Ionizing Radiation

Introduction

Radiation that has sufficient energy to remove electrons from atoms is called "ionizing radiation." Ionization results in the production of negatively charged free electrons and positively charged ionized atoms. Ionizing radiation can be classified into two groups: photons (includes X-radiation and gamma radiation) and particles (includes alpha and beta particles and neutrons). The radioactive compound thorium dioxide, which decays by emission of alpha particles, was first listed in the *Second Annual Report on Carcinogens* (1981), and radon and its most common isotopic forms (radon-220 and radon-222), which also emit primarily alpha particles, were first listed in the *Seventh Annual Report on Carcinogens* (1994). Three types of ionizing radiation (X-radiation, gamma radiation, and neutrons) were first listed in the *Eleventh Report on Carcinogens* (2004). X-radiation and gamma radiation are included in one listing. The profiles for X-radiation and gamma radiation, neutrons, radon, and thorium dioxide, which are listed as *known to be human carcinogens*, follow this introduction.

X-Radiation and Gamma Radiation*

Known to be Human Carcinogens
First Listed in the *Eleventh Report on Carcinogens* (2004)

Carcinogenicity

X-radiation and gamma radiation are *known to be human carcinogens* based on sufficient evidence in humans. Epidemiological studies of radiation exposure provide a consistent body of evidence for the carcinogenicity of X-radiation and gamma radiation in humans. Exposure to X-radiation and gamma radiation is most strongly associated with leukemia and cancer of the thyroid, breast, and lung; associations have been reported at absorbed doses of less than 0.2 Gy (see "Properties," below, for explanation of radiation dose measurement). The risk of developing these cancers, however, depends to some extent on age at exposure. Childhood exposure is mainly responsible for increased leukemia and thyroid-cancer risks, and reproductive-age exposure for increased breast-cancer risk. In addition, some evidence suggests that lung-cancer risk may be most strongly related to exposure later in life. Associations between radiation exposure and cancer of the salivary glands, stomach, colon, bladder, ovary, central nervous system, and skin also have been reported, usually at higher doses of radiation (1 Gy) (Kleinerman *et al.* 1995, Ron 1998, Ron *et al.* 1999, Brenner *et al.* 2000, Garwicz *et al.* 2000, Lichter *et al.* 2000, Sont *et al.* 2001, Yeh *et al.* 2001, Bhatia *et al.* 2002).

The first large study of sarcomas (using the U.S. Surveillance, Epidemiology, and End Results cancer registry) (Yap *et al.* 2002) added angiosarcomas to the list of radiation-induced cancers occurring within the field of radiation at high therapeutic doses. Two studies, one of workers at a Russian nuclear bomb and fuel reprocessing plant (Gilbert *et al.* 2000) and another of Japanese atomic-bomb survivors (Cologne *et al.* 1999), suggested that radiation exposure could cause liver cancer at doses above 100 mSv (in the worker population especially with concurrent exposure to radionuclides). Among the atomic-bomb survivors, the liver-cancer risk increased linearly with increasing radiation dose. A study of children medically exposed to radiation (other than for cancer treatment) provided some evidence that radiation exposure during childhood may increase the incidence of lymphomas and melanomas. In addition, chronic lymphatic leukemia, Hodgkin's disease (malignant lymphoma), and cancer of the cervix, prostate, testis, and pancreas are generally considered not to be associated with radiation exposure.

X-radiation and gamma radiation are clearly carcinogenic in all species of experimental animals tested (mouse, rat, and monkey for X-radiation and mouse, rat, rabbit, and dog for gamma radiation). Among these species, radiation-induced tumors have been observed in about 17 tissues or organs, including those observed in humans (i.e., leukemia, thyroid gland, breast, and lung) (IARC 2000). Susceptibility to induction of benign and malignant tumors depends on tissue site, species, strain, age, and sex. Early prenatal exposure does not appear to cause cancer, but exposure at later stages of prenatal development has been reported do so. It has been suggested that radiation exposure of mice before mating increases the susceptibility of their offspring to cancer, but study results are conflicting.

Additional Information Relevant to Carcinogenicity

X-radiation and gamma radiation have been shown to induce a broad spectrum of genetic effects, including gene mutations, minisatellite mutations (changes in numbers of tandem repeats of DNA sequences), micronucleus formation (a sign of chromosome damage or loss), chromosomal aberrations (changes in chromosome structure or number), ploidy changes (changes in the number of sets of chromosomes), DNA strand breaks, and chromosomal instability. Genetic damage by X-radiation or gamma radiation has been observed in humans exposed accidentally, occupationally, or environmentally, in experimental animals exposed *in vivo*, and in cultured human and other mammalian cells. X-radiation and gamma radiation induce genetic damage in somatic cells and transmissible mutations in mammalian germ cells (sperm and egg cells and their precursors). The DNA molecule may be damaged directly, by interaction with ionizing radiation, or indirectly, by interaction with reactive products of the degradation of water by ionizing radiation (i.e., free electrons, hydrogen free radicals, or hydroxyl radicals) (IARC 2000, NTP 2003). The observed genetic damage is primarily the result of errors in DNA repair, but may also arise from errors in replication of damaged DNA. Epigenetic mechanisms (factors other than the primary DNA sequence) that alter the action of genes also may be involved in radiation-induced carcinogenesis. Proposed mechanisms for delayed or indirect radiation-induced genetic damage include genomic instability, induction of mutations by irradiation of the cytoplasm of the cell, and "bystander effects," in which genetic damage is induced in cells that were not directly exposed to ionizing radiation, apparently through cell signaling pathways.

Properties

As forms of electromagnetic radiation, X-rays and gamma rays are packets of energy (photons) having neither charge nor mass. They have essentially the same properties, but differ in origin. X-rays are emitted from processes outside the nucleus (e.g., bombardment of heavy atoms by fast-moving electrons), whereas gamma rays originate inside the nucleus (during the decay of radioactive atoms). The energy of ionizing radiation is expressed in electronvolts (eV), a unit equal to the energy acquired by an electron when it passes through a potential difference of 1 volt in a vacuum; 1 eV = 1.6×10^{-19} joules (J) (IARC 2000).

The energy of X-rays typically ranges from 5 to 100 keV. Lower in energy than gamma rays, X-rays are less penetrating; a few millimeters of lead can stop medical X-rays. The energy distribution of X-radiation is continuous, with a maximum at an energy about one third that of the most energetic electron. The energy of gamma rays resulting from radioactive decay typically ranges from 10 keV to 3 MeV. Gamma rays often accompany the emission of alpha or beta particles from a nucleus. Because of scattering and absorption within the radioactive source and the encapsulating material, the emitted photons have a relatively narrow energy spectrum (i.e., are monoenergetic). Gamma rays are very penetrating; they can easily pass through the human body, but they also can be absorbed by tissue.

Several feet of concrete or a few inches of lead are required to stop the more energetic gamma rays (BEIR V 1990).

As photons interact with matter, their energy distribution is altered in a complex manner as a result of energy transfer. The amount of energy deposited by ionizing radiation per unit of path length in irradiated material is called the "linear energy transfer" (LET), expressed in units of energy per unit length (e.g., kiloelectronvolts per micrometer). X-rays and gamma rays are considered low-LET radiation. In tissue, they transfer their energy primarily to electrons. Compared with high-LET radiation (such as neutrons and alpha particles), low-LET radiation tends to follow more tortuous paths in matter, with more widely dispersed energy deposition.

Use

X-rays, gamma rays, and materials and processes that emit X-rays and gamma rays are used in medicine, the nuclear power industry, the military, scientific research, industry, and various consumer products.

Medical use of ionizing radiation in both diagnosis and therapy has been widespread since the discovery of X-rays by Wilhelm Conrad Roentgen in 1895, and radioactive sources have been used in radiotherapy since 1898. Advances in the latter half of the 20th century increased the use of medical radiation, and some newer techniques, particularly radiotherapy, computed tomography, positron emission tomography, and interventional radiation involving fluoroscopy, use higher radiation doses than do standard diagnostic X-rays. Radiation therapy may involve use of external beams of radiation, typically high-energy X-rays (4 to 50 MeV) and cobalt-60 gamma rays (UNSCEAR 2000).

Military uses of materials and processes that emit X-radiation and gamma radiation include the production of materials for nuclear weapons and the testing and use of nuclear weapons. In 1945, atomic bombs were detonated over Hiroshima and Nagasaki, Japan. Between 1945 and 1980, nuclear weapons were tested in the atmosphere of the northern hemisphere; during the most intense period of testing, between 1952 and 1962, approximately 520 tests were carried out (IARC 2000).

Several industrial processes use ionizing radiation. Industrial radiography uses gamma radiation to examine welded joints in structures. In the oil industry, gamma radiation or neutron sources are used to determine the geological structures in a bore hole (a process called "well logging") (NCRP 1989). Ionizing radiation also is used to sterilize products and irradiate foods (to kill bacteria and parasites) (IARC 2000).

Ionization-type smoke detectors contain americium-241 (^{241}Am), which emits gamma radiation and alpha particles. In the past, detectors with up to 3.7 megabecquerels (MBq) of ^{241}Am were used in commercial and industrial facilities, but current smoke detectors contain less than 40 kBq (IARC 2000). Television sets emit low-energy X-rays through a process by which electrons are accelerated and bombard the screen (ATSDR 1999). Other products containing sources of ionizing radiation (of unspecified types) include radioluminescent clocks and watches, gaseous tritium light devices (e.g., self-luminous signs), thoriated gas lamp and lantern mantles, radioactive attachments to lightning conductors, static elimination devices, fluorescent lamp starters, porcelain teeth, gemstones activated by neutrons, and thoriated tungsten welding rods. All of these products have restrictions as to the maximum radioactivity allowable in the product and contribute little to the overall population exposure to ionizing radiation (IARC 2000).

Sources

The most important sources of X-radiation and gamma radiation include natural sources, medical uses, atmospheric nuclear weapons tests, nuclear accidents, and nuclear power generation. Ionizing radiation is present naturally in the environment from cosmic and terrestrial sources. Cosmic radiation is a minor source of exposure to X-radiation and gamma radiation; most natural exposure is from terrestrial sources. Soil contains radioactivity derived from the rock from which it originated. However, the majority of radioactive elements are chemically bound in the earth's crust and are not a source of radiation exposure unless released through natural forces (e.g., earthquake or volcanic activity) or human activities (e.g., mining or construction). Generally, only the upper 25 cm of the earth's crust is considered a significant source of gamma radiation. Indoor sources of gamma radiation may be more important than outdoor sources if earth materials (stone, masonry) were used in construction (IARC 2000).

Exposure

Biological damage due to ionizing radiation is related to dose and dose rate, which may affect the probability that cancer will occur (IARC 2000). Radiation dose is a measure of the amount of energy deposited per unit mass of tissue and may be expressed as the absorbed dose, equivalent dose, or effective dose. The standard unit for absorbed dose is the gray (Gy), which is equal to 1 J/kg of deposited energy. The absorbed dose formerly was expressed in rads (1 Gy = 100 rads). The biological effect of high-LET radiation is greater than that of low-LET radiation at the same absorbed dose; therefore, a dose measurement independent of radiation type was derived to reflect the biological effectiveness of radiation in causing tissue damage. The "equivalent dose" (also known as the "dose equivalent") is obtained by multiplying the absorbed dose by a radiation weighting factor (WR; formerly called the "quality factor"). Radiation weighting factors are assigned to radiation of different types and energies by the International Commission on Radiological Protection based on their biological effects relative to those of a reference radiation, typically X-rays or gamma rays; WR ranges from 1 (for low-LET radiation) to 20 (for high-LET radiation). The standard unit for the equivalent dose is the sievert (Sv). The equivalent dose formerly was expressed in rems (1 Sv = 100 rem). Because WR = 1 for both X-rays and gamma rays, the absorbed and equivalent doses are the same (ICRP 1991). Another measurement, the "effective dose," takes into account the fact that the same equivalent dose of radiation causes more significant biological damage to some organs and tissues than to others. Tissue weighting factors (WT) are assigned to different organs and tissue types, and the effective dose is calculated as the sum of the tissue-weighted equivalent doses in all exposed tissues and organs in an individual. The effective dose is expressed in sieverts. The collective radiation dose received by a given population may be expressed as the "collective equivalent dose" (also known as the "collective dose equivalent"), which is the sum of the equivalent doses received by all members of the population, or as the "collective effective dose," which is the sum of the effective doses received by all members of the population. Both the collective equivalent dose and the collective effective dose are expressed in person-sieverts.

All individuals are exposed to ionizing radiation from a variety of natural and anthropogenic sources. Of the general population's exposure to all types of ionizing radiation (not just X-radiation and gamma radiation), natural sources contribute over 80%; radon gas and its decay products account for about two thirds of natural exposure, and the other third is from cosmic radiation, terrestrial radiation, and internally deposited radionuclides. The remaining exposure to ionizing radiation is from anthropogenic sources, such as medical procedures (15%), consumer products (3%), and other sources (totaling less than 1%), which include occupational exposures, nuclear fallout, and the nuclear fuel cycle (BEIR V 1990). In 2000, the worldwide estimated average annual per-capita effective doses of ionizing radiation (of any type) were 2.4 mSv (with a range of 1 to 20 mSv) for natural background exposure and 0.4 mSv (with a range of 0.04 to 1 mSv) for medical diagnostic exposure. Average annual effective doses from past atmospheric nuclear testing, the nuclear power plant accident in Chernobyl, Ukraine, and nuclear power production were only 0.005 mSv, 0.002 mSv, and 0.0002 mSv, respectively (UNSCEAR 2000). Of the estimated worldwide

exposure to X-radiation and gamma radiation, about 43% is from natural sources and about 55% from medical diagnosis and treatment; all other sources contribute less than 2% (UNSCEAR 1993, IARC 2000).

Radiation exposure from medical uses is much more variable than that from natural background radiation (even though the latter varies considerably among locations) because of marked differences in the quality of medical care among cultures. In the more developed nations, higher percentages of the population receive regular medical care, and thus exposures from diagnostic radiology and radiotherapy tend to be higher than in developing nations. Exposure to diagnostic X-rays varies but generally is low; plain film examinations of the chest and extremities involve relatively low effective doses (0.05 to 0.4 mSv), whereas examinations of the abdomen and lumbar spine or pelvis may result in higher effective doses (1 to 3 mSv). Radiation therapy uses much larger doses of radiation than do diagnostic procedures. For example, treatment for leukemia usually involves irradiation of the total bone marrow, with absorbed doses of about 10 to 20 Gy delivered in several fractions (UNSCEAR 2000).

Excluding uranium miners and other workers whose radiation exposure is individually monitored, approximately 5 million people (worldwide) are occupationally exposed to natural sources of ionizing radiation (of any type) at levels above the natural background. About 75% are coal miners (whose estimated average annual effective dose is 1 to 2 mSv), about 13% are other underground miners (whose estimated average annual dose is 1 to 10 mSv), and about 5% are airline crews (who receive an estimated average annual dose of up to 3 mSv). Miners are exposed mainly through inhalation of radon; thus, they are exposed primarily to alpha particles, but also to gamma radiation. Airline crews are exposed primarily to gamma radiation, but also to neutrons (UNSCEAR 1993, IARC 2000).

Medical workers may be exposed to many different types of radionuclides and radiation. In the early 20th century before radiation hazards were recognized, radiologists were exposed to high doses of X-radiation (IARC 2000). The first dose limit established for radiologists in 1902 allowed exposure of approximately 30 Gy per year (Mabuchi 2002), but doses are now much lower (< 1 mSv) (Mostafa *et al.* 2002). From 1985 to 1989, the average annual effective dose of ionizing radiation to medical workers was about 0.5 mSv (UNSCEAR 1993). Other settings with potential for occupational exposure to ionizing radiation include the nuclear industry, military activities, research laboratories, and various industries where radioactive materials or radiography are used (IARC 2000).

Regulations

DOT

Rules have been set governing the marking, labeling, packaging, handling, and transportation of radioactive materials

EPA

Clean Air Act:

Emissions of radionuclides, other than radon, to the air shall not exceed those amounts that would cause any member of the public to receive in a year an effective dose equal to or greater than 10 mrem

Comprehensive Environmental Response, Compensation, and Liability Act:

Reportable Quantity (RQ) = 0.001-1,000 curies (range for 758 radionuclides)*

Marine Protection, Research, and Sanctuaries Act:

Ocean disposal of high level nuclear waste is prohibited and any request for ocean disposal of low level waste requires a permit that must be approved by both houses of Congress

Nuclear Waste Policy Act:

Numerous requirements have been set that will limit the total amount of radiation entering the environment from the Yucca Mountain site for over 10,000 years

Disposal systems for waste shall be designed to provide a reasonable expectation that for 10,000 years after disposal any member of the general population in the general environment shall not receive a combined annual dose of radiation greater than 15 mrem

Regulations have been developed to limit radiation releases from disposal systems for spent nuclear fuel of high-level or transuranic nuclear waste

Resource Conservation and Recovery Act:

Radioactive waste mixed with various specified RCRA hazardous wastes are prohibited from land disposal

Safe Drinking Water Act:

Maximum Contaminant Level (MCL) = 4 mrem (beta particle and photon activity)

The EPA also has authority under the Atomic Energy Act, the Low-Level Radioactive Waste Policy Act, the Waste Isolation Pilot Plant Land Withdrawal Act, the Clean Water Act, and the Public Health Service Act to regulate radioactive contaminants in the environment.

FDA

Rules have been set that govern ionizing radiation for the treatment of foods for human consumption and the production and processing of animal feed and pet food

Performance standards have been set for ionizing radiation-emitting, light-emitting, and sonic and ultrasonic products

Rules have been established for use of radioactive drugs in research

Rules have been set for radiology and diagnostic therapeutic devices including mammography

NRC

Standards for Protection Against Radiation: Occupational radiation dose limits for adults = 5 rem/yr (total effective dose) or 50 rems (sum of the deep-dose equivalent to any individual organ or tissue other than the lens of the eye); 15 rems (eye-lens dose equivalent); 50 rems (shallow-dose equivalent to the skin or any other extremity). Additional limits have been established for minors and fetuses/embryos

Requirements have been set for the medical use of radioactive material and the issuance of licenses authorizing use of the material

Requirements have been set for the packaging, preparing for shipping, and transporting of licensed radioactive material

Rules have been established governing the receiving and storing of radioactive materials in geological repositories

OSHA

Comprehensive regulations have been set for workers exposed to ionizing radiation (including both X- and gamma-radiation) which include monitoring requirements, restricting areas with radiation, established exposure limits, and various precautionary procedures

Guidelines

ACGIH

Effective Dose = 50 mSv (single year); 20 mSv (averaged over 5 years)

Annual Equivalent Dose = 150 mSv (lens of eye); 500 mSv (skin); 500 mSv (hands and feet)

Embryo-fetus exposures once the pregnancy is known = 0.5 mSv (monthly equivalent dose); 2 mSv (dose to surface of women's abdomen for remainder of pregnancy); 1/20 of Annual Limit on Intake (ALI) for radionuclides

See Introduction for information on where to obtain additional detail on regulations and guidelines.

*No separate CAS registry number assigned to X-radiation and gamma radiation.

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