

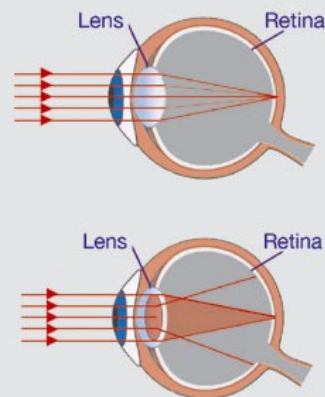
Chapter 5 Radiation effects

Radiation doses of different sizes, delivered at different rates to different parts of the body, can cause different types of health effect at different times.

A very high dose to the whole body can cause death within weeks. For example, an absorbed dose of 5 gray or more received instantaneously would probably be lethal, unless treatment were given, because of damage to the bone marrow and the gastrointestinal tract. Appropriate medical treatment may save the life of a person exposed to 5 gray, but a whole body dose of, say, 20 gray would almost certainly be fatal even with medical attention. A very high dose to a limited area of the body might not prove fatal, but other early effects could occur. For example, an instantaneous absorbed dose of 5 gray to the skin would probably cause erythema — painful reddening of the skin — within a week or so, whereas a similar dose to the reproductive organs might cause sterility. These types of effect are called *deterministic effects*: they occur only if the dose or dose rate is greater than some threshold value, and the effect occurs earlier and is more severe as the dose and dose rate increase. Deterministic effects in an individual can be identified clinically to be the result of radiation exposure (although on the few occasions when they have occurred as a result of accidents — see Chapter 14 — they have not always been immediately recognized as such).

One type of deterministic effects occurs a longer time after exposure. Such effects are not usually fatal, but can be disabling or distressing because the function of some parts of the body may be impaired or other non-malignant changes may arise. The best-known examples are cataracts (opacity in the lens of the eye) and skin damage (thinning and ulceration). High absorbed doses of several gray are normally required to induce these conditions.

If the dose is lower, or is delivered over a longer period of time, there is a greater opportunity for the body cells to repair, and there may be no early signs of injury. Even so, tissues may still have been damaged in such a way that the effects appear only later in life (perhaps decades later), or even in the descendants of the irradiated person. These types of effect are called *stochastic effects*: they are not certain to occur, but the



Deterministic effects on vision

Normal lens — light is focussed normally on the retina

Lens with cataract — opacity of the lens blocks or distorts light from being focussed on the retina, resulting in reduced vision

likelihood that they will occur increases as the dose increases, whereas the timing and severity of any effect does not depend on the dose. Because radiation is not the only known cause of most of these effects, it is normally impossible to determine clinically whether an individual case is the result of radiation exposure or not.

Induction of cancers

The most important of these stochastic effects is cancer, which is always serious and often fatal. Although the exact cause of most cancers remains unknown or poorly understood, exposure to agents such as tobacco smoke, asbestos and ultraviolet radiation, as well as ionizing radiation, are known to play a role in inducing certain types of cancer. The development of cancer is a complex, multistage process that usually takes many years. Radiation appears to act principally at the initiation stage, by introducing certain mutations in the DNA of normal cells in tissues. These mutations allow a cell to enter a pathway of abnormal growth that can sometimes lead to the development of a malignancy.

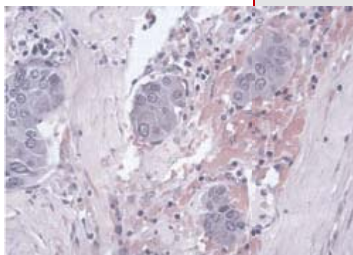
Given that we cannot distinguish between those cancer cases resulting from radiation exposure and those with other causes, how can we calculate the risk of cancer from radiation? In practice, we have to use epidemiology — the statistical study of the incidence (the number of cases and their distribution) of specific disorders in specific population groups. Suppose that we know the number of people in an irradiated group and the doses they have received. Then by observing the occurrence of cancer in the group and comparing with the doses and the number of cancers expected in an otherwise similar but unirradiated group, we can estimate the raised risk of cancer per unit dose. This is commonly called a *risk factor*. It is most important to include data for large groups of people in these calculations so as to minimize the statistical uncertainties in the estimates and take account of factors, such as age and gender, that affect the spontaneous development of cancer.

Not all cancers are fatal. Average mortality from radiation-induced thyroid cancer is about 10 per cent (although it is much lower — less than 1 per cent — for the cases caused in children and teenagers by the Chernobyl accident), from breast cancer about 50 per cent, and from skin cancer about 1 per cent. Overall, the total risk of inducing cancer by uniformly irradiating the whole body is about half as great again as the risk of inducing a fatal cancer. In radiological protection the risk of fatal cancer is of more concern because of its extreme significance. The use of fatal cancer risks also makes it easier to compare them with the other fatal risks encountered in life. In contrast, comparisons of non-fatal risks are fraught with difficulty.

Risk assessments

The main sources of information on the additional risk of cancer following exposure of the whole body to gamma radiation are studies of the survivors of the atomic bombs

*Follicular
Carcinoma of
Thyroid*
A.K. Padhy/IAEA



dropped on Hiroshima and Nagasaki in 1945. Because a substantial number of the people who survived the bombings are still alive today, it is necessary to predict how many extra cancers will eventually be found to have occurred in the exposed population. Various mathematical methods are used for this purpose, but this is inevitably another source of uncertainty in the risk estimates. Yet another source of uncertainty is that the doses received by the survivors can only be estimated from whatever information is available, and different assessments have reached somewhat different conclusions.

Other risk estimates for the exposure of various tissues and organs to X rays and gamma rays come from people exposed to external radiation for the treatment of non-malignant or malignant conditions and for diagnostic purposes, and also from people in the Marshall Islands exposed to severe fallout from atmospheric nuclear weapons tests. Information on the effects of alpha-emitting radionuclides comes from miners exposed to radon and its decay products, from workers exposed to radium-226 in luminous paint, from some patients treated with radium-224 for bone disease, and from other patients given an X ray contrast medium containing thorium oxide.

Information of this nature is assessed periodically by UNSCEAR and by the International Commission on Radiological Protection (ICRP) in order to determine the most appropriate risk estimates; in the case of ICRP, these risk estimates are developed for the purpose of developing recommendations for protection. The IAEA develops its radiation safety standards taking account of the advice of UNSCEAR and ICRP.

Risk factors for cancers

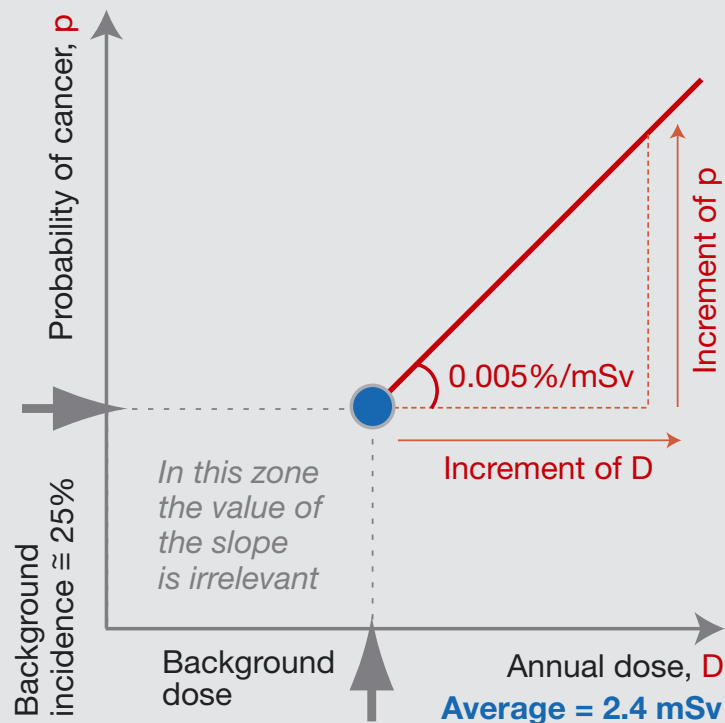
Most of the Japanese atomic bomb survivors and other exposed groups studied received high doses over short periods of time. Observations of the cancer incidence in these groups, along with estimates of the doses they received, indicate that, for high doses and high dose rates, there is a linear relationship between dose and risk. Thus, for example, doubling the dose would double the risk.

However, most radiation exposure involves low doses delivered over long periods. At these low levels of exposure, studies of cancer incidence in the exposed population do not provide any direct evidence about the relationship between dose and risk, because the number of extra cancers that might be expected to result from the radiation exposure is too small (compared to the total number of cancer cases in the population) to detect. It is, therefore, necessary to consider other scientific information about the effects of radiation on cells and organisms and to form a judgement as to the most likely form of the dose–risk relationship. For many years, the internationally accepted solution has been to assume that the relationship is linear for low doses, all the way down to zero (known as the ‘linear–no threshold’ or LNT hypothesis), i.e. that any radiation dose has a detrimental effect, however small. However, some radiobiological experiments have been interpreted as suggesting that low doses of radiation have no detrimental effect, because the body can successfully repair all of the damage

caused by the radiation, or even that low doses of radiation may stimulate the repair mechanisms in cells to such an extent that they actually help to prevent cancer. Other experiments have been used as the basis for theories that low doses of radiation are more harmful (per unit of dose) than high doses, or that the hereditary effects of radiation could get worse from generation to generation.

After a major review of biological effects at low doses of ionizing radiation, UNSCEAR concluded in 2000 that “...an increase in the risk of cancer proportionate to radiation dose is consistent with developing knowledge and it remains, accordingly, the most scientifically defensible approximation of low dose response”. However, UNSCEAR also accepted that there are uncertainties and stated that “... a strictly linear dose response relationship should not be expected in all circumstances”.

Dose–risk
hypothesis



For some types of strongly ionizing radiation, such as alpha particles, the *risk factor* is the same at low doses as at high doses, but for weakly ionizing radiation, such as gamma rays, there is considerable radiobiological evidence that the picture is more complicated. For these types of radiation, a linear relationship is a good approximation of dose response for both the low dose and high dose regions, but the risk per unit dose (the slope of the linear relationship) is less at low doses and dose rates than at high doses and dose rates. ICRP has estimated the risk factors for fatal cancers from low doses and dose rates in this way using a judicious reduction factor of two.

In reality, the risk to an actual person from a given dose will depend on that person's age at the time of the exposure and on their gender. For example: if a person receives a dose late in life, a radiation-induced cancer may not have time to appear before the person dies of another cause; and the risk of breast cancer is virtually zero for men and twice the listed 'average' value, 0.4×10^{-2} or 1 in 250 per Sv, for women. Furthermore, recent advances in knowledge indicate that a person's genetic constitution can influence their risk of cancer after irradiation. At present, we can identify only rare families who may carry increased risk, but experts may in future be able to take some account of such inherited traits.

Risk factors are also different for different populations. This is partly because different populations have different distributions of ages. For example, since the average age of a population of workers is generally higher (and therefore their life expectancy is shorter) than that of the population as a whole, the risk factor for the former is somewhat lower than that for the latter. The ICRP risk factor for workers is 4×10^{-2} or 1 in 25 per Sv. Different risk factors can also result from differences in the prevailing incidence of cancer (or even particular types of cancer) from all causes, because the risk from radiation is assumed to be related to this prevailing incidence. For example, the risk factor for countries with a relatively high level of cancer mortality (e.g. developed countries) would be higher than for those where cancer is less common (e.g. developing countries). However, such differences are fairly small compared to the uncertainty in the ICRP risk factors, and therefore the ICRP values — which are based on 'averaging' over the characteristics of five disparate national populations — can reasonably be used internationally.

ICRP risk factors for fatal cancers for the whole population

<i>Tissue or organ</i>	<i>Risk factor ($\times 10^{-2} \text{ Sv}^{-1}$)</i>
<i>Bladder</i>	0.30
<i>Bone marrow (red)</i>	0.50
<i>Bone surfaces</i>	0.05
<i>Breast</i>	0.20
<i>Colon</i>	0.85
<i>Liver</i>	0.15
<i>Lung</i>	0.85
<i>Oesophagus</i>	0.30
<i>Ovary</i>	0.10
<i>Skin</i>	0.02
<i>Stomach</i>	1.10
<i>Thyroid</i>	0.08
<i>Remainder</i>	0.50
<i>Total (rounded)</i>	5.00

Hereditary disease

Apart from cancer, the other main late effect of radiation is hereditary disease. As with cancer, the *probability* of hereditary disease — but not its severity — depends on dose. Genetic damage arises from irradiation of the testes and ovaries, which produce sperm cells in males and the egg cells in females. Ionizing radiation can induce *mutations* in these cells or in the germ cells that form them, mutations which may give rise to harmful effects in future generations. Mutations occur as a result of structural changes to the DNA in single germ cells, which subsequently carry the hereditary information in the DNA through future generations. The hereditary diseases that may be caused vary in severity ranging from early death and serious mental defects to relatively trivial skeletal abnormalities and minor metabolic disorders.

Although mutations appear to arise in human beings without any apparent cause, natural radiation and other agents in the environment may also cause them and contribute to the prevailing occurrence of hereditary disease. There has, however, been no conclusive evidence in human offspring for hereditary defects attributable to exposure from natural or artificial radiation. Extensive studies of the offspring of the survivors of the atomic bombs, in particular, have failed to show increases of statistical significance in hereditary defects. Instead, the negative findings help to provide an upper estimate of the risk factor for them.

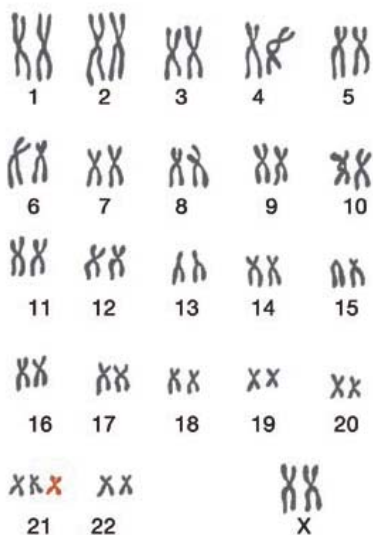
Large experimental studies have been made of the hereditary damage that ionizing radiation induces in animals, mainly mice. These have covered a wide range of doses and dose rates and clearly demonstrate that ionizing radiation does cause mutations. The results also show how often hereditary defects are induced by known doses. When considered with the findings for the atomic bomb survivors, this information allows estimates to be made of hereditary risk for human beings.

Against this background, ICRP has assessed the risk of severe hereditary disease in a general population exposed to low doses and dose rates. It estimated a risk factor of $1.0 \times 10^{-2} \text{ Sv}^{-1}$ or 1 in 100 per Sv for such diseases appearing at any time in all future generations. Mutations leading to diseases that are strictly heritable, such as haemophilia and Down's Syndrome, make up about half of the total: the remainder comes from a group of so-called multifactorial diseases, such as diabetes and asthma. This estimate of risk carries considerable uncertainty especially for the multifactorial diseases where the interplay of the genetic and environmental factors that influence the disorders is poorly understood.

Irradiation of the testes and ovaries only carries a risk of hereditary effects if it occurs before or during the reproductive period of life. Since the proportion of a working population that is likely to reproduce is lower than that in the general population, the risk factor for workers is smaller. The ICRP estimates the risk to a working population at $0.6 \times 10^{-2} \text{ Sv}^{-1}$ or 1 in 170 per Sv for severe hereditary diseases in all future generations.

More recent assessments indicate that the risks of hereditary effects may actually be lower than these earlier estimates, particularly for the multifactorial diseases. In its 2001 Report to the UN General Assembly, UNSCEAR presented a comprehensive review of hereditary risks of exposure to radiation. For a population exposed to radiation in one generation only, the risks to the first post-irradiation generation were estimated to be 0.3–0.5 per cent per Gy. This is between one-third and one half the ICRP estimate for all generations quoted above. The risks to generations other than the first are much lower than this. Put another way, this new estimate of risk per gray is of the order of 0.4–0.6 per cent of the baseline frequency of these disorders in the human population.

Chromosome 21
abnormality
in female with
Down's Syndrome



Communal risk

An important consequence of the assumption that risk is proportional to dose, without a low dose threshold, is that the collective effective dose becomes an indicator of communal harm. Under this concept it makes no difference mathematically whether, in a community of 50 000 people, each receives an effective dose of 2 mSv, or in a community of 20 000 people, each receives 5 mSv; the collective dose in each community is 100 man Sv, and the communal cost in each community may be five cancer deaths and one severe hereditary defect in future generations. Members of the smaller community, however, run the greater individual risk of fatal cancer. However calculations of collective dose should not be taken too far: the product of an infinite number of people and an infinitesimal dose is likely to be meaningless.

Irradiation in pregnancy

The risks to children irradiated while in the womb deserve special mention. If an embryo or foetus is exposed to radiation at the time when organs are forming, developmental defects such as a reduced diameter of the head or mental retardation may be caused. Studies on survivors of the atomic bombs who were exposed before birth have indicated that mental retardation mainly follows exposure during the period between 8 and 15 weeks after conception. There has been debate over the form of the relationship between dose and response and the existence of a threshold below which there is no effect. For exposures during the most sensitive 8–15 week period, however, ICRP assumes that the decrease in IQ depends directly on the dose without a threshold and with a loss of 30 IQ points per Sv. So, for example, exposure of the foetus to 5 mSv during this stage of pregnancy would lead to a loss in IQ of 0.15 point, which would be undetectable.

High doses to the embryo and foetus can cause death or gross malformation. The threshold for these effects is between 0.1 Sv and 1 Sv or more depending on the time after conception. Genetic risks to foetuses are judged to be the same as those for a fully reproductive population after birth, namely $2.4 \times 10^{-2} \text{ Sv}^{-1}$ or 1 in 40 per Sv. Irradiation before birth can also lead to an increased risk of malignancy in childhood. The risk of fatal cancer up to age 15 years is estimated to be about $3.0 \times 10^{-2} \text{ Sv}^{-1}$ or 1 in 30 per Sv, and the overall risk of cancer about twice this value.

For all of these reasons it is best for pregnant women to avoid diagnostic X rays of the abdomen unless a delay until the end of pregnancy would be undesirable. Indeed for all women of reproductive age where pregnancy cannot be reasonably excluded, it may be prudent to restrict diagnostic procedures that give high doses in the pelvic area to the early part of the menstrual cycle when pregnancy is least likely. Special restrictions apply to the doses that pregnant women may receive if they are employed in work with radiation sources, with the intention that the unborn child should receive the level of protection accorded to members of the public.

Harmful radiation effects

Circumstances of exposure	Health consequences	Sources of information
<i>High dose and dose rate to much of the body to area of skin to testes and ovaries</i>	<p>Early effects</p> <p>Death Erythema Sterility</p>	<i>Human data from various sources</i>
<i>Any dose or dose rate Risk depends on dose Appear years later</i>	<i>Various cancers</i>	<i>Risk factors for human beings estimated by extrapolating human data for high doses and dose rates</i>
<i>Any dose or dose rate Risk depends on dose Appear in offspring</i>	<i>Hereditary defects</i>	<i>Risk factors for human beings inferred from animal data and the absence of human evidence</i>
<i>High dose at any rate Various times to appear</i>	<i>Functional damage</i>	<i>Human data from various sources</i>
<i>Dose in the womb Appears in the child</i>	<i>Mental retardation</i>	<i>Limited human data</i>