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Projet d'exploitation éventuelle d'une
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Radiobiology
129 INSIDE SCIENCE

Radiation and risk

Matthew Gaines

**huge doses, radiation can kill you within hours. In small doses, it can lead to a slow death by cancer.
nd we are all constantly bombarded by natural and artificial radiation, from the sky, from the ground,
om the food we eat and the air we breathe. So just how do we quantify the danger?**

ERY SECOND, more than 100 cosmic rays fly
rough your body. At the same time, several
dioactive atoms in the air you have inhaled dis-
tegrate inside your lungs and a few thousand
tassium atoms and two or three uranium atoms,
hich arrived in your food and drink, break apart
side you and bombard your body with radia-
n. As if that isn't enough, more than 50 000
mma rays enter your body from the soil and the
ilding materials around you. All this is entirely natural. Many of us are also exposed to the artificial radiation that is used in medicine, industry, agriculture and research.

Radiation consists of various kinds of energetic particle. When such fast-moving particles plough through a living body, they alter or destroy the molecular machinery of its cells.

At high intensities, this can kill cells. At low levels, the damaged proteins and other molecules can usually be replaced. Even at low levels, though, radiation can have a significant effect if it interferes with a cell's DNA—the blueprint for making proteins.

BOMBARDED BODIES
Biological effects

Radiation can affect DNA directly by breaking the strands of these molecules. It also leaves a trail of ionised water molecules behind (see Figure 2), and the highly reactive OH⁻ (hydroxide) ions created in this way can change the chemical bases that make up the genetic code.

If vital genes are affected, a cell can be crippled or killed. But with billions of cells in the human body, the losses caused by low levels of radiation do not matter. If the genes that control growth are damaged, however, a cell could begin to divide uncontrollably and become a potentially deadly tumour.

But the development of cancer involves several stages and takes years. And cells aren't helpless. They can repair their DNA to some extent. They have to—even in the absence of radiation, each cell in the body sustains 5000 to 10 000 DNA damage events an hour through processes such as the constant onslaught of **free radicals**, which are produced as a by-product of the reactions within the cell. Cells can even adapt to radioactive environments: a low dose of radiation appears to protect them from the effects of a second dose. Also, cells are programmed to commit suicide when they become too crowded, which can prevent tumours from getting started.

Some scientists, especially in the US and France, believe that with very low doses of radiation these defence mechanisms should always or almost always prevent cancer. In other words, they think that there is a **dose threshold** below which the risk of cancer is nearly zero. But although some studies of biology and disease do hint at such a threshold, there is no firm evidence for it yet. As far as we know, a single particle speeding

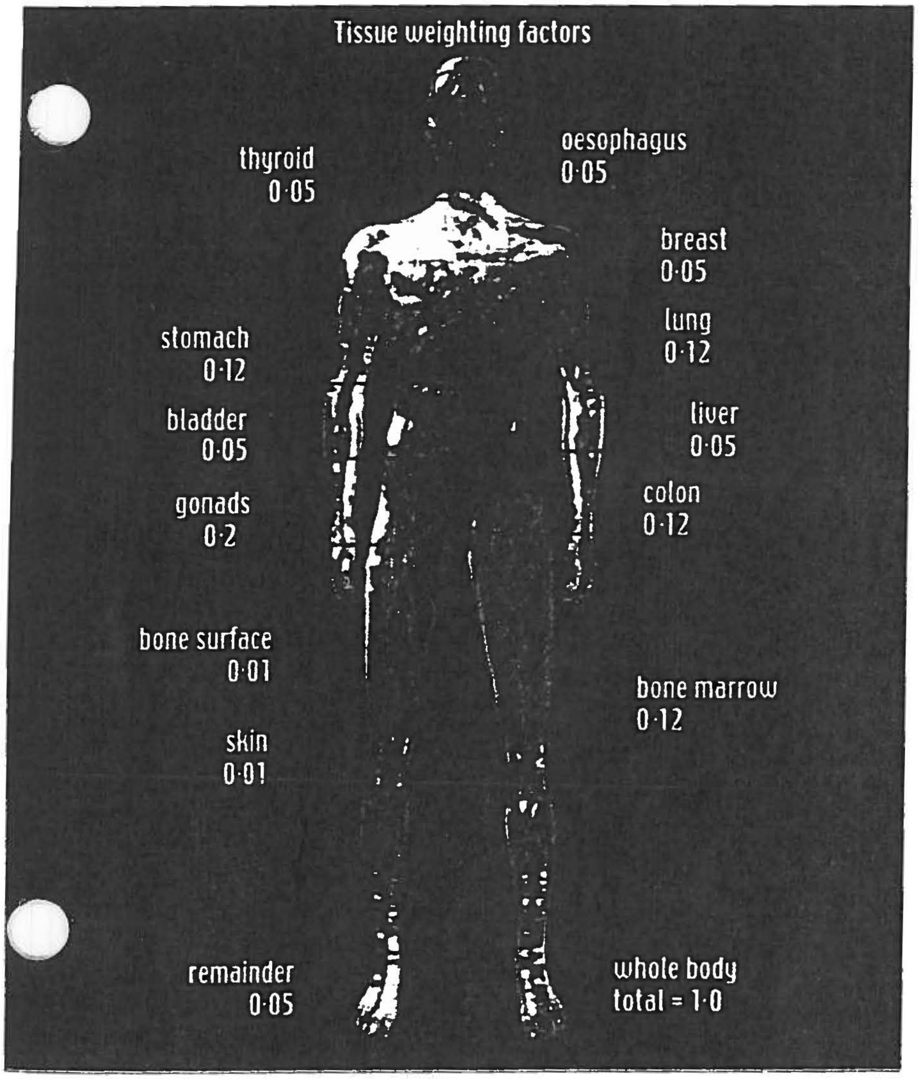

Figure 1: Vulnerable points: the cells in different organs of the body have different susceptibilities to radiation. A certain dose received in the lungs, for example, is more than twice as likely to cause cancer as the same dose hitting the liver

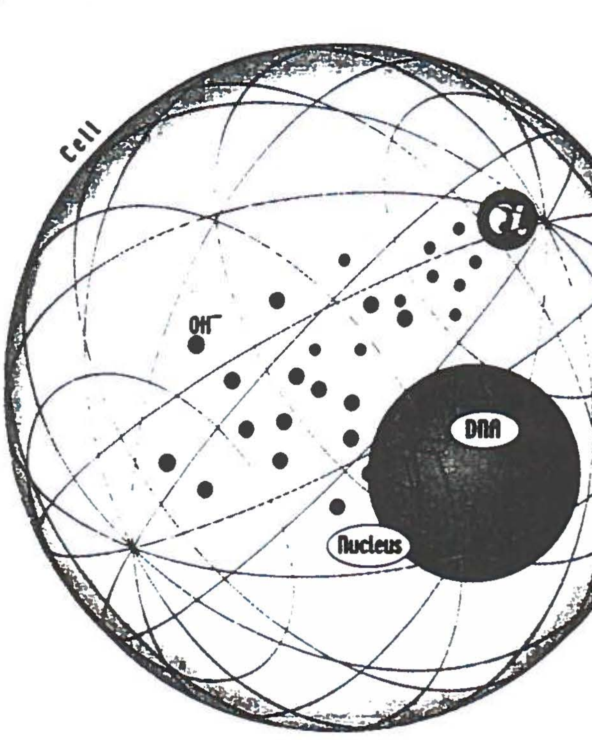

Figure 2: Trail of destruction: a high-energy alpha particle races through a cell, and it can damage DNA directly. It also creates hydroxide ions. These ions are highly reactive, so they attack and damage parts of the cell, including the DNA in the cell's nucleus. That damage can lead to cancer

through a cell nucleus could lead to cancer.

So scientists in most countries make the so-called "**linear, no-threshold**" assumption—that the risk of cancer is in direct proportion to the dose. This means that we try to avoid even very low individual doses, because the more people who receive such doses, the more likely it is that one of them will develop cancer.

Quantifying the risk from radiation is straightforward for high doses. There are many studies of people who have received high doses in a short time—such as the Japanese who survived the bombing of Hiroshima and Nagasaki, and patients who have been deliberately irradiated to kill cancer tumours.

We start by assessing the amount of energy deposited by radiation in a person's tissues—called the **absorbed dose**. The unit is the joule per kilogram, called the **gray** (Gy).

For a person irradiated suddenly, the absorbed dose in grays is a good measure of the risk. In other words, the severity of the symptoms doesn't depend strongly on the type of radiation.

Below 0·25 Gy, there should be no short-term effects. With a dose of between 0·25 and 1 Gy, a person would become nauseous and temporarily sterile. At 1 to 3 Gy, they would vomit, have diarrhoea, and rapidly lose weight. At 3 to 6 Gy, they would have a 1 in 2 chance of dying within weeks from damage to bone marrow and the digestive tract, and those who did survive might be left sterile and blinded by cataracts.

For all survivors, there is a risk of mutations in the DNA of sperm or egg cells that could affect any offspring. In other words, radiation damage can in theory be passed to your children.

More importantly, even low doses carry a risk of cancer. The amount of DNA damage depends on the degree of ionisation, which varies according to the type of radiation. To take account of this, the absorbed dose is multiplied by a "**radiation weighting factor**", which gives the **equivalent dose** (unit, the **sievert**, Sv).

For **beta particles**, which are fast-moving electrons or positrons, and for gamma-rays and X-rays, the weighting factor is 1. **Alpha particles**—heavy particles consisting of two protons and two neutrons—are highly ionising, so they have a much higher factor of 20. For **neutrons** of various energies, the factor ranges from 5 to 20.

What's more, different organs and tissues vary in their sensitivity to radiation. To take account of this, the equivalent dose is multiplied by a tissue weighting factor (see Figure 1 for values) to give the **effective dose** (unit, Sv), which is commonly called the **dose**.

By calculating the dose in this way, different radiation doses to different organs and tissues can be added together to give the total dose. For example, if a radioactive material exposes the lungs, liver and bones to equivalent doses of 100, 70 and 300 millisieverts, the effective dose can be calculated as follows: $100 \times 0{\cdot}12 + 70 \times 0{\cdot}05 + 300 \times 0{\cdot}01 = 18{\cdot}5$ mSv. The risk of harmful effects would be the same as that from 18·5 mSv received uniformly throughout the whole body.

OUR DAILY DOSE

The rocks beneath our feet

The final stage is to convert the effective dose to a risk of death. The **International Commission on Radiation Protection** (ICRP), based in Stockholm, has calculated an average risk factor for the world population of 0·05 Sv^{-1} (or 5×10^{-5} mSv^{-1}). This means that if you receive a dose of 1 Sv, your risk of dying from cancer caused by this radiation is 5 per cent; if you receive 1 mSv your risk is 5×10^{-5}, or 5 in 100 000.

As the worldwide average dose received by a person is 2·7 mSv per year, the corresponding risk of death from cancer is $2{\cdot}7 \times 5 \times 10^{-5}$, or 1 in 7400 per year. For comparison, the yearly risk of death in Britain from smoking 10 cigarettes a day is 1 in 200, while being killed in a road accident is 1 in 17 000, and being murdered is 1 in 100 000 each year. So radiation risk is certainly not negligible.

For a working population, the risk factor is lower, because it does not contain children (who have more years in which to develop cancer after exposure). ICRP's risk of death for workers is 0·04 Sv^{-1}.

Clearly, no practice involving exposure to radiation should be adopted unless it produces a net benefit to those exposed or to society as a whole. This is the principle of "**justification**". Even then, radiation doses and risks should be kept as low as possible, taking economic and social factors into account. This conclusion follows from the linear, no-threshold assumption and has resulted in huge efforts to reduce doses to patients, workers and the general public.

It is considered unacceptable to expose someone to a high risk of death, even if society would benefit. Just what should the limit be? Two bodies in Britain have attempted to quantify "acceptable" risk: the Royal Society, reporting in 1983, and the Health and Safety Executive—the government's main health and safety organisation—in 1988 and 1992.

Workers choose to risk exposure, whereas the public is likely to be exposed unwillingly or unknowingly. So the studies looked at the different attitudes in each case, comparing the risks from radiation with commonly accepted risks such as those from driving a car.

For workers, the Health and Safety Executive recommends a dose limit of 20 mSv in a year, equivalent to an annual risk of death due to irradiation of 1 in 1000. The public dose limit is 1 mSv in a year, equivalent to a risk of fatal cancer of 1 in 20 000. The ICRP says a higher dose is acceptable in some years, providing the average over 5 years does not exceed 1 mSv a year. Most developed countries have enshrined these principles of radiation protection in law.

Natural sources of radiation are generally hard to avoid (Figure 3). **Cosmic rays**, for example, are high-energy protons and electrons that come from the Sun and outer space. Cosmic rays are more intense at high altitudes, because they are gradually absorbed by the atmosphere, so aircrews and people living at altitude receive more radiation (Figure 4). The intensity of cosmic rays is about 20 per cent lower indoors, because buildings also absorb them.

The Earth is laced with radioactive isotopes. Uranium and thorium emit alpha particles, and potassium-40 (which makes up about three millionths of the Earth's crust) emits beta particles. These materials also give off gamma rays when they decay and uranium and thorium both leave behind further unstable isotopes in the rocks and soils. People are exposed to this radiation even indoors, because building materials are extracted from the Earth and are therefore radioactive. So the radiation dose rate depends upon the local geology and the building materials.

We all also eat, drink and breathe natural radioactive materials. Drinking water contains radioisotopes, as do edible plants and animals, and even the dust in the air.

Radioactive materials, especially potassium-40, are particularly concentrated in some foods, so people who eat a lot of these foods can receive doses well above the average. The main culprit is shellfish: eating an 80-gram jar of mussels every week would add about 50 per cent to your dietary dose in Britain.

Finally, uranium and thorium in rocks and soil decay to form the radioactive gas **radon**. Radon leaks into the atmosphere where people inhale it and its decay products, irradiating their lungs. Outdoors the gas disperses, but in buildings high concentrations can build up. Studies from Britain and Sweden have shown a link between radon in houses and death from lung cancer.

The radon risk depends on local geology, weather and ventilation, but its concentration tends to be higher in houses built on granite, limestone and alum shale, especially if these materials are also used in construction. The global average annual dose due to radon is 1·3 mSv, but the highest dose ever recorded was nearly a hundred thousand times greater. In one house in Pennsylvania, residents received lung doses of 91 Sv a year, with a risk of fatal cancer of about 13 in 100 a year. This frighteningly high concentration was discovered when the occupant triggered the alarm bells at the nuclear power station where he worked—as he was entering the site.

Fortunately, there's an easy way to get rid of radon: a fan under the floor can blow it out through a pipe before it enters a building. Compared with all the natural sources of radiation, artificial sources, such as discharges from nuclear and conventional power stations, give people much lower doses.

Fallout from nuclear weapons and reactors is less of a problem than it once was. More than 500 atmospheric nuclear tests were conducted in the 1950s and 1960s, but the consequent doses to people peaked in the early 1960s and are now much lower: in Britain, the yearly doses have fallen from 0·140 mSv in 1963 to 0·004 mSv now.

Meanwhile, the US is spending billions of dollars to clean up areas contaminated by its ground-based nuclear testing programme of the 1940s and 1950s. This expense is one reason to question the linear, no-threshold assumption. If the cancer risk to individuals from very low doses is zero, or much smaller than the linear assumption implies, then there is little point in spending vast sums to clean these areas up because even the total risk to the populace will be low. The money could be better spent elsewhere.

The Chernobyl accident in 1986 released huge amounts of radioactive material over Europe and beyond. At the time, 31 people, mostly firemen, died from acute radiation poisoning after being exposed to huge doses. Since then several children and adolescents in the Chernobyl region have died of thyroid cancer, caused by radioactive iodine. The accident also caused psychological trauma, including anxiety and depression, in the surrounding population.

ENVIRONMENTAL EFFECTS

What to do with the wastes?

It is harder to assess the number of deaths from the Chernobyl accident farther afield, but the risks are not negligible. In Bucharest, for example, a rainstorm collected radioactive dust from the air and deposited it onto the city. Outside Ukraine, Russia, Belarus and Romania, doses were low. In Britain in 1986, the average individual dose was 0·02 mSv a year, which has now declined to 0·001 mSv. So although the NRPB estimated that up to 3000 extra cancer deaths will eventually occur in Western Europe because of Chernobyl, this estimate relies on the linear no-threshold assumption. There were also some long-term environmental effects. Even now, sheep from some areas of Scotland, Wales and Cumbria—nearly 3000 kilometres away from Chernobyl—cannot be sent to market because the land is still contaminated.

There have also been accidents at Windscale (which was subsequently renamed Sellafield) in Britain in 1957 and at Three Mile Island in Pennsylvania in 1979. Radioactive iodine from the Windscale accident is estimated to have given some infants thyroid doses of up to 160 mSv. At Three Mile Island, the highest individual dose was 0·8 mSv.

The worldwide nuclear industry now takes more care in the design, construction and operation of reactors. Since the Chernobyl accident, huge sums have been spent to improve the safety of similar reactors in the former Soviet Union, and another accident on the scale of Chernobyl seems unlikely.

Occasionally, a satellite containing radioactive materials has crashed to Earth, but this is rarely much of a danger. In 1978 the Soviet nuclear-powered satellite Cosmos 954 crashed in northern Canada. A large area was contaminated, but fortunately it was sparsely populated wilderness.

The routine discharges of radioactivity from civil nuclear plants, defence installations, hospitals, industry and research centres have to be authorised by governments and monitored, mainly by collecting and analysing samples of grass, milk, food, water and so on. For all discharges—nuclear and non-nuclear combined—the average total dose to people worldwide is 0·001 mSv each year.

If waste is not discharged, it has to be stored in the plant and eventually disposed of in a more permanent way. The aim is to reduce the chance that water will dissolve waste and carry it back to people. This is done by having several layers of containment.

Low-level waste includes contaminated paper, clothing, lab equipment, soil and building materials. In Britain it is put in metal drums and buried in shallow trenches.

Intermediate-level wastes, such as sludges that accumulate in the cooling ponds where the spent fuel from nuclear plants is stored, can be mixed with inert material such as concrete, bitumen or resin before being put into drums.

High-level wastes include spent nuclear fuel

Sources and average worldwide doses of radiation

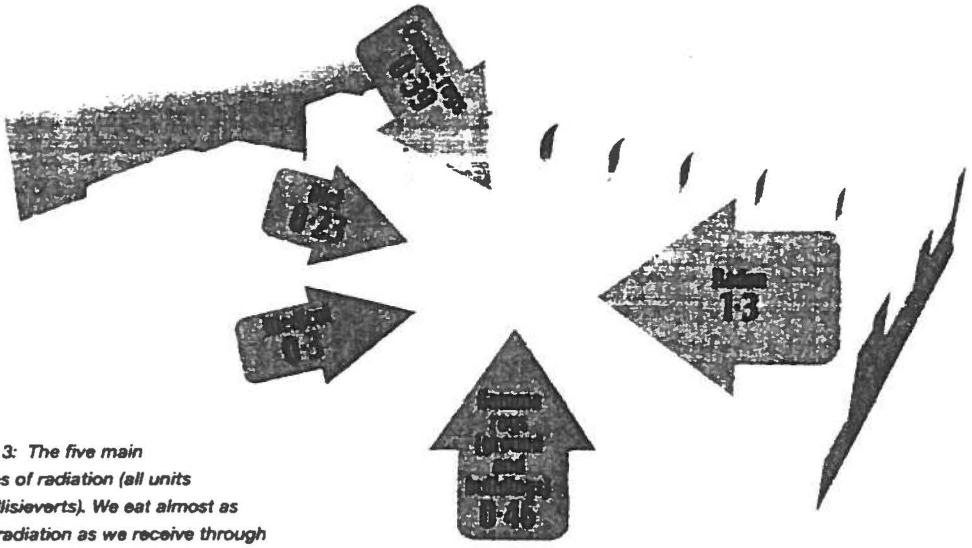

Figure 3: The five main sources of radiation (all units are millisieverts). We eat almost as much radiation as we receive through medical X-rays and other treatments. Then come cosmic rays and radiation from rocks and building materials. But the greatest source is radon gas

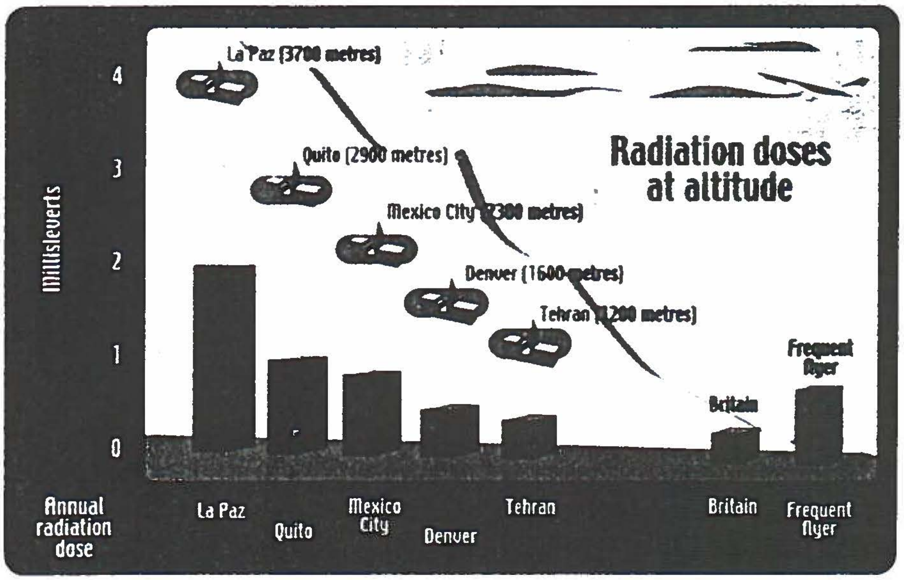

Figure 4: High risk: yearly doses from cosmic rays vary with altitude. Frequent flyers can get around twice the average cosmic-rays dose, and the residents of La Paz, 4000 metres above sea level, get a whopping 2 millisieverts a year

and the liquors left over when fuel is reprocessed, as at Sellafield. They are not very bulky, but the intensity of their radioactivity means that they give off a lot of heat, making their storage and disposal difficult. They can be stored temporarily as liquids in cooled tanks. In the long term, most countries plan to incorporate them into glass blocks, which are then put in metal and concrete vessels and buried, preferably in rocks that allow little ground water to pass through.

In Britain, no permanent waste disposal facility for medium and high-level waste yet exists. At Sellafield, for example, most radioactive waste is stored in the plant—clearly only a short-term solution. But other countries have made much more progress. Sweden already operates an underground repository at Forsmark, about 120 kilometres north of Stockholm, for low and intermediate level wastes. Finland also has an underground facility and France, the US, Belgium, Canada, Germany, Japan, Spain and Switzerland are all planning deep disposal sites.

The proposed US repository at Yucca Mountain in Nevada is supposed to keep high-level waste safe for at least 10 000 years. Environmental groups dispute the geological stability of this site. But in defence of deep burial, scientists point out that a natural nuclear reactor operated at Oklo in Gabon, Africa, more than 1·7 billion years ago, and the radioactivity never moved from the site (*New Scientist*, 31 May 1997, p 5).

Various forms of radiation are widely used in industry, for example, to analyse welds, check levels in containers and sterilise medical products. When workers are regularly exposed to radiation, the doses they receive can be measured by small film badges which darken after a high dose, or by **thermoluminescent dosimeters**, which release light in proportion to the radiation dose when they are subsequently heated.

The UN estimates that more than 9 million people worldwide are exposed to radiation at work. Most are exposed to artificial radiation, but those with increased natural radiation exposure, such as miners and office workers in high-radon areas, usually get much greater doses. Taking natural and artificial occupational doses into account, the average dose to monitored workers worldwide is 1·4 mSv in a year.

INDUSTRIAL APPLICATIONS

In sickness and in health

The main source of artificial radiation for most of us is medicine. Many diagnostic tests, such as chest, spine and skull X-rays, and barium enemas and meals, involve much lower doses than in the past: they have fallen by about 30 per cent in the past decade. But the newer technique of **computed tomography** (CT), while providing a lot more information for the doctor than a conventional X-ray, gives much higher doses. In CT, a scanner rotates a fan-shaped beam of X-rays around the patient. A computer uses the resulting information to construct an image of a slice through the patient. For an ordinary chest X-ray examination the dose is 0·017 mSv, but it is 8 mSv for a CT scan of the same part of the body.

In diagnostic nuclear medicine, the patient is given a radioactive isotope, such as technetium-99m, attached to a substance that is taken up by the organ or tissue being investigated. The distribution of the radioisotope, which is revealed by the gamma radiation it emits, shows how well the organ is functioning. Doses vary between 1 and 7 mSv, depending upon the organ examined.

Much higher doses are needed to treat diseases such as cancer, because the diseased cells must be killed. The dose to the tumour can be tens of grays. To give surrounding healthy cells a better chance of recovery, it is spread over many days.

A radioactive material can be swallowed (iodine-131 is used to treat overactive thyroid glands, for example) but beams of radiation are more common. X-rays, gamma rays or electrons are often directed at the diseased tissue from various directions, to give a high dose to the tumour but reduce the dose to the healthy tissue around it. The total exposure is the same, but spreading it over a greater area gives the healthy body cells smaller individual doses and therefore a greater chance of recovery. The average yearly dose worldwide from radiology and nuclear medicine combined is about 0·3 mSv.

In the past, radioactive materials were used in jewellery, uranium as colouring in glassware and radium in watch dials and other instruments, but their use is now considered to be unjustified in most countries. Some products containing artificial radioactivity, such as smoke detectors, are still in use. They give annual doses to the public that are tiny—about 0·0005 mSv worldwide, on average. That's equivalent to a 1 in 40 million risk of death from cancer per year.

What of the future? The linear, no-threshold assumption has meant heavy expenditure to reduce some very small doses. Roger Clarke, the chairman of ICRP, believes that greater efforts should be made to reduce the more significant doses, especially to patients and workers. The emphasis should be on the individual: if the risk of harm to the health of the most exposed person is negligible, then the total risk should be considered negligible, no matter how many people are exposed.

FURTHER READING

Living with Radiation by the National Radiological Protection Board (from NRPB or HMSO, £10·95)

At a Glance series of broadsheets, free in small quantities from NRPB; *Radiation* (a poster for schools), Hobsons Publishing, Cambridge; *Radioactivity* (a poster from *New Scientist*, tel 020 7331 2715), which includes a chart of all the radioactive isotopes; *Canada: Living with Radiation* (Canadian Atomic Energy Control Board: available in English and French); *Henri Becquerel and the Discovery of Radioactivity* (the Association for Science Education/NRPB).

Matthew Gaines was press officer for the NRPB from 1972 to 1997.
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