degree of mental retardation, percentage of animals killed promptly), the RBE factor of the first exposure relative to the second is defined as the ratio:

$$\frac{\text{absorbed dose in rads from exposure 2}}{\text{absorbed dose in rads from exposure 1}}$$

RBE factors can vary from less than 0.01 to over 100, depending on such things as the type of ionizing radiation being used, total dosage level, rate at which the dose is delivered as well as the specific biological endpoint, not to mention such things as the species, age and sex of the target organisms.

Clearly, the physical unit of exposure, "rads", does not translate directly or easily into a biological unit of injury.

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B.23. Linear Energy Transfer (LET)

One important consideration affecting RBE is the "quality" of the ionizing radiation being used. In general, a given dose of alpha or neutron radiation is much more effective in causing biological damage than an equal dose of beta, gamma or x-radiation. This difference in effectiveness is related to a physical quantity called Linear Energy Transfer (LET).

Equal doses of alpha and beta radiation will cause the same degree of ionization in tissue; however, since

the track of an alpha particle is shorter and thicker than that of a beta particle, the ionization is much more dense. Karl Z. Morgan, "the father of Health Physics", has said that the difference between a beta particle and an alpha particle going through tissue is like the difference between a jackrabbit and a bulldozer going through a cornfield.

Sparsely ionizing radiation such as beta, gamma or x-rays will create many ions, but these are farflung and widely separated from each other. The LET (or linear energy transfer) coefficient, which measures the number of ions created per unit of track length, is relatively small. Accordingly, beta, gamma and x-rays are described as "low-LET radiation".

On the other hand, most of the ions created by an alpha particle are quite close together, confined in fact to just a few cells. The same can be said for protons which are set in motion by collisions with neutrons. Thus alpha particles and neutrons are described as "high-LET radiation".

Experimental evidence indicates that high-LET radiation always has a higher RBE factor than low-LET radiation. However, the exact value of the RBE depends on circumstances. Also, it should not be assumed that low-LET radiations of different types necessarily have the same biological effectiveness. Experiments have shown, for example, that gamma rays from cobalt-60 seem to be about twice as effective as x-rays of moderate energy (RBE=2).

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B.24. Units of Dose Equivalence: the Quality Factor (Q)

In an attempt to account for such differences in biological effectiveness, a new unit of "dose equivalence" was introduced, called a REM (an acronym for "Roentgen Equivalent Man"). This unit is intended to indicate, however roughly, the relative degree of biological damage caused by a particular exposure to ionizing radiation.

In practice, the dose equivalent (in rems) is calculated by multiplying the absorbed dose (in rads) by a "quality factor" Q, which is normally taken to be unity (Q=1) for beta, gamma or x-radiation, and twenty (Q=20) for alpha particles or fast neutrons. Thus a dose of 1 rad of gamma radiation delivers a dose equivalent of 1 rem, whereas a dose of 1 rad of alpha radiation delivers a dose equivalent of 20 rems.

It should be emphasized that the concept of dose equivalence is rather arbitrary, and sometimes quite misleading. The quality factor for alpha particles and neutrons was taken to be ten (Q=10) as recently as 1976, so that dose equivalents expressed in rems before that date would be only half as large as the same dose equivalents expressed in rems today. Moreover, some researchers use their own experimentally-derived quality factors to convert rads to rems, based on a careful measurement of Relative Biological Effectiveness (RBE). More often than not, the rem is neither a physical nor a biological unit, but an administrative unit used for regulatory purposes.

The rem is now superseded by the SIEVERT (Sv); 1 Sv = 100 rem. Thus the dose equivalent in sieverts can be found by multiplying the absorbed dose in gray by the same quality factor Q discussed above (since 1 Gy = 100 rad).

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B.25. Delayed Effects and The Latency Period

Cancers and leukemias brought about by exposure to ionizing radiation are not observable at all until years later. For this reason, such diseases are called "delayed effects". Other effects which are not life-threatening, such as cataracts and genetic damage, are included in the category of delayed effects.

The evidence for other possible delayed effects of radiation exposure, such as premature aging or non-specific life-shortening, while frequently discussed in the scientific literature, is more controversial.

Cancer is the most commonly-cited example of a delayed effect. In the case of the German children given radium-224 injections (see B.8), bone cancers began to appear about four years after the initial injections. Shortly thereafter, in 1951, the injections were stopped. Since radium-224 has a half-life of only 2.64 days, we know that the offending material was gone from the children's bodies within a few months of the final injections. Nevertheless, new cancers continued to appear for two decades afterwards, illustrating the delayed nature of the carcinogenic effect.

There is a certain period of time that apparently must elapse before the first radiation-induced cancers begin to occur. This minimum waiting time is called the "latency period". Once the latency period is past, the cancer rate increases and remains elevated not just for one or two years but for decades.

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B.26. Length of Latency Period

Each type of radiation-induced cancer has its own latency period. Among the dial painters, the first bone cancers appeared less than five years after initial ingestion of radium paint, whereas the first head cancers did not begin to appear until almost twenty years afterwards. Both types of cancer have continued to occur ever since, with new cases emerging more than half a century after the practice of licking brushes was discontinued. However, the excess in bone cancers has gradually diminished over time, while the excess in head cancers has not. The reason for this difference is unknown. In these cases, of course, even though no new radium has been ingested, the skeleton continues to be irradiated by long-lived deposits of radium-226 stored in the bones. Moreover, radon gas (radon-222) continues to migrate into the head. It is therefore impossible to know how long the cancer incidence would persist if the irradiation of the tissues were stopped.

This difficulty does not arise in the case of more than 14,000 British patients whose spines, from 1935 to 1955, were exposed to therapeutic x-rays as a treatment for ankylosing spondylitis. Within a few years, an elevated incidence of leukemia became evident among these patients. The excess peaked about five years after exposure, then declined, but excess leukemias were still being observed more than fifteen years after exposure.

Several other types of radiation-induced cancer have also appeared in this rather large group of people. After fifty years of follow-up, it appears that the most common types are lung cancer and breast cancer, but there have also been smaller increases in cancers of the colon, pancreas, stomach, bladder, lymph nodes, prostate, esophagus, bone and brain. Such cancers generally have a latency period of ten to twenty years or more.

In summary, it appears that (1) bone cancers and leukemias have relatively short latency periods, with the excess incidence peaking in about five years and then declining towards "normal" incidence rates after about two decades; whereas (2) other cancers have latency periods of ten years or more (in some cases more than twenty years), and the magnitude of the excess lasts for a much longer time, showing less likelihood to decline after peaking.

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B.27. Stochastic Effects and the Linear Hypothesis

As previously noted, the severity of many prompt effects is dose-dependent. But the severity of most delayed effects doesn't depend at all on the dose received. There is no such thing as a "little bit" of cancer. Either you have it or you don't. The same can be said for having a genetically defective child. It makes no difference whether the cancer or the genetically defective child resulted from a large or a small dose of

ionizing radiation, the end result is the same. Effects of this "all-or-nothing" nature are said to be "stochastic".

Stochastic effects are probabilistic in nature. In other words, there is an element of chance involved. Not everyone exposed to a certain dose of ionizing radiation will get cancer, but some will. The frequency of occurrence depends on the total dose to the entire population. The lower the population dose, the fewer the number of victims -- but those victims are just as hard-hit as the victims resulting from larger population doses. Similar comments apply to genetic defects.

In most instances, the frequency of occurrence of stochastic effects is found to be proportional to the population dose. This proportionality relationship is referred to as the "linear hypothesis". It is hypothetical in that it can only be verified within certain limited dose ranges. In some cases, at very low doses or very high doses, departures from linearity are observed. These departures may be sub-linear (resulting in a lower-than-expected frequency of occurrence) or supra-linear (resulting in a greater-than-expected frequency of occurrence). Much of the controversy presently surrounding the risk estimates from low levels of ionizing radiation is linked to differing interpretations of or modifications to the linear hypothesis.

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FOOTNOTES

24. Grubbe subsequently required several operations on his hand, including amputation of some fingers. He died of cancer in 1960.
25. The most energetic gamma rays come not from radium-226 itself, but from the short-lived bismuth-214 and lead-214 decay products (radon progeny). In a sealed radium source, equilibrium with radon and its short-lived progeny occurs in about a month. It is more common nowadays to use radon filled capsules called "seeds" for this purpose.
26. Radium-228, called "mesothorium", with a half-life of 5.8 years, was also implicated in some cases; however, the "body burden" left in the skeleton was mainly radium-226.
27. The beta and gamma radiation came from the radon progeny, most of which were not to be found in the bone tissue where the radium was located. This was because the radon gas produced by radioactive decay had mostly migrated away from the bone.
28. Radium-224 is a decay product of the primordial radionuclide thorium-232.
29. William F. Bale (Rochester) and John Harley (New York).
30. To the present day, there remains much uncertainty and controversy over the fate of the unattached decay products. Animal research conducted in the 1970s in France indicates that damage from this quarter may be much greater than hitherto thought.
31. The nucleus of a cell "dissolves" for a short period immediately preceding cell division. In some species, the cells do not have nuclei at all.
32. In addition, a child with "cri-du-chat" syndrome has an abnormally small head, low-set ears and gives a cry resembling that of a cat. A child with the "Wolf-Hirschhorn" syndrome typically suffers from multiple malformations -- such as cleft lip, cleft palate, heart malformations, anomalies of the urinary tract and skeletal deformities.
33. Other than these four, any trisomies which may occur in the uterus probably result in early

abortions -- so they are never seen.

34. These diseases are associated with mental retardation and an elevated incidence of congenital heart disease, together with a host of other symptoms peculiar to each syndrome.
 35. The specified degree of ionization is achieved when a quantity of charged particles of either sign carrying 2.58×10^{-4} coulombs of electrical charge has been produced in dry air, assuming that all the ionizing electrons are stopped in air.
 36. One gray represents one joule (10^7 ergs) of absorbed ionizing energy per kilogram.
 37. This is known as the LD-50, or "lethal dose - 50 percent" value.
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