The effect of radiation on living beings

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Abstract

This overview covers the effects of radiation on living organisms, including risks and legal requirements. It defines basic radiation terms, such as ionization, activity, energy dose, or equivalent dose, and explains direct and indirect radiation effects. It also lists foods that should be avoided after a reactor accident, including the topic of iodine prophylaxis.

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Introduction

Inspired by Wilhelm Conrad Rontgen's (1845-1923) discovery of "X-rays," Antoine Henri Becquerel (1852-1908) [1, 2] investigated uranium compounds for their phosphorescence in 1896 and demonstrated a hitherto unknown type of radiation that blackens photographic plates independently of external influences, in particular excitation by solar radiation: uranium rays. In the same year, he published seven papers on this subject [3-9]. In 1901, Becquerel wrote retrospectively in Nature [10]:

"At the commencement of the year 1896, in carrying out some experiments with the salts of uranium, the exceptional optical properties of which I had been studying for some time, I observed that these salts emitted an invisible radiation, which traversed metals and bodies opaque to light as well as glass and other transparent substances. This radiation impressed a photographic plate … The phenomenon does not appear to be influenced by any known external cause, such as a variation of temperature or a luminous excitation; it is entirely different from phosphorescence; is not weakened in an appreciable manner by time, even at the end of several years; and is emitted spontaneously without any apparent exciting cause."

Becquerel certainly could not have imagined the benefits his discovery would bring to radiology. Today, radioactive substances have become indispensable in modern diagnostics and are of great benefit to many patients: in single-photon emission computed tomography (SPECT), positron emission tomography (PET) or their hybrid technologies combining nuclear medicine with radiology. The use of radioactive substances has also become useful in drug research: For example, some active pharmaceutical ingredients can be directly radioactively labelled with (diagnostic) gamma or positron emitters in order to visualize the mechanism of action of the new drug in the body and to determine pharmacokinetic and pharmacodynamic data from it [11], e.g., in eletriptan, a migraine drug, the intracranial distribution could be studied with PET by directly labelling eletriptan with the positron marker ^{11}C [11, 12].

But radioactive substances are also used for treatment. For example, monoclonal antibodies or peptides are being developed for the treatment of various types of cancer (e.g., non-Hodgkin's lymphomas, neuroendocrine carcinomas), which can be labelled with a beta emitter and used for internal, receptor-mediated radiation therapy [13, 14]. Already early, external radiation with radioactive isotopes was performed: Famous composer Giacomo Puccini, e.g., was treated with radium in 1924 for his laryngeal cancer [15].

Not even 50 years after Becquerel´s discovery, on August 6, 1945, the world's first atomic bomb fell on Hiroshima, and three days later the second on Nagasaki. The extent of the destruction and the effects of the exposed radiation, which continue to this day, exceed anything previously imaginable in an unbearable way. Numerous nuclear weapons tests followed, e.g., at the Bikini Atoll between 1946 and 1958 or in the Nevada Desert between 1951 and 1992, and the peaceful use of nuclear energy also showed its dangers in the reactor meltdown at Chernobyl in 1986 and in 2011 in Fukushima.

Legal requirements

The disasters of Hiroshima and Nagasaki have triggered the formation of various organizations that regulate the legal basis for the use of ionizing radiation at the international, European and national levels. Particularly noteworthy here are the recommendations of the *International Commission of Radiological Protection (ICRP)*, which are the basis for the *European Atomic Energy Act* (EUROATOM) at the international level and, e.g., the Atomic Energy Act in Germany. EURATOM was founded on 25 March 1957 by France, Italy, Benelux countries and Germany within the framework of the *Treaties of Rome* and deals with the handling of radioactive substances.

In addition to EURATOM, there are a number of other organisations; however, their influence on national legislation can be assessed as small:

- UNSCEAR: United Nations Scientific Committee on the Effects of Atomic Radiation (Wien),
- ILO: International Labour Organization of the UN (Geneva),
- IAEA: International Atomic Energy Agency (Vienna),
- WHO: World Health Organization

Radiation risk

When it comes to the effect of radiation on living beings, a distinction must be made between stochastic and deterministic risk:

- **Stochastic risk** is a random event without a threshold dose. If the dose increases, the probability of the risk also increases. Examples of a stochastic radiation risk are genetic DNA damage or tumor induction. The dose size is the effective dose in the mSv range.
- In the **case of deterministic risk**, on the other hand, there is a threshold dose above which the extent of the damage increases with increasing dose. Examples of deterministic radiation damage are radiation erythema or so-called radiation sickness. The dose size is the organ dose in the Sv range.

Stochastic risk

The ICRP 60 (1990) publication bases its recommendations and findings primarily on studies of survivors of the atomic bomb explosions of Hiroshima and Nagasaki [16]. In doing so, it reassessed its earlier data from publication 26 (from 1977) due to a longer observation period, a new dosimetry system and new relative/multiplicative risk models for the extrapolation of stochastic risk. ICRP 60 (1990) determined deaths from radiation-induced cancer per 10,000 people and per sievert at 500 (5%/Sv). The formula 5%/Sv is the stochastic radiation risk for the occurrence of a fatal radiation-induced cancer.

Deterministic risk

In humans, the threshold dose for deterministic radiation damage is 2Sv; transient signs of fatigue and concentration disorders already occur here. At 3 to 4Sv, the median lethal dose $LD_{50/30d}$ is reached. This means that 50% of people die after 30 days at this dose. At 7Sv you have reached the absolute lethal dose, and at >100Sv you are dead immediately.

Poisoning with radioactive material is a case of its own. Pollonium-210 (^{210}Po), e.g., a powerful alpha emitter which decays to lead (^{206}Pb) and has a physical half-life of 138 days, is a radioactive element to which every human being is constantly exposed, but if ingested in high amounts it can lead to vomiting, pain in the abdomen, diarrhea and severe dehydration at the beginning and, in the following days, to hair loss, mucositis and a decrease in platelets and leukocytes until finally multi-organ failure occurs [17].

The $LD_{50/30d}$ for living organisms, bacteria and viruses differs because they have different sensitivity to ionizing radiation.

Radiation terms

Ionizing radiation

Radioactive substances generate ionizing radiation. Ionizing radiation is any particle or electromagnetic radiation that can remove electrons from atoms or molecules so that positively charged ions or molecular residues remain (ionization). These can be the following types of radiation: gamma radiation, X-rays, shorter-wave UV radiation, alpha radiation, beta radiation or free neutrons.

In addition to the direct radiation effect of these ionizing radiation, it is the indirect radiation effect in particular that can cause decisive damage to the cell. This results in reactive products of the radiolysis of the water, which are not provided for in the cell environment and produce an indirect radiation effect through chemical reactions with biomolecules [18].

Activity

The activity of a radioactive substance is the average number of atomic nuclei that decay radioactively per second. The SI unit is the becquerel (Bq), where 1Bq=1 decay/s.

Energy dose

The energy dose D is the mass-specific amount of energy absorbed by an irradiated object over a period of exposure. It depends on the intensity of the irradiation, the absorption capacity of the irradiated material for the given type and energy of radiation, and geometric factors. The SI unit is the gray (Gy), where 1Gy=1J/kg.

Equivalent dose

The equivalent dose H is a measure of the strength of the biological effect of a given radiation dose. This means that equivalent doses of the same size are comparable in their effect on a living being, regardless of the type and energy of radiation.

The following applies: $H=w_R \times D$ where w_R is the radiation weighting factor (formerly quality factor); for gamma radiation and beta radiation it is 1 each, for other types of radiation it can be up to 20 (e.g., w_R of alpha radiation: 20). The dose conversion factor can be used to estimate the equivalent dose from the activity. The SI unit of the equivalent dose is sievert (Sv), where 1Sv =1J/kg.

Direct/indirect radiation effects

Direct radiation effects

Direct radiation effects occur when energy is transferred directly to a biomolecule (DNA, RNA, protein, etc.) by ionizing radiation. A single event may be sufficient to trigger a biological effect (single-hit process); however, multiple hits are sometimes necessary (multi-hit process).

Indirect radiation effect

An organic cell consists mainly of water. Ionizing radiation is therefore very likely (up to 80%) to be absorbed by water molecules. This produces the following reactive products of water radiolysis:

- hydrogen peroxide,
- molecular hydrogen,
- hydrated electrons,
- H and OH radicals,
- in the presence of O_2, also superoxide radicals O_2^- and HO_2.

These products are not intended to be present in the cellular environment and cause indirect radiation effects through chemical reactions with biomolecules.

Mainly the OH radicals produced during water radiolysis (and the subsequent radicals formed by them) react with proteins and cause damage there [18]. They cause the following reactions in proteins (biomolecules):

- Protein (P) + $^{\cdot}$OH→ P-OH→ radical migration
- P$^{\cdot}$OH+P$^{\cdot}$OH→HO-P-P-OH→ recombination reaction, which leads to conformational and possibly structural changes in the protein molecule

Both reactions (radical migration and recombination) are dose-dependent. The probability of recombination increases when the dose rate reaches high values and decreases at low dose rates.

Factors influencing the effect of radiation

The effect of radiation on biomaterial must be regarded as a complex biophysical process that depends on a variety of factors:

- the radiation dose,
- the type of radiation,
- the spatial dose distribution,
- the temporal dose distribution (in fractionated irradiation, radiation damage to healthy cells in the low dose range can be repaired during the irradiation-free intervals; in tumor tissue, the repair capacity is lower; in prolonged irradiation, cell damage can accumulate to a greater extent),
- the tissue environment (a high oxygen content increases the sensitivity of cells to ionizing radiation),
- the radiation sensitivity of the tissue (tissue with a high cell division rate is more sensitive to radiation than tissue with a low cell division rate).

Accumulation in the food chain

After a reactor accident, certain foods should be avoided. At the site of the accident, radioactive substances are deposited in the soil and can then be found in the food chain, sometimes for decades. Important radionuclides in this context are ^{131}I and ^{137}Cs:

- ^{131}I has a physical half-life of 8.02 days. The limit for this radionuclide in Japan at the time of the Fukushima accident was 2000Bq/kg in food and 300Bq/l in tap water.
- ^{137}Cs, on the other hand, has a physical half-life of 30.17 years. The limit for this long-lived radionuclide in Japan was 500Bq/kg in food.

Since the half-life of a radioactive substance is subject to the law:

$$N(t) = N_0\left(\frac{1}{2}\right)^{\frac{t}{t_{1/2}}}$$

with: *N(t):* activity by time t, N_0: initial activity (at time t=0), $t_{1/2}$: physical half-life,
1/8 of the initial activity is measured after 3 half-lives and 1/1024 after 10 half-lives. In ^{137}Cs, the activity is still present at 1/8 after 90 years.

The problem in the food chain is the animals, as they cannot recognize contaminated food. In particular, food contaminated with ^{131}I and ^{137}Cs is fish from the region of a reactor accident. If one looks at the reactor accident in Fukushima, these were mainly fish from the North Pacific such as Alaska pollock, plaice, wild salmon or monkfish. The neighbouring countries and regions were also affected. In the disaster area itself, people had to do without fresh food from the field (especially spinach leaves), meat, fresh milk, sausage and dairy products, mushrooms and berries, and resort to canned food.

Potassium iodide tablets with stable ^{127}I are intended to prevent released radioactive ^{131}I from entering the thyroid gland, in whose follicles iodine is produced for the production of the thyroid hormones triiodothyronine and tetraiodothyronine, also known as thyroxine. This is done by saturating the thyroid gland with non-radioactive ^{127}I from the potassium iodide tablet. This saturation prevents further uptake of radioactive ^{131}I, as the thyroid gland does not distinguish between radioactive and non-radioactive iodine.

However, iodine tablets should never be taken on your own initiative, but only on the recommendation of authorities. From about 45 years of age, there is also a risk of induction of thyroid disease when taking iodine tablets indiscriminately. You should also ask about a possible iodine allergy.

The intake of iodine tablets after the reactor accident in Fukushima was not necessary in Europe.

Radiation in medical diagnostics

In medical imaging diagnostics, radioactive substances and X-rays are used in a targeted manner. However, the radiation doses used are very low and are within the range of radiation exposure that we are already exposed to in Europe through natural annual terrestrial radiation. In our opinion, this does not justify any fear of radiation used in medical diagnostics, and overall, as with all other medical procedures, especially ionizing imaging techniques, it is necessary to carefully weigh the benefits and risks.

Conclusion

In 1908, Becquerel became president of the *Académie des Sciences*. In the same year, on August 25, he died at the age of only 55 from radiation disease in *Le Croisic (Loire-Atlantique)* in Brittany. Becquerel was able to experience the *Belle Époque*; fortunately, he was spared from World War I. His discovery is invaluable to medicine and has also catalyzed many other discoveries in modern atomic physics. Becquerel certainly could not have foreseen the danger that his discovery might bring at the time.

A new type of weapon had been found.

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