Radiation Matching:

Dose	Source
(1) 0.005 mrem	a) Airplane flight from NY to LA
(2) 0.009 mrem	b) Background dose for one day
(3) 0.01 mrem	c) Dental X-ray
(4) 0.03 mrem	d) Eating one banana
(5) 0.12 mrem	e) Living in a stone, brick, or concrete building for a year
(6) 0.5 mrem	f) Living within 50 miles of a coal power plant for one year
(7) 1 mrem	g) Living within 50 miles of a nuclear power plant for one year
(8) 4 mrem	h) Lowest one-year dose clearly linked to increased cancer risk
(9) 7 mrem	i) Radiation poisoning (acute dose)
(10)100 mrem	j) Sleeping next to someone
(11)10,000 mrem	k) Spending a day on the Colorado plateau
(12)26,000 mrem	l) Typical dose over two weeks in Fukushima Exclusion Zone
(13)40,000 mrem	m) Yearly dose living in Ramsar, Iran

Getting to know radiation units:

(1) Convert between Gray and a Rad:

1 rad = _________________________ Gray

(2) List units of absorbed radiation dose: _________________ and ___________________

(3) List units of dose equivalent radiation: _________________ and __________________

(4) List units of exposure: _________________ and __________________

(5) Convert 1 Gray/year to rem/year

Given: 1 Sievert = 1 Gray * QF
In this case, the source is gamma radiation (ie the quality factor =1).

(6) The acute exposure data of the Hiroshima survivors suggests that the threshold (NOAEL = no observed adverse effects level) for a short-duration radiation dose to induce leukemia is about 500 mSv. How many rem is this?

(7) The dose-rate threshold (NOAEL = no observed adverse effects level) for gamma radiation-induced reduction in lifespan in dogs is estimated at 700 mGy per year. How many rem per year is this?

Answers to Radiation Matching
(1) j (2) g (3) d (4) f (5) k (6) c (7) b (8) a (9) e (10) l (11) h (12) m (13) i

1. 1 rad = 0.01 Gray
2. Rad and Gray
3. Rem and Sievert
4. Roentgen and Coulomb/Kilogram
5. 1 Gray *1 = 1 Sieverts
   1 Sieverts = 100 rem
   For gamma radiation: 1 Gray/year = 100 rem/year
6. 50 rem
7. 70 rem per year

Current radiation protection limits: An urgent need for change

Appropriate revisions to radiation protection guidelines for medical and nuclear power applications will ultimately lead to major public health and economic benefits.

By Jerry M. Cuttler and William H. Hannum

Following the February 24 signing of Executive Order 13777, "Enforcing the Regulatory Reform Agenda," by President Donald Trump, Environmental Protection Agency Administrator E. Scott Pruitt issued a memorandum to EPA staff on March 24. This led to the EPA's April 11 announcement that it was seeking input on regulations that may be appropriate for repeal, replacement, or modification. On April 13, the EPA published a notice in the *Federal Register* that established Docket ID EPA-HQ-OA-2017-0190 to receive comments up until May 15. A total of 98,543 submissions were received as of May 20, with 31,378 results after filtering out those that did not meet the acceptance criteria. The authors provided comments on May 12 regarding the EPA's radiation protection regulations, as detailed in this article.

Current EPA regulations are based on the linear no-threshold (LNT) dose-response model. These regulations have long been considered to be conservative, and it is widely recognized that they are excessively restrictive. There is emerging evidence that the effects of low or even moderate levels of ionizing radiation are in fact beneficial. Researchers are now postulating that rather than being a simple cause of additional cell damage, the principal effect of low-level radiation is to stimulate the body's natural defense mechanisms—for instance, against cancer cells.

Many organisms receiving very high, but nonfatal, doses appear to have life expectancies as great as those receiving only normal background radiation. Higher-

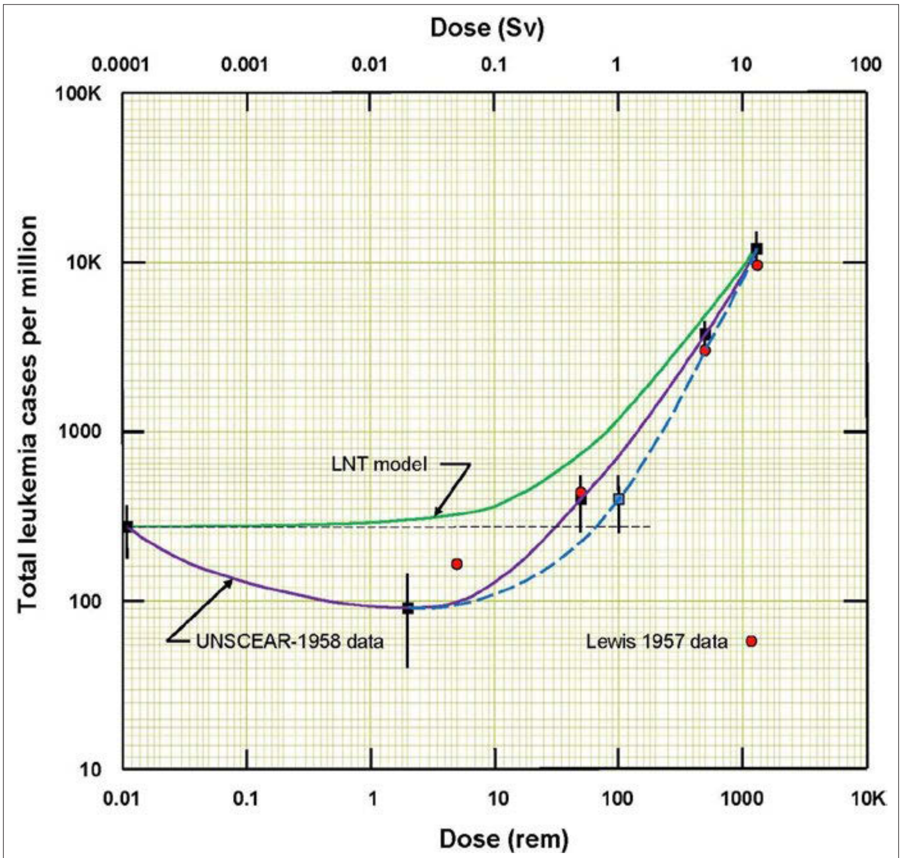

Fig. 1. Leukemia incidence from 1950 to 1957 among Hiroshima atomic bomb survivors.[1]

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than-normal background radiation does appear to increase longevity. Data from sources as diverse as Hiroshima survivors and beagle dog laboratory studies (conducted from the 1960s to the 1990s) are consistent in their conformance to a hormetic dose-response model, with surprisingly high thresholds for the transition between beneficial and harmful effects.

Confirmation and recognition of the potential benefits of low-level radiation will require a thorough review and revision of radiation protection guidelines for both medical and nuclear power applications. Appropriate revisions will lead to major public health and economic benefits.

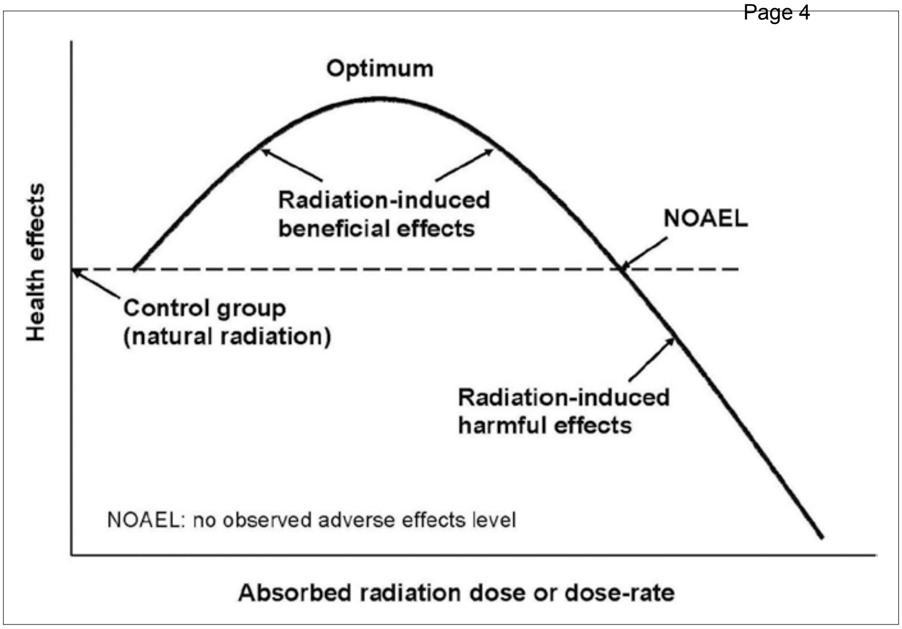

Fig. 2. Health effects caused by signals that are induced by radiation.

Background

Most of us are frightened by the thought of being exposed to nuclear radiation. Very high doses kill within days to weeks, and survivors of acute radiation illness show an increased risk of cancer. While most of the casualties of the atomic bombs that were used in Japan to end World War II died from the blast or the heat, many received very high doses of ionizing radiation. Some died from organ failure and others died from cancer that developed years later. Many emergency workers responded to the Chernobyl disaster, and 134 of them were heavily irradiated. Of these, 28 died within weeks, and 106 remained alive.

What about those who received high doses but survived? Since the most radiation-sensitive tissues are the blood-forming cells in bone marrow, leukemia is the cancer most likely to occur among the Japanese atomic bomb survivors, beginning at about five years after exposure. Figure 1 shows that there was no excess leukemia incidence for Hiroshima survivors when the dose was below about 500 mSv (50 rem). This suggests that the thresholds for initiating other types of cancer or other health risks are likely higher than 500 mSv.[1]

Of the 106 heavily irradiated Chernobyl emergency workers who remained alive, 22 died over the next 19 years, a mortality rate of 1.09 percent per year. This rate is lower than the average local mortality rate of about 1.4 percent in 2000. In 2001, this group's mortality structure was 26 percent cancer deaths among all mortality causes, which is not much different from the normal ratio in Central Europe.[2]

So how much radiation is too much? X-rays and nuclear radiation were discovered 120 years ago. Until the mid-1900s, before antibiotics and other modern remedies were discovered, medical practitioners used these radiations extensively to treat and cure patients who suffered from a wide variety of illnesses. In the early 1900s, geneticists began to study the incidence of radiation-induced mutations in the sex genes of fruit flies. Using very high doses at very high dose rates, they found that the mutation rate was roughly proportional to the radiation dose. By the 1920s, scientists determined a radiation level that is safe for all radiologists, a tolerance dose of 0.2 roentgen per day, or about 700 mSv per year. This limit was based on evidence of statistically recognizable adverse health effects, which occurred well above this level.[3]

While this forms a reasonable base for very large doses of radiation, whole-body exposures to a very high dose of radiation at a high dose-rate are extremely rare. The much more common situation is dealing with a long-term radiation level, as in coping with widespread contamination or other events that cause increases in background radiation. Because of the high natural incidence of cancers and the many factors that may affect cancer risk, it is impossible to establish a statistical relationship between low levels of radiation and an increased incidence of cancer.

In recent years, much has been learned about the body's responses to stress, including radiation stress, which causes cell and DNA damage.[4] Our bodies absorb several million energy deposition events—so-called hits—from gamma rays and about 15,000 particles every second. A third of these are from naturally radioactive atoms in our body and the rest are from outer space and natural materials in the environment. It has been that way throughout human existence. Our bodies have very powerful protection systems that prevent damage, repair damaged cells, and remove and replace unrepaired cells. These systems also cope with many internal and external toxins and diseases, enabling survival to an average age of about 70 years.[4]

By far, the greatest damage to our cells is caused by breathing air. We know that oxygen combines with food molecules to produce the energy that keeps us alive, but in the 1980s, scientists discovered that oxygen also attacks and damages cells. If not for our antioxidant production, each day every cell in our body would be damaged by a billion "free radical" molecules, mostly reactive oxygen species (ROS). Our body's natural damage prevention system lowers the potential damage rate to a million DNA alterations per cell per day. Most of these are harmless, but in about 1 of 10 cells, a double-strand break occurs per cell per day, on the basis of observed data. Our repair system lowers this damage rate further to about 1 mutation per cell per day. Most of the mutations are relatively harmless, but some change normal cells into cancer cells. To address this hazard, our body has further defense mechanisms, such as signal-induced cell death and the immune system, which recognizes cancer cells as foreign bodies and destroys them.[4,5,6]

So how does radiation fit into this picture? While the overall effects of high doses are well known, the detailed cell response mechanisms at both high and low doses are complicated and likely involve all levels of biological organization. Since about 75 percent of the human body is water, radiation-induced ROS is a very important effect. ROS and direct hits are a double-edged sword. They damage molecules, but some of the affected cells send signals to stimulate or inhibit genes.[4,5]

To obtain a perspective on the hazard, the rate of radiation-induced DNA damage should be compared with the rate of spontaneous ROS-induced DNA damage.

Continued

Natural radiation (1 mGy/year) induces on average about 0.01 DNA alterations per cell per day (1 percent are double-strand breaks), which is 100 million times less than the 1 million DNA alterations per cell per day that are calculated to be caused by breathing air. The radiation level would have to be quite high to induce the same rate of DNA damage as the spontaneous rate. This suggests that the observed health effects of a low dose or a low-level exposure are due primarily to cell signaling induced by radiation.[6]

The dose-response characteristic shown in Fig. 2 illustrates the nature of this signaling. As the radiation dose or dose-rate level increases above the ambient level, the stimulation of protection systems begins, and beneficial health effects start to be observed. As the dose or level increases further, the benefit increases until an optimum level is reached. Exposures beyond the optimum level reveal decreased benefit, which suggests that stimulation has decreased and inhibition has increased. At the level at which there is no observed adverse effect (NOAEL), the health effect is the same as for unexposed individuals. If the radiation dose or dose-rate exceeds the NOAEL, the inhibition of protection systems exceeds their stimulation, and health detriment is observed. The NOAEL point is the dose or dose-rate threshold for the onset of harmful effects.[7]

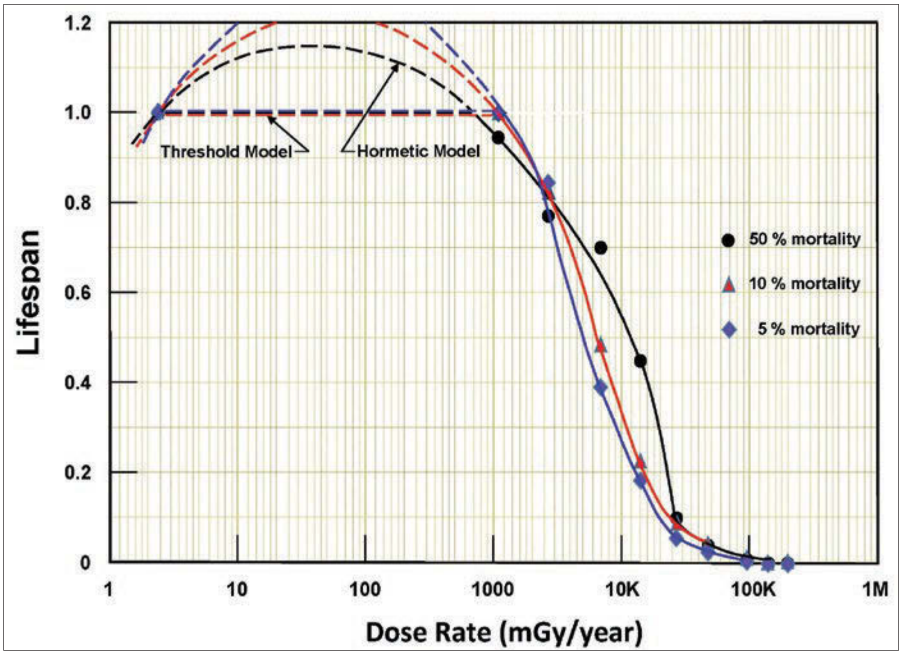

Fig. 3. Lifespans of groups of dogs at different gamma radiation dose rates.[5]

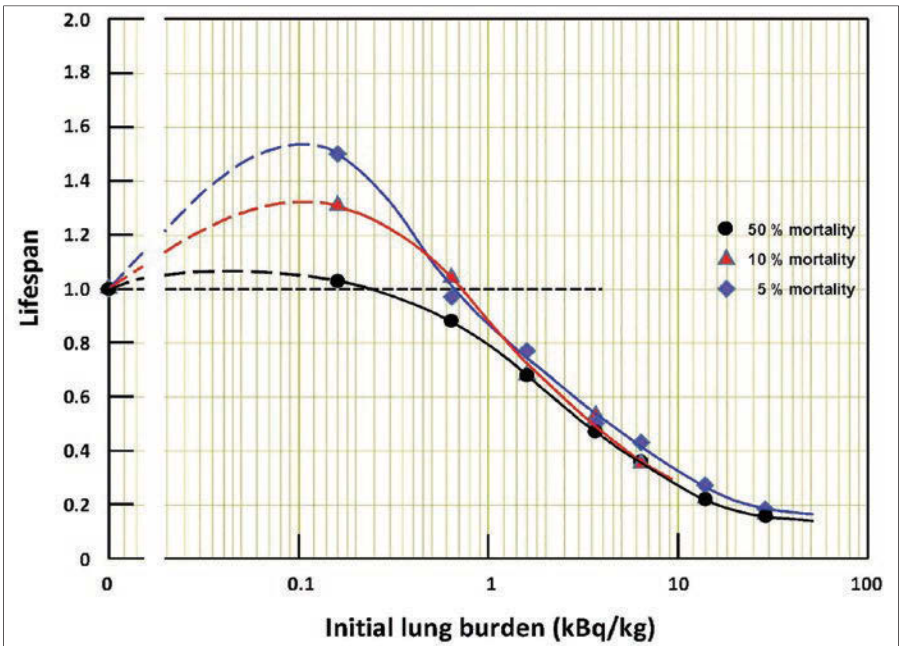

Fig. 4. Lifespans of groups of dogs at different initial lung burdens of inhaled plutonium aerosols.[5]

Many studies have been carried out by the U.S. Department of Energy and its predecessor agencies since the 1950s to determine the effects of radiation on humans. Beagle dogs are assumed to model humans well and have been the preferred choice for many studies. A recent analysis of data measured in two of these early studies sought to assess the effect of continuous radiation exposure on longevity for radiation-sensitive and for average individuals.[5]

Figure 3 presents evidence of a dose-rate threshold (NOAEL) at about 700 mGy per year for gamma radiation–induced reduction of lifespan in dogs. Figure 4 shows evidence of a threshold (NOAEL) for inhaled plutonium particulates. Figures 3 and 4 suggest an increased lifespan when the radiation level is below the threshold for harm, and also demonstrate that short-lived dogs are more radiation sensitive than average dogs. Short-lived dogs benefit more than average dogs when the radiation level is below the threshold and suffer more when the level is above the threshold. This evidence also implies that even sensitive individuals do not require special protection against low-level radiation.[5] The acute exposure data of the Hiroshima survivors shown in Fig. 1 are also consistent with the dose-response characteristic shown in Fig. 2, suggesting that the threshold (NOAEL) for a short-duration radiation dose to induce leukemia is about 500 mSv.[1]

Current regulations

After World War II, radiation protection became politicized, as many scientists tried to stop further testing and prevent the development of advanced nuclear weapons. Radiation exposure has never been shown to cause hereditary effects in human populations, but X-rays and nuclear radiations are known to cause mutations in cells, which can contribute to the risk of cancer. In 1956, without documented evidence, the U.S. National Academy of Sciences issued a report recommending that the risk of radiation-induced genetic mutations be assessed using an LNT dose-response model.[8] That is, the inferred health effect would be based on an integration of dose over time and over population groups, with no credit given for biological protection mechanisms. Government regulators worldwide accepted this advice,[8] causing broad public fear of low-level radiation.

The International Commission on Radiological Protection (ICRP) rejected the concept of a safe threshold dose limit and instead adopted a concept intended to keep cancer and genetic risk small compared with other hazards in life. According to the ICRP, "Since no radiation level higher than natural background can be regarded as absolutely safe, the problem is to choose a practical level that, in the light of present knowledge, involves negligible risk."[9] Cancers that exceed the number expected to occur naturally are attributed to the "stochastic effects" of radiation. The probability of occurrence, not the severity, was assumed to be proportional to the size of the dose. The ICRP employs the LNT model to calculate the risk of "health effects," which means that there is assumed to be a risk of excess cancer deaths in a population that receives a low radiation exposure, no matter how small. The risk of cancer is assumed to increase linearly with the cumulative radiation dose received (or number of cells damaged), regardless of the dose rate. Observations of radiation-induced beneficial effects (a lower cancer incidence) are disregarded. The ICRP does not accept the fitting of data with the hormetic dose-response model to predict positive health effects.

The international consensus to use this method of risk assessment continues to the present time. Since 1956, all medical personnel have been taught this primitive dose-response model and the idea that every exposure to ionizing radiation increases the risk of cancer, cumulatively. Radiation oncologists employ high radiation doses locally to destroy cancerous tumors, shielding healthy tissue. Radiologists apply low-dose radiation only for medical imaging, not treatment, and they justify and optimize all such exposures to minimize the hypothetical risk of cancer.[10]

High cost of regulations

Are there reasons to reevaluate these standards? The use of the LNT model is said to be conservative, but it leads to costly precautionary emergency measures that cause enormous suffering with no reduction in actual health risk. In response to concerns about hypothetical cancer risks, the regulatory bodies have set exposure standards that are based on the principle of dose minimization.[11] These standards are a barrier to many applications of low doses of radiation for medical diagnostics and treatments.[12] Tight regulatory restrictions and social fears obstruct the progress of projects to construct nuclear power plants that would generate reliable and secure electricity.[10]

The scientific advances in radiobiology over the past 35 years have been enormous. The detailed cell response mechanisms are complicated and involve all levels of biological organization.[4] Nevertheless, there is a good understanding of the biology that underlies the dose-response relationship shown in Fig. 2. Unfortunately, nearly all physicians today are still being taught the recommendation of 1956, thereby perpetuating the false cancer scare. The scientific evidence, shown in Figs. 1, 3, and 4, and the scientific misconduct that has occurred are being ignored.[8] This information is not being adequately communicated to the public, so the extreme social fear of exposure to a low level of (human-made) radiation continues.

The body's immune system generally detects and destroys cancer cells to prevent the development and spread of cancer. A weakened or impaired immune system is usually a precondition for cancer mortality. The DNA damage rate caused by low-level radiation has been shown to be negligible when compared with the spontaneous rate of damage that is managed by the protection systems (more than 150 genes), which include the immune system.[6]

Low doses of radiation stimulate the protection systems, enabling organisms to exceed their life expectancies. Studies have shown that low doses or low levels of radiation increase lifespan in animals and humans.[5,10] People living in high natural background regions tend to have greater, not shortened longevity. The 120 years of medical experience in the use of low radiation doses for diagnostic imaging and therapies, such as nasopharyngeal radium irradiation, have shown no significant risk of cancer or any other disease.[10] Whole-body or half-body treatments with low doses of radiation have been employed to cure hundreds of cancer patients.[10,12] It is not rational to set the safe limit at 1 mSv per year and enforce a radiation protection policy of "as low as reasonably achievable" (ALARA) when the natural background radiation level extends to 260 mSv per year in Ramsar, Iran, a city of about 35,000 people.

Overly conservative regulatory limits require hugely expensive measures to prevent even a minimal release of any radioactive material or an exposure to low-level radiation during normal power plant operation and from potential accidents of every beneficial application of X-rays, nuclear materials, and nuclear power. They preclude or restrict the constructive use of radiation in medicine.[10,12]

Among the most egregious consequences of the precautionary emergency measures following the 2011 Fukushima Daiichi nuclear accident in Japan are the effects on the health of the residents (about 1,500 premature deaths among the evacuees) and the impact of the radiation scare on the economy. It has become obvious that society is paying a very high price because of public fear of low-level radiation. The same can be said about the 1986 Chernobyl accident in Ukraine. The cost of the cleanup activities could have been much lower. Accident mitigation was very costly when vast areas around the Fukushima and Chernobyl power plants were deemed unfit for residency or farming.

There are many nuclear sites from the weapons program that need remediation to isolate from the environment materials that are unduly radioactive. The application of overly restrictive requirements is increasing the costs for these actions astronomically, and is thus hampering the effective cleanup of actual hazards and nuclear wastes.

Urgent need for change

The science shows that the "no-threshold" basis for radiation regulation is wrong.[11] While there is need for a constructive debate to establish safe limits, rational thresholds should be adopted now for dose and dose rate, based on current knowledge, and all radiation protection standards should be changed to reflect such thresholds.[10]

Since there is credible evidence of significant stimulatory benefits from exposures to different types of ionizing radiation, in a defined range of dose or dose rate, studies to quantify and optimize these effects should be encouraged.[12]

Responsible regulations, based on scientific medical evidence, would restore public confidence in the safety of nuclear energy and the efficacy of medical applications of low doses of radiation and would avoid the needless expenditure of enormous amounts of money.[13]

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23 April 2011

World Health Organization

CHERNOBYL at 25th anniversary Frequently Asked Questions April 2011

1. What happened?

On 26 April 1986, an explosion and fires at the Chernobyl nuclear plant in Ukraine caused the largest uncontrolled radioactive release in the history of the civil nuclear industry. Over the next 10 days, large quantities of radioactive iodine and caesium were released into the air. Most of this material was deposited near the installation, but lighter material was carried by wind currents over Belarus, the Russian Federation and Ukraine and, to some extent, over parts of Europe.

2. What were the main radionuclides to which people were exposed?

The main radionuclides to which individuals were exposed were iodine-131, caesium-134 and caesium-137.

Iodine-131 has a short radioactive half-life (eight days) and can be transferred to humans rapidly through the air and by consumption of contaminated milk and leafy vegetables. Iodine becomes localized in the thyroid gland. Because many infants and children consume relatively large quantities of milk and dairy products, and because of the size of their thyroid glands and the nature of their metabolism, exposure to radioactive iodine is usually higher for children than for adults.

Caesium isotopes have longer half-lives (caesium-134 and caesium-137 have half-lives of 2 years and 30 years, respectively). There are thus longer-term exposures to these radionuclides through the ingestion pathway and through external exposure from their deposition on the ground.

3. What levels of exposure did people experience?

The average effective doses among 530,000 recovery operation workers was 120 millisieverts (mSv); among 115,000 evacuees, 30 mSv; among residents of contaminated areas, 9 mSv (during the first two decades after the accident); and among residents of other European countries, less than 1 mSv (in the first year after the accident)[1].

In more distant countries, doses of exposure decreased progressively in subsequent years. Since such doses are below the global average annual dose of 2.4 mSv from natural background radiation, the radiation exposures in countries distant from Chernobyl are considered to be of little radiological and public health significance.

[1] UNSCEAR Chernobyl report (2011): http://www.unis.unvienna.org/unis/en/pressrels/2011/unisinf398.html

4. What were the impacts on health from Chernobyl?

In 2006, WHO published its report summarizing the data from two decades of research on the health consequences of the Chernobyl accident[2]. It included reviews of studies carried out on cancers, non-cancer diseases, immune and genetic effects, and reproductive and children's health, as well as evidence-based recommendations for national health authorities and for further research.

In 2011, the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) published a report entitled "Health effects due to radiation from the Chernobyl accident." The findings were based on more than two decades of experimental and analytical studies of the health consequences of radiation exposure from the Chernobyl accident. The report is the most comprehensive evaluation to date of exposure levels and health effects from the Chernobyl accident[3].

Radiation sickness

According to the UNSCEAR report, the Chernobyl accident caused a number of severe radiation effects almost immediately. Of 600 workers present on the site during the early morning of 26 April 1986, 134 received very high doses (0.8-16 Grey[4]) and suffered from acute radiation sickness. Of those, 28 workers died in the first three months.

Radiation-induced cataracts

Among those who survived radiation sickness, recovery took several years. Many of them developed radiation-induced cataracts in the first few years after the accident. Recent studies of the recovery operation workers indicate that opacities of the eye lens might result from radiation doses lower than previously expected (about 500 mSv[3]).

Cancers

For the last two decades, attention has been focused on investigating the association between exposure to radionuclides released in the Chernobyl accident and late effects, in particular thyroid cancer. In the first few months after the accident, radiation dose exposures to the thyroid received were particularly high in children and adolescents living in Belarus, Ukraine and the most affected regions of the Russian Federation, and in those who drank milk with high levels of radioactive iodine. By 2005, more than 6,000 thyroid cancer cases had been diagnosed in this group. It is most likely that a large fraction of these thyroid cancers are attributable to radioiodine intake. Furthermore, it is expected that increases in thyroid cancer incidence due to the Chernobyl accident will continue for many more years, although long-term increases are difficult to quantify.

Apart from the dramatic increase in thyroid cancer incidence among those exposed at a young age, there is some indication of increased leukaemia and cataract incidence among workers. Otherwise, there is no clearly demonstrated increase in the incidence of solid cancers or leukaemia due to radiation in the exposed populations. There also is no convincing proof so far of increases in other non-malignant disorders that are related to ionizing radiation.

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[2] Report of the UN Chernobyl Forum Expert Group "Health", WHO, Geneva, 2006: http://whqlibdoc.who.int/publications/2006/9241594179_eng.pdf

[3] UNSCEAR Chernobyl report (2011): http://www.unis.unvienna.org/unis/en/pressrels/2011/unisinf398.html

[4] See basic facts on radiation units and doses: http://www-naweb.iaea.org/nahu/dmrp/faq.shtm

Among 530,000 registered recovery operation workers who worked between 1986 and 1990, the average dose was 120 mSv (ranging from 20 to 500 mSv). That cohort is still potentially at risk of cancer and other diseases and their health continues to be closely followed.

Among Russian recovery operation workers with higher average doses (above 200 mSv), evidence is emerging of some increase in the incidence of leukaemia. Based on other studies, the annual incidence of radiation-induced leukaemia would be expected to fall within a few decades after exposure.

There is a tendency to attribute increases in rates of all cancers over time to the Chernobyl accident, but it should be noted that increases in cancer in the affected areas were also observed before the accident. Moreover, a general increase in mortality has been reported in recent decades in most areas of the former Soviet Union, and this must be taken into account when interpreting the results of the accident-related studies.

Persistent psychological or mental health problems

Several international studies have reported that exposed populations, compared to controls, had anxiety symptom levels that were twice as high and were more likely to report multiple unexplained physical symptoms and subjective poor health. Given that rates of mental health problems increase after a disaster and may manifest years after the event, WHO recommends improving availability and access to normal community mental health services in disaster-affected areas.

One of the objectives of the on-going UN inter-agency International Chernobyl Research and Information Network (ICRIN) project[5] (see below) is to alleviate the stigma of psychological trauma in society, encourage self-reliance, and empower local communities to take control over their own lives. One of the ways to achieve these goals is to promote healthy lifestyles, including physical activity and healthy diet, and to explain the environmental, behavioural, and other risks for various chronic diseases, including cancer.

Concerns related to fertility and birth defects:

In the Chernobyl-affected regions, there is no evidence of decreased fertility among males or females in the general population. However, birth rates may be lower in contaminated areas because of a high rate of medical abortions.

Since 1986, there has been a reported increase in congenital malformations in both contaminated and uncontaminated areas of Belarus which predated Chernobyl and may be the result of increased registration of such cases. Based on dose levels to which the majority of the population was exposed, there is unlikely to be a major effect on the number of stillbirths, adverse pregnancy outcomes, delivery complications, or the overall health of children, but monitoring remains important.

Potential impact on health in other European countries

So far, there has been no clear evidence of any measurable increases in adverse health effects related to the Chernobyl radiation in countries outside of Belarus, the Russian Federation and Ukraine.

[5] Launch of ICRIN project, April 2009: http://www.who.int/mediacentre/news/releases/2009/chernobyl_anniversary_20090424/en/index.html

5. What is the current health risk to people residing in contaminated areas?

Currently, concentrations of radioactive caesium (Cs-137) in agricultural food products produced in areas affected by the Chernobyl fallout are generally below national and international standards for actions. In some limited areas with high radionuclide contamination (e.g. in parts of the Gomel and Mogilev regions in Belarus and the Bryansk region in the Russian Federation) or areas with organic poor soils (the Zhytomir and Rovno regions in Ukraine), milk may still be produced with activity concentrations of Cs-137 that exceed national standards for action (100 Becquerel per kilogram). In these areas, countermeasures and environmental remediation may still be warranted[6].

6. What are some of the actions taken by the World Health Organization?

See: http://www.who.int/ionizing_radiation/chernobyl/Overview_WHO_past_involvement.pdf for more details on WHO involvement since 1986.

1991: The governments of Belarus, the Russian Federation and Ukraine asked the UN to examine the health effects of the Chernobyl accident and to visit the areas in question. WHO secured US$20 million in extra-budgetary funding to create a project on the health effects of Chernobyl.

1994: WHO's Regional Office for Europe initiated an international project on thyroid pathologies, which ran until September 2000. The project helped Belarus, the Russian Federation and Ukraine enhance the diagnosis, monitoring, and treatment of thyroid pathologies and improve the methods of identification of causes, nature, and estimated scope of radiation-induced thyroid cancer. Special priority was accorded to screening for thyroid cancer, establishment of an integrated database, medical examinations for iodine deficiency, design of testing systems for measuring thyroid gland hormones, capacity-building, including staff training. http://un.by/en/chernobyl/initiatives/

1995 A WHO conference in Geneva brought together a broad variety of scientists from all over the world and resulted in publication of a set of key papers in a special 1996 issue of the *WHO Bulletin* (a copy of the journal is available upon request).

2002 The UN Strategy for Recovery gave all UN agencies and the international community a framework for rebuilding the most-affected areas of Belarus, the Russian Federation and Ukraine.

2003 Within the UN Strategy for Recovery, representatives from the International Atomic Energy Agency (IAEA), the UN Food and Agriculture Organization (FAO), the UN Office for the Coordination of Humanitarian Affairs (OCHA), the UN Development Programme (UNDP), the UN Environment Programme (UNEP), UNSCEAR, WHO and the World Bank and Belarus, the Russian Federation and Ukraine established and launched the Chernobyl Forum.

2006: The Chernobyl Forum released the most authoritative scientific findings of that time on the accident’s consequences for health and the environment. The health impact of the accident was

[6] Chernobyl Legacy: Forum's digest report:
http://www.who.int/ionizing_radiation/chernobyl/chernobyl_digest_report_EN.pdf

summarized in the report developed by WHO — *Health Effects of the Chernobyl Accident and Special Health Care Programmes*[7].

The WHO Expert Group "Health" (EGH) set criteria for inclusion in the report based on solid methodology and reliable estimates of exposure assessment. Consequently, reports published in peer-reviewed literature, and available by the time of the Expert Group meetings, were included. National experts from Belarus, the Russian Federation, and Ukraine participated in each EGH meeting and shared the set criteria. The report was finalized at the end 2005 and published in spring 2006.

2006 The International Agency for Research on Cancer (IARC), an international cancer research institution established by WHO, published estimated projections of 25,000 potential excess cancers for Europe (Cardis et al. 2006) through 2065 that might be attributable to exposure to radiation from Chernobyl of which 16,000 cases could be fatal.

2007-2008 Following the UN inter-agency Chernobyl Forum in 2006, the UN launched its Action Plan for the third decade of Chernobyl until 2016. As part of the UN family, WHO has a mandate to implement this Action Plan according to UN General Assembly resolutions.

2009-2011 The International Chernobyl Research and Information Network (ICRIN) was launched by four United Nations agencies, as a part of the UN Action Plan implementation programme, to meet the information needs of affected communities in Belarus, the Russian Federation and Ukraine. This three-year initiative is part of a larger effort to help local communities "return to normal" in the course of the decade that ends in 2016 and aims to translate the latest scientific information on the consequences of the accident into sound practical advice for residents of the affected territories. Activities planned under the ICRIN project include the dissemination of information, through education and training for teachers, medical professionals, community leaders, and the media; providing local residents with practical advice on health risks and healthy lifestyles; the creation of internet-equipped information centers in rural areas; and small-scale community infrastructure projects aimed at improving living conditions and promoting self-reliance.

2010 IARC completed an EC-funded project on the development of a strategic research agenda (SRA) for Chernobyl studies,[8] where a group of experts and advisors supports proposals for the long-term funding of a Chernobyl Health Effects Research Foundation (similar to the action taken to create the Radiation Effects Research Foundation some years after the atomic bomb exposures in Japan) together with a series of individual studies covering the main health consequences. These include a focus on thyroid cancer, breast cancer, inherited molecular-genetic alterations, various other cancers, cataracts, and other non-cancer diseases in nuclear plant workers and in the general, exposed population.

2011 An UNSCEAR report[9] on Chernobyl recognized that while new research data has become available, major conclusions regarding the scale and nature of the health consequences of the 1986 Chernobyl accident were "essentially consistent with previous assessments".

UNSCEAR reported more than 6,000 cases of thyroid cancer, of which 15 have been fatal, among people who were children or adolescents in Belarus, the four most affected regions in the Russian

[7] Report of the UN Chernobyl Forum Expert Group "Health", WHO, Geneva, 2006 — is available at: http://whqlibdoc.who.int/publications/2006/9241594179_eng.pdf
[8] Additional information can be found at: : http://arch.iarc.fr/documents/ARCH_SRA.pdf.
[9] See: http://www.unscear.org/unscear/en/chernobyl.html

Federation, and Ukraine. A substantial proportion of cases were associated with radiation exposure. The report also reconfirmed that radiation doses to the public from the 1986 accident were relatively low and most residents "need not live in fear of serious health consequences".

Ongoing: Since the start of the ICRIN project in 2009, WHO has developed information materials and carried out trainings and workshops targeting primary health care workers, teachers, and mass-media workers of the most affected regions of Belarus, the Russian Federation and Ukraine. An ICRIN side event co-sponsored by WHO was featured in conjunction with the international conference held in Kiev, Ukraine on 20-21 April 2011. Four WHO Collaborating Centres in the Russia Federation and Ukraine are leading the health research project on Chernobyl-affected populations.

7. What is WHO's relationship with the IAEA?

WHO and the IAEA are both UN entities. WHO is the directing and coordinating authority for health within the United Nations system. It is responsible for providing leadership on global health matters, shaping the health research agenda, setting norms and standards, articulating evidence-based policy options, providing technical support to countries, and monitoring and assessing health trends.

The IAEA is the UN system agency which works with its Member States and multiple partners worldwide to promote safe, secure and peaceful nuclear technologies.

WHO collaborates with the IAEA on a number of areas including the medical use of radiation, radiation protection and the safety of the public and workers, and radio-nuclear emergency preparedness and response.

Under the auspices of the UN Chernobyl Forum, WHO carried out its own independent health assessment of the accident. The IAEA assessed the environmental impact and UNDP the socio-economic impact.

A digest document including summaries of the three reports (WHO Health report, IAEA environmental report, and UNDP socio-economic impact report) entitled *Chernobyl Legacy* was then prepared jointly by three agencies to present a comprehensive picture of the event, and was endorsed by all participants of the Chernobyl Forum, including eight UN Agencies and the Governments of Belarus, the Russian Federation, and Ukraine.

Mention has often been made of WHO's 1959 agreement with the IAEA. This is a standard agreement similar to agreements it has with other UN agencies as a means of setting out respective areas of work. This agreement has never once been used to stop or restrict WHO’s work.

The agreement serves the purpose of promoting co-operation and consultation between WHO and IAEA. It was approved by the highest governing body of each Organization.

The agreement between WHO and IAEA does not affect the impartial and independent exercise by WHO of its statutory responsibilities, nor does it subordinate one Organization to the other.

The clause appearing in Article III dealing with the safeguarding of confidential information is a standard provision in many agreements of this kind (including WHO agreements with the UN, ILO, FAO, UNESCO, and UNIDO). On the one hand, it ensures each Organization will continue to meet its obligations to protect certain information it is duty bound to safeguard. In the case of information held by WHO, such a clause is relevant, for example, for the protection of clinical and other similar data on individuals. On the other hand, the provision makes clear that subject to such situations, each Organization "shall keep [the] other fully informed [of] all … work" of mutual interest. Thus, such provisions actually work to improve information flow as they limit the exceptions to the free-flow of information. WHO environmental health experts will continue the scientific collaboration with radiation and health experts at IAEA. This entails not only nuclear safety issues and assistance in radiation emergencies, but also the application of clinical techniques connected with such issues.

WHO activities on nuclear matters are not in any way hampered by the WHO/IAEA agreement. Both Organizations are working tirelessly to assist countries and the global community to deal with this complex emergency.

8. What have been the wider impacts of the Chernobyl accident?

In countries beyond those most directly affected, Chernobyl triggered questions concerning the safety of crops, milk, food, and water; the effects of radiation exposure on different population groups; and the kind of preventive measures that were to be put in place. In many countries, the accident prompted important political discussions regarding the use of nuclear energy and national energy policies.

Chernobyl underscored the critical need for international coordination and cooperation related to environmental hazards. Chernobyl also prompted UN agencies to develop international agreements and arrangements for nuclear emergencies. In 1986, two international conventions were adopted by the IAEA's General Conference: the Convention on Early Notification of a Nuclear Accident and the Convention on Assistance in the Case of Nuclear Accident or Radiological Emergency. WHO, which is a party to both conventions, set up the Radiation Emergency Medical Preparedness and Assistance Network - WHO REMPAN - in 1987. Today, the network includes more than 40 centres world-wide specialized in radiation emergency medicine, dosimetry, diagnosis and treatment of radiation injuries, public health interventions and long-term follow-up.

9. What are other sources of information about Chernobyl?

Key Chernobyl documents:

- General Assembly Resolution on Chernobyl (2010) : http://chernobyl.undp.org/english/docs/a_65_l.25_e.pdf
- Reports of the Secretary-General and committees to the General Assembly on Chernobyl : http://chernobyl.undp.org/english/sg_reports.shtml
- UN Action Plan on Chernobyl to 2016 : http://chernobyl.undp.org/english/docs/action_plan_final_nov08.pdf
- Joint news release for the 20th anniversary : http://www.who.int/mediacentre/news/releases/2005/pr38/en/index.html
- Chernobyl Forum 2003-2005 : http://www-ns.iaea.org/meetings/rw-summaries/chernobyl_forum.asp
- WHO report on Health Effects of the Chernobyl Accident and Special Health Care Programmes (2006) : http://whqlibdoc.who.int/publications/2006/9241594179_eng.pdf
- IAEA report on Environmental Consequences of the Chernobyl accident (2006) : http://www-pub.iaea.org/MTCD/publications/PDF/Pub1239_web.pdf
- ICRIN project web information portal : www.chernobyl.info

World Health Organization

Ionizing radiation

FAQs: Fukushima Five Years On

1. What happened?

On 11 March 2011, a magnitude 9 earthquake occurred off the east coast of Japan, generating a tsunami that severely damaged coastal areas and resulted in 15 891 deaths and 2579 missing people. As a consequence of the tsunami, the Fukushima Daiichi Nuclear Power Station (FDNPS), located along the shoreline, lost its core cooling capacity which caused severe damage to the reactor's core and led to a nuclear accident rated as Level 7 on the International Nuclear Events Scale (INES). Substantial amounts of radioactive materials (radionuclides) were released into the environment following explosions at the FDNPS on March 12, 14 and 15.

2. What were the main radionuclides to which people were exposed?

People living in the vicinity of the FDNPS were exposed externally to irradiation from the radioactive cloud and ground deposits and internally from inhalation and ingestion of radionuclides. The main radionuclides to which individuals were exposed included iodine-131 (^{131}I) and caesium-137 (^{137}Cs). ^{131}I has a radioactive half-life of eight days and can be inhaled with the air and ingested with contaminated food or water, mainly by consumption of contaminated milk and leafy vegetables. In the human body, iodine concentrates in the thyroid gland. Exposure to radioactive iodine is usually higher for children than for adults because of the size of their thyroid glands and the nature of their metabolism. ^{137}Cs has a half-life of 30 years and this implies long term risk of exposure through ingestion and through exposure from ground deposition.

3. What levels of radiation have people been exposed to?

Doses of radiation have been estimated based on models and measurements for different representative groups of individuals of the Japanese population. The assessment of the doses included both external and internal (through inhalation of the radioactive plume and ingestion of radioactivity in food) exposure pathways. A large survey of the health of residents of Fukushima Prefecture, the Fukushima Health Management Survey, has estimated individual doses based on typical scenarios of evacuation and time spent indoors and outdoors. Based on this survey and the dose assessments done by WHO and by UNSCEAR, the average lifetime effective doses for adults in the Fukushima prefecture were estimated to be around 10 mSv or less, and about twice for 1-year old infants.

Preliminary dose estimation from the nuclear accident after the 2011 Great East Japan Earthquake and Tsunami
WHO publication

Sources, effects and risks of ionizing radiation
UNSCEAR 2013 REPORT Vol. I

The doses incurred by workers were reported by the Tokyo Electric Power Company (TEPCO) and by some of its contractors. According to TEPCO records, the average workers' effective dose over the first 19 months after the accident was about 12 mSv. About 35% of the workforce received total doses of more than 10 mSv over that period, while 0.7% of the workforce received doses of more than 100 mSv. Based on the UNSCEAR assessment, 12 of the most exposed workers received thyroid doses in the range of 2 to 12 Gy, mostly from inhalation of ^{131}I.

4. What were the main public health consequences of the disaster?

There were public health consequences related to the response actions to the disaster, such as evacuation and relocation of people. These measures were taken based on radiation safety considerations and the massive damage to the infrastructure and facilities following the earthquake and tsunami. These measures resulted in a wide range of social, economic, and public health consequences. A sharp increase in mortality among elderly people who were put in temporary housings has been reported, along with increased risk of non-communicable diseases, such as diabetes and mental health problems. The lack of access to health care further contributed to deterioration of health.

Similar to what was observed and reported for the Chernobyl population, the displaced Fukushima population is suffering from psycho-social and mental health impact following relocation, ruptured social links of people who lost homes and employment, disconnected family ties and stigmatization. A higher occurrence of post-traumatic stress disorder (PTSD) among the evacuees was assessed as compared to the general population of Japan. Psychological problems, such as hyperactivity, emotional symptoms, and conduct disorders have been also reported among evacuated Fukushima children6. While no significant adverse outcomes were observed in the pregnancy and birth survey after the disaster, a higher prevalence of postpartum depression was noted among mothers in the affected region.

Psychological distress and the perception of radiation risks: the Fukushima health management survey
pdf, 1.31Mb
WHO bulletin 2015

5. What are the health implications of the Fukushima Daiichi NPS (FDNPS) nuclear accident?

In 2013, WHO published a health risk assessment from the FDNPS accident. It included an evaluation of the risks of cancers, non-cancer diseases as well as public health considerations. The following year, UNSCEAR published a report on the levels and effects of radiation exposure due to the accident. In 2015, UNSCEAR released a white paper that evaluates new information in the peer-reviewed literature.

Health risk assessment from the nuclear accident after the 2011 Great East Japan earthquake and tsunami, based on a preliminary dose estimation
WHO publication 2013

Sources, effects and risks of ionizing radiation
UNSCEAR 2013 REPORT Vol. I

Developments since the 2013 UNSCEAR Report on the levels and effects of radiation exposure due to the nuclear accident following the great east-Japan earthquake and tsunami
UNSCEAR Fukushima 2015 White Paper

There were no acute radiation injuries or deaths among the workers or the public due to exposure to radiation resulting from the FDNPS accident.

Considering the level of estimated doses, the lifetime radiation-induced cancer risks other than thyroid are small and much smaller than the lifetime baseline cancer risks. Regarding the risk of thyroid cancer in exposed infants and children, the level of risk is uncertain since it is difficult to verify thyroid dose estimates by direct measurements of radiation exposure.

For the twelve workers who were estimated to have received the highest absorbed radiation doses to the thyroid, an increased risk of developing thyroid cancer and other thyroid disorders was estimated. About 160 additional workers who received whole body effective doses estimated to be over 100 mSv, an increased risk of cancer could be expected in the future although it will not be detectable by epidemiological studies because of the difficulty of confirming a small incidence against the normal statistical fluctuations in cancer incidence.

From a global health perspective, the health risks directly related to radiation exposure are low in Japan and extremely low in neighbouring countries and the rest of the world.

6. Is there a risk of radiation-induced thyroid cancer among children of Fukushima prefecture?

Given the exposure to radioactive iodine during the early phase of the emergency, WHO specifically assessed the risk of thyroid cancer. The greatest risk was found among girls exposed as infants (i.e. < 1="" year="" old)="" in="" the="" most="" affected="" area="" in="" the="" fukushima="" prefecture.="" even="" if="" those="" levels="" of="" risk="" might="" not="" be="" clinically="" detectable,="" who="" anticipated="" that="" the="" thyroid="" ultrasound="" screening="" programme="" being="" conducted="" in="" fukushima="" prefecture="" was="" likely="" to="" lead="" to="" an="" increase="" in="" the="" incidence="" of="" thyroid="" diseases="" due="" to="" earlier="" detection="" of="" non-symptomatic="">

There have been recent reports about thyroid cancer cases being diagnosed among children exposed to low doses of radioactive iodine as a result of the Fukushima accident. These reports should be interpreted with caution. A large excess of thyroid cancer due to radiation exposure, such as occurred after the Chernobyl accident, can be discounted because the estimated thyroid doses due to the Fukushima accident were substantially lower than in Chernobyl. Nevertheless, the highly-sensitive thyroid screening of those under 18 years old at the time of the accident is expected to detect a large number of thyroid cysts and solid nodules, including a number of thyroid cancers that would not have been detected without such intensive screening. Similar or even slightly higher rates of cysts and nodules were found in prefectures not affected by the nuclear accident. The substantial number of cases that have already been observed in the Fukushima Health Management Survey have been considered likely due to the sensitivity of the screening rather than to radiation exposure. Further analysis of epidemiological data being currently collected in Japan will be necessary to evaluate a potential attribution of thyroid cancer to radiation exposure.

7. Is there any risk from radioactive food contamination in Japan today?

Radioactive iodine and caesium in concentrations above the Japanese regulatory limits were detected in some food commodities as a result of food monitoring in the early period after the accident. Since the early phase of the emergency, the Japanese authorities have monitored food contamination closely and implemented protective measures to prevent sale and distribution of contaminated food in Japan and outside of Japan.

WHO works closely with FAO through the International Food Safety Authorities Network (INFOSAN) to ensure that the global community receives the best advice on the matters related to the radioactive contamination in food. Food is still monitored by the Ministry of Health, Labour and Welfare of Japan, which informs INFOSAN about any residual radioactivity levels in food.

8. What are the public health lessons learned from the response to Fukushima?

The Fukushima nuclear accident as a part of a triple disaster was unprecedented in its scale and nature. A number of lessons were learned that help Japan and all countries better plan, prepare, respond and recovery from potential nuclear accidents. These include:

- Evacuation aims to minimize or prevent health risks of radiation exposure. However the process of evacuation itself, especially under the conditions of a severe natural disaster, may pose serious health risks, particularly for vulnerable populations (such as those with disabilities, older populations, young children).
- Relocating thousands of people has caused a wide range of health consequences including increase of disaster-related deaths, psychosocial and access to health care issues. Disrupted infrastructure, disconnection of evacuees from their municipalities, reduced number of health workers and failure of local public health and medical systems due to relocation made it more difficult to address these issues.
- Strengthening of public health services and improving access to health care are key issues for the well-being of evacuees, in addition to mental health and psychological support, behavioral and societal support.
- Risk communication proved to be essential and should be carried out by trained specialists. Health care workers also need education and training on health effects of radiation.

9. What is WHO's current response?

- WHO continues to support Member States in building national capacities for preparedness and response to radiation emergencies and implementing the International Health Regulations (IHR 2005).
- WHO develops technical tools, training and exercises, promotes international cooperation and provides an information-sharing platform with its Radiation Emergency Medical Preparedness and Assistance Network (REMPAN) and its global network of biodosimetry laboratories (BioDoseNet). Through these partnerships, it contributes to the development, promotion, and harmonization of international radiation safety standards.
- WHO supports countries to increase their Disaster Risk Management capacities pursuant to the Sendai framework for disaster risk reduction.
- WHO collaborates with international organizations using the existing inter-agency framework and arrangements under the Joint Radiation Emergency Management Plan of the International Organizations for preparedness for and response to a radiation incident or emergency.
- WHO continues its efforts towards implementation of the International Basic Safety Standards by promoting international cooperation, harnessing research, providing advice on risk assessment and evidence-based policies development.

10. What are next steps to mitigate the public health impact of the Fukushima accident?

The Fukushima Health Management Survey (FHMS) is expected to contribute to future health effect assessments. Population health surveillance will permit the identification of additional needs for the delivery of health care. Moreover, as part of the occupational health programmes, a special protocol for medical follow-up of emergency workers is being implemented.

To date, the biggest challenge for the mitigation of the public health consequences of the triple disaster is the restoration of the social fabric and social trust. The Sendai Framework for Disaster Risk Reduction post-2015 underlines that response to major disasters should include social mobilization and empowerment of local communities. Community representatives should be involved in the decision-making on protective and restoration actions that would consider the needs and priorities of local communities.

Steps towards improving the psycho-social and socio-economic consequences of the disaster should be considered. Health systems need to provide effective counselling services and social support in a team approach and people-centered care. Efforts are needed, both inside and outside Japan, to share the lessons learned from Fukushima around the world.

Towards long-term responses in Fukushima
The Lancet article, volume 386, Issue 9992, 1–7 August 2015

Related links

NCRP Commentary No. 27: Implications of Recent Epidemiologic Studies for the Linear-Nonthreshold Model and Radiation Protection

National Council on Radiation Protection and Measurements

Overview

In May 2018, the National Council on Radiation Protection and Measurements (NCRP) published Commentary No. 27, *Implications of Recent Epidemiologic Studies for the Linear-Nonthreshold Model and Radiation Protection*.

For over 40 years, the linear-nonthreshold (LNT) dose-response model has been used to develop practical and prudent guidance on ways to protect workers and members of the public from the potential for harmful effects of ionizing radiation, specifically, from low linear-energy transfer* (low-LET) radiation.

Commentary No. 27 was produced by an interdisciplinary group of radiation experts who critically assessed recent epidemiologic studies of populations exposed to low dose and low dose-rate ionizing radiation. The studies were then judged as to their strength of support for the LNT model as used in radiation protection.

NCRP concludes that the recent epidemiologic studies support the continued use of the LNT model for radiation protection. This is in accord with judgments by other national and international scientific committees, based on somewhat older data, that no alternative dose-response relationship appears more pragmatic or prudent for radiation protection purposes than the LNT model.

The Commentary provides a critical review of 29 high-quality epidemiologic studies of populations exposed to radiation in the low dose and low dose-rate range, mostly published within the last 10 years. Studies of total solid cancers and leukemia are emphasized, with briefer consideration of breast and thyroid cancer, heritable effects, and some noncancers, *e.g.*, cardiovascular disease and cataracts.

The epidemiologic methods, dosimetry and statistical approaches for each study were evaluated. These components of study quality were used to classify each study as to its support of the LNT model for use in radiation protection. The classifications were: strong, moderate, weak-to-moderate, no support, and inconclusive.

The 29 epidemiologic studies are listed below with literature references and the classification for support of the LNT model. Full references are provided in the Commentary.

*Linear energy transfer (LET) is a measure of the energy lost by ionizing radiation as it travels through matter. Low-LET radiations (*e.g.*, x rays, gamma rays, and electrons) transfer their energy at a low rate. High-LET radiations (*e.g.*, protons, alpha particles, and heavy ions) transfer their energy at a higher rate.

NCRP Commentary No. 27: Implications of Recent Epidemiologic Studies for the Linear-Nonthreshold Model and Radiation Protection

Epidemiologic Study (or groups of studies)	Classification (support for LNT model)
Life Span Study, Japan atomic bombs (Grant et al., 2017)	Strong
INWORKS (French, United Kingdom, United States combined worker cohorts) (Richardson *et al*., 2015)	Strong
Tuberculosis fluoroscopic examinations, breast cancer (Little and Boice, 2003)	Strong
Childhood Japan atomic-bomb exposure (Preston *et al*., 2008)	Strong
Childhood thyroid cancer studies (Lubin *et al*., 2017)	Strong
Mayak nuclear workers (Sokolnikov *et al*., 2015)	Moderate
Chernobyl fallout, Ukraine and Belarus thyroid cancer (Brenner *et al*., 2011)	Moderate
Breast cancer studies, after childhood exposure (Eidemuller *et al*., 2015)	Moderate
In utero exposure, Japan atomic bombs (Preston *et al*., 2008)	Moderate
Techa River, nearby residents (Schonfeld *et al*., 2013)	Moderate
In utero exposure, medical x ray (Wakeford, 2008)	Moderate
Japan nuclear workers (Akiba and Mizuno, 2012)	Weak-to-moderate
Chernobyl cleanup workers, Russia (Kashcheev *et al*., 2015)	Weak-to-moderate
U.S. radiologic technologists (Liu *et al*., 2014; Preston *et al*., 2016)	Weak-to-moderate
Mound nuclear workers (Boice *et al*., 2014)	Weak-to-moderate
Rocketdyne nuclear workers (Boice *et al*., 2011)	Weak-to-moderate
French uranium processing workers (Zhivin *et al*., 2016)	Weak-to-moderate
Medical x-ray workers, China (Sun *et al*., 2016)	Weak-to-moderate
Taiwan radiocontaminated buildings, residents (Hsieh *et al*., 2017)	Weak-to-moderate
Background radiation levels and childhood leukemia (Kendall *et al*., 2013)	Weak-to-moderate
In utero exposures, Mayak and Techa River (Akleyev *et al*., 2016)	No support
Hanford ^{131}I fallout, thyroid cancer (Davis *et al*., 2004)	No support
Kerala, India, high background radiation area (Nair *et al*., 2009)	No support
Canadian worker study (Zablotska *et al*., 2014)	No support
U.S. nuclear weapons test participants (Caldwell *et al*., 2016)	No support
Yangjiang, China, high background radiation area (Tao *et al*., 2012)	Inconclusive
Computed-tomography examinations of young persons (Pearce *et al*., 2012)	Inconclusive
Childhood medical x rays and leukemia (aggregate of >10 studies) (Little, 1999; Wakeford, 2008)	Inconclusive
Nuclear weapons test fallout (aggregate of eight studies) (Lyon *et al*., 2006)	Inconclusive