REVIEW ARTICLE

Effect of Ionizing Radiation on Human Health

Ashish Chaturvedi[1]*, Vinod Jain[2]

DOI: 10.18811/ijpen.v5i03.8

Abstract

The effects of radiation was first recognized in the use of X-rays for medical diagnosis. The rush in exploiting the medical benefits led fairly to the recognition of the risks and induced harm associated with it. In the early days, the most obvious harm resulting from high doses of radiation, such as radiation burns were observed and protection efforts were focused on their prevention, mainly for practitioners rather than patients. Although the issue was narrow, this lead to the origin of radiation protection as a discipline. Subsequently, it was gradually recognized that there were other, less obvious, harmful radiation effects such as radiation-induced cancer, for which there is a certain risk even at low doses of radiation. This risk cannot be completely prevented but can only be minimized. Therefore, the balancing of benefits from nuclear and radiation practices against radiation risk and efforts to reduce the residual risk has become a major feature of radiation protection. In this paper, we shall be looking at the precautionary measures for protecting life, properties and environment against ionizing radiation.

Keywords: Alpha particles, Beta particles, Gamma rays, Radiation, X-rays

International Journal of Plant and Environment (2019)

[1]Department of Pathology, King George's Medical University, Lucknow-226020, INDIA

[2]Department of General Surgery, King Geor King George's Medical University, Lucknow-226020, INDIA

Author for correspondence: Mr. Ashish Chaturvedi, Department of Pathology, King George's Medical University, Lucknow-226020, INDIA, Mobile: +91-9453938212, Email: ashishchaturvedi.jr.sc@gmail.com

How to cite this article: Chaturvedi, A. (2019). Effect of Ionizing Radiation on Human Health. International Journal of Plant and Environment 5(3): 200-205

Source of support: Nil

Conflict of interest: None

Submitted: 01.11.2018 **Accepted:** 01.07.2019 **Published:** 31.07.2019

Introduction

Radiation is naturally present in our environment and it has been there since the birth of the planet. In our life, with the evolution of an environment a significant levels of ionizing radiation is there. Generally, it arises in outer space (cosmic), the ground (terrestrial), and even from within our own bodies (Internal). It is present all around in the air we breathe, the food we eat, the water we drink and in the construction materials used to build our homes. The homes which are made of brick and stone have higher natural radiation levels than homes made of wood. The levels of natural or background radiation can vary greatly from one location to another. Radioactivity is present in our earth - it has existed all along. Naturally occurring radioactive materials (NORM) are present in the earth's crust, the floors and walls of our homes, schools, and offices as well as the food we eat and drink. Our own bodies- muscles, bones and tissues, contain naturally occurring radioactive elements. Most people's reaction, when they hear about the word radioactivity, is that it is something very harmful or deadly; especially events like the atomic bombs that were dropped at Hiroshima and Nagasaki in 1945, or the Chernobyl Disaster of 1986. On the contrary however, people will learn to appreciate that radiation has peaceful and beneficial applications to our everyday lives. New challenges with regards to global levels of radiation, exposure continues to arise. New biological information on the effects of radiation exposure is also available. The excess of radiation sources are creating a situation that is prone to illicit trafficking and other criminal activities. Moreover, the potential risks from low level radiation exposure, i.e., exposure to radiation comparable with natural background radiation, are the cause of lively debate and controversy (Pierce and Preston, 2000; Streffer, 2008; Wahl and Berkeley, 2010; Chen, 2014).

Ionizing radiation

The radiation that has enough energy to remove tightly bound electrons from atoms, thus creating ions refers to as ionizing radiation. This is the type of radiation which we leverage on its benefits to generate electric power, to kill cancer cells, and in many manufacturing processes. Radiation is the type of energy released by atoms that travels in the form of electromagnetic waves (gamma or X-rays) or particles (neutrons, beta or alpha). This spontaneous disintegration of atoms is called radioactivity. The excess energy is emitted in the form of ionizing radiation. Consequently, people are exposed to natural sources of ionizing radiation, such as in soil, water, vegetation, and in human-made sources, such as x-rays and medical devices. Though; ionizing radiation has many beneficial applications, including devlopment of plant varieties uses in medicine, industry, agriculture and research, so does the potential for health hazards if not properly used or contained (Valentin, 2002; Mosse, 2012; Chen, 2014).

Ionizing radiation contains sufficient electromagnetic energy to strip atoms and molecules from the tissue and alter chemical reactions in the body (converting molecules totally or partly into ions). X-Rays and Gamma rays are two forms of ionizing radiation. These rays are known to cause damage, that is why a lead vest must be worn when X-rays are taken of our bodies, and heavy shielding should surrounds nuclear power plants. The living creatures are constantly exposed to low levels of ionizing radiation from natural sources. This type of radiation is referred to as natural background radiation, and its main sources are: Visible light, ultraviolet light and infrared light (sunlight); Radioactive materials on the earth's surface (contained in coal, granite, etc.); Radioactive gases leaking from the earth (radon); Cosmic rays from outer space entering the earth's atmosphere through the ionosphere; Natural radioactivity in the human body (Edwards and Lloyd, 1996; Little and Muirhead, 1996; Frischknecht *et al.,* 2000).

There are mainly three types of ionizing radiations:

Alpha (α)

Particles, which include two protons and two neutrons. They are heavily, positively charged particles which do not travel very far in the air and cannot penetrate the skin. But if ingested or inhaled, it can be harmful. Accordingly, these particles are easily stopped by a thin sheet of paper or the human body skin. However, if alpha emission enters the body, it poses risk to sensitive body organs such as the lungs and the bones. But this risk can be reduced by ensuring that the inhalation or ingestion of emitted alpha particles is kept at minimum level by either installing dust controls or by the appropriate use of respiratory protection devices such as dust masks.

Beta (β)

Particles, which are generally fast moving and negatively charged and can travel much further through air than alpha particles. They are quite penetrating even through the skin but can easily be shielded with a sheet of plastic. They are more harmful if ingested or inhaled.

Gamma (γ) and X-ray

Gamma rays are waves of energy similar to light and they have much higher energy and can travel great distance through air. Therefore, they are very penetrating and require shielding of concrete or lead plating to stop them. Unshielded gamma rays are harmful inside and outside the body while X-ray has lower energy than gamma rays but are similar in nature to light. They can easily penetrate the skin than the bones.

Generally everyone is aware from high degree of danger associated with atomic radiation. Gamma rays, as well as alpha and beta particles emitted from radioactive material and nuclear reactions, are forms of ionizing radiation; these rays and particles can cause chemical or physical damage when they transfer their energy in living tissue. Health effects resulting from exposure to radiation may vary from no effect to death, and can cause disorders such as leukemia or bone, breast, and lung cancer. In addition, to the children of women who were exposed to high doses of radiation during pregnancy have shown an increased risk of birth defects. These effects have been observed in various studies of medical radiologists, uranium miners, radium workers, radiotherapy patients, and the people exposed to radiation from chernobyl and the atomic bombs dropped on Hiroshima and Nagasaki.

Due to the extremely high frequencies and energies of EMR, they have sufficient energy to break chemical bonds in living tissue. Well-known biological effects of X-rays are associated with the ionization of molecules.

There are many types of X-ray devices which include: Radiographic systems (dental, podiatry, veterinary, medical, chiropractic); Fluoroscopic imaging systems; (hospitals, radiologists); Cancer therapy; CT Scan (Computed Tomography); Mammography; Cabinet X-ray systems for security (baggage inspection at airports); Industrial radiography (pipe welds, circuit board analysis); Bone Density Scans for detection of osteoporosis; Other medical and research applications.

Sources of radiation

Radiation is the energy that travels through space, in the form of particles or electromagnetic waves such as radio, microwaves, infra-red, visible light, ultraviolet, alpha particles, X-rays and Gamma-rays etc. These sources of ionizing radiation could be from natural background radiation such as radon and thoron, cosmic and terrestrial radiation, or man-made radiation such as those from x-ray or nuclear medicine (NM) procedures. The details are illustrated in Fig. 1:

Natural radiation

In the literature, there are three sources of natural background radiation; Cosmic Radiation, Terrestrial Radiation and Internal Radiation (Moulder, 1999).

Cosmic radiation

This is simply the radiation from the sun and stars. Flying based at high altitudes much frequently and for long duration will attract extra cosmic radiation exposure.

Terrestrial radiation

This is the radiation due to the presence of radioactive materials such as uranium, thorium, and radium that exist naturally in soil, water and rocks. Essentially air contains radon, which is responsible for the dose from natural background sources, and all organic

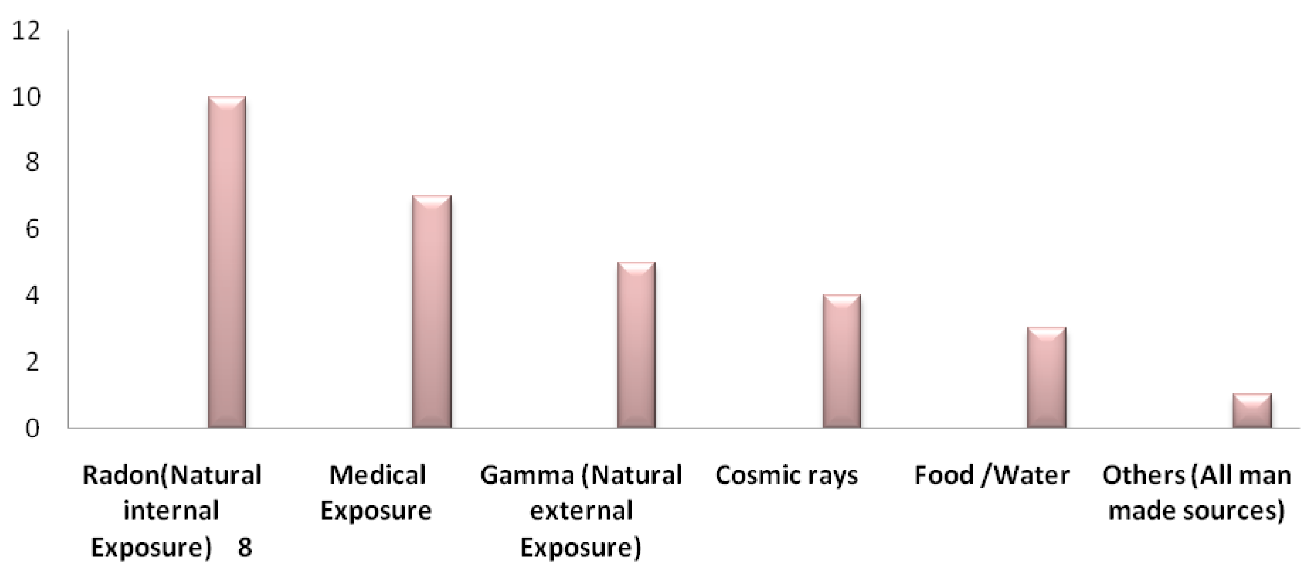

Fig. 1: Figure showing sources of radiation.

matter (plant and animal) also contains radioactive carbon and potassium. However, the dose from these sources varies in different parts of the world, but locations with higher soil concentrations of uranium and thorium generally have higher doses. Therefore, the background radiation levels vary in certain areas due to geological differences and sometimes the exposure can be more than 200 times higher than the global average. The highest known level of background radiation affecting a substantial population is in Kerala and Madras States in India.

Health effects of ionizing radiation

Ionizing radiation transfers energy into the body tissue and may thereby interfere in the structure of molecules. In living organisms, this energy transfer may disturb or destroy cellular functions (somatic effect fatal and nonfatal cancer) or it may change the genetic code of cells (hereditary effect). Accordingly deterministic (acute) effects will occur only if the radiation dose is substantial, such as in accidents. Stochastic effects (cancer and hereditary effects) may be caused by damage in a single cell (Hamada and Fujimichi, 2014). As the dose to the tissue increases from a low level, more and more cells are damaged and the probability of stochastic effects occurring increases. The first category consists of exposure to high doses of radiation over short periods of time producing acute or short term effects (Deterministic) while the second category represents exposure to low doses of radiation over an extended period of time producing chronic or long term effects (Stochastic). The long-term effects of radiation are those which may manifest themselves years after the original exposure. The body has repair mechanisms against damage induced by radiation as well as by chemical carcinogens. However, biological effects of radiation on living cells may result in three outcomes: Injured or damaged cells repair themselves, resulting in no residual damage; Cells die, much like millions of body cells do every day, being replaced through normal biological processes; Cells incorrectly repair themselves resulting in a biophysical change.

Ionizing radiation effects

The deleterious effect ionizing radiation has on human tissue can be divided into two types: non-stochastic (deterministic) or stochastic effects.

Deterministic (non-stochastic) effects

Deterministic effects generally occur only after high-dose acute exposure and are characterized by non-linear dose-responses, with a threshold dose below which the effect is not observed. Deterministic effects are of most relevance in radiotherapy; normal tissue therapy doses are limited to avoid these effects. Deterministic effects are thought to arise from the killing of large groups of cells in the tissues concerned, leading to functional deterioration in the organs affected. Deterministic effects generally arise within days (*e.g*. prodromal syndrome, gastrointestinal syndrome, central nervous system syndrome) or weeks (*e.g.* haematopoietic syndrome, pulmonary syndrome) of exposure; however, certain deterministic effects (*e.g.* cataracts, hypothyroidism) are manifest only over periods of years.

Mechanisms

Deterministic effects are caused by significant cell damage or death. The physical effects will occur when the cell death burden is large enough to cause obvious functional impairment of a tissue or organ. Few examples are as follows:

Skin Erythema/Necrosis/Epilation

Erythema occurs 1 to 24 hours after 2 Sv have been received. Breakdown of the skin surface occurs approximately four weeks after 15 Sv have been received. Epilation is reversible after 3 Sv but irreversible after 7 Sv and occurs three weeks following exposure.

Cataract

Cataract occurs due to accumulation of damaged or dead cells within the lens, the removal of which cannot take place naturally. Cataract occurs after 2 to 10 Gy have been received, but may take years to develop.

Sterility

Radiation can impair oocyte function, leading to impaired or non-fertility. The radiation dose required to have this effect decreases with age due to falling total oocyte numbers. Similarly, radiation exposure to the testes can result in temporary or permanent azoospermia. Permanent sterility occurs after 2.5 to 3.5 Gy have been received by the gonads.

Radiation sickness

Radiation sickness (correctly termed acute radiation syndrome) involves nausea, vomiting, and diarrhea developing within hours or minutes of a radiation exposure. This is due to deterministic effects on the bone marrow, GI tract, and CNS.

IUGR/teratogenesis/fetal death

Deterministic radiation exposure effects during pregnancy depend not only on the radiation dose received but also on the gestational age at which it occurred. The embryo is relatively radio-resistant during its preimplantation phase but highly radiosensitive during its organogenesis (two to eight weeks) and neuronal stem cell proliferation phases (eight to 15 weeks). Fetal radiosensitivity falls after this period. High levels of radiation exposure in pregnancy can lead to growth retardation, in particular microcephaly.

Stochastic effects

Current thinking is that stochastic effect occurrence follows a linear no-threshold hypothesis. This means that although there is no threshold level for these effects, the risk of an effect occurring increases linearly as the dose increases. Stochastic effects are the main late health effects that are expected to occur in populations exposed to ionizing radiation; somatic risks dominate the overall estimate of health detriment. For both somatic and genetic effects the probability of their occurrence, but not their severity, is taken to depend on the radiation dose. The dose-response may be non-linear, as for deterministic effects. However, in contrast to the situation for deterministic effects, for most stochastic effects it is generally accepted that at sufficiently low doses there is a non-zero linear component to the dose-response *i.e.* there is no threshold. There is little evidence, epidemiological 13, 15 or biological 16, for thresholds for stochastic effects.

Mechanism

Stochastic effects occur due to the ionizing radiation effect of symmetrical translocations taking place during cell division. Few examples are as follows:

Cancer

Over time, anecdotal evidence suggested that ionizing radiation could cause cancer. However, reliable evidence has only relatively recently become available. Data from the Radiation Effects Research Foundation on individuals exposed to radiation from the atomic bombs in Hiroshima and Nagasaki have shown an increased relative risk of developing malignancy (leukemia, oral cavity, esophagus, stomach, colon, lung, breast, ovary, urinary bladder, thyroid, liver, non-melanoma skin, and nervous system) as a result of radiation exposure. As such, multiple bodies,including the U.S. Department of Health and Human Services, have classified ionizing radiation as a human carcinogen.There is some controversy concerning the extrapolation of the linear no-threshold hypothesis to very low doses given that no increased incidence of cancer is seen in areas of high background radiation or in airline pilots. Caution should be exercised in multiple radiation exposures however, given that stochastic effects are cumulative. Similarly, multiple high-dose diagnostic imaging procedures such as CT can easily exceed the levels known to impart an increased relative risk for malignancy.

Hereditary defects (e.g., down syndrome)

Although no increased incidence of hereditary defects in patients exposed to radiation in Japan and Chernobyl was documented, animal experiments would suggest that this risk does exist. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and ICRP propose a hereditary defect risk of between 0.3 to 0.8% per Sv.

Gastrointestinal effects

Prominent gastrointestinal effects due to high acute doses of radiation can occur, usually after oral intakes of radionuclides or after whole-body exposures. The large doses necessary to cause these effects and the absence of effects following dental x rays demonstrate that salivary glands are not very sensitive to radiation. The structures near the stomach, which have stratified squamous epithelial coverings, seem to be much less severely affected than the stomach, small and large intestines, and colon, largely due to the lower cell turnover rates associated with this type of epithelium. The gastrointestinal epithelium, which includes the epithelium covering the stomach and intestines, is the most sensitive to the effects of radiation due to the high cell turnover rates.

Hematological and lymphoreticular effects

Hematological effects are one of the syndromes seen after acute doses to bone marrow of about 50 rad (0.5 Gy). The magnitude of effect on hematopoiesis is dependent on the total dose absorbed, regardless of the route of exposure. Like the gastrointestinal system, the hematopoietic system contains a large population of cells that requires the frequent replacement of senescent cells. To meet this need, a pool of undifferentiated precursor cells called stem cells in the red marrow of many bones (e.g., ribs, pelvis, vertebrae, skull, and ends of long bones) undergo high rates of mitotic activity and differentiate into the various cell types to replace those that die off naturally. This pool of cells is critical for the production of replacement cell populations for erythrocytes, granulocytes, lymphocytes, and thrombocytes. The dose of radiation received by stem cells damages or kills these cells, thereby depressing the marrow activity, resulting in anemia, leukopenia, thrombocytopenia, septicemia, infections, and death.

Reproductive effects

Cells that reproduce frequently, such as those found in intestinal crypts, bone marrow, and the reproductive systems of animals, are more radiosensitive than cells that are highly differentiated and reproduce slowly. This radiosensitivity is dependent on of the type of ionizing radiation or the source. Specific cells in the reproductive tract of both males and females replicate at accelerated rates, making them more at risk to the effects of ionizing radiation. In males, the spermatogonia are the cells most sensitive to the effects of ionizing radiation. These are the germ cells responsible for producing spermatocytes and later, spermatids and mature sperm.

Central nervous system (CNS) effects

As a whole, the central nervous system of the adult human and laboratory animal is extremely resistant to the effects of radiation. In contrast to the rapidly dividing cells of the gastrointestinal and hematopoietic systems, the central nervous system has a relatively static population of cells, with cell mitosis occurring between long intervals of latency, if at all. Birioukov *et al.* (1993) reported that one man exposed to 200-350 rad (2-3.5 Gy) had clinical symptoms such as permanent headache and vision impairment after accidental exposure to gamma radiation during and after the Chernobyl atomic power plant accident.

Respiratory and cardiovascular effects

The respiratory tract has long been known to be a target organ of both internal and external radiation. Respiratory effects have been reported in humans who had received radiotherapy for breast cancer and those who had been accidentally overexposed, as well as in laboratory animals No harmful effects have been seen in the millions of people who receive occasional diagnostic x rays of the chest. Local injury is tolerated much more than diffuses injuries.

Dermal effects

Clinically observable dermal radiation effects ranging from erythema (skin reddening) to necrosis have been observed following external beta, gamma and x ray exposure above threshold doses at high dose rates. A transient erythema, the earliest sign of overexposure of the skin, occurs after a dose of about 300 rad (3 Gy), and was once used by physicians to calibrate x ray machines. The erythema appears several hours after exposure, and disappears within a day.

Teratogenic/embryotoxic effects

The rapidly dividing cells in the developing fetus, like those in the reproductive system, are also at a much higher risk of radiation damage, independent of the type of ionizing radiation, or the source or route of exposure, than slowly dividing, differentiated cells. External exposure to the fetal animal by alpha and beta radiation is of no concern because α and β radiation cannot penetrate the mother's body tissues and the placental sac. Gamma radiation is very penetrating and can expose the fetus. The embryo/fetus is always uniformly exposed to external gamma rays from background radiation. There may also be partial body exposure from medical x rays or from internal exposure to a radionuclide such as 90Sr, which results in preferential uptake during fetal bone development. During the early days of development, the human embryo largely consists of a mass of undifferentiated cells, which are the cells most sensitive to the effects of ionizing radiation. These cells transform into more specialized (differentiated) cells at specific times during gestation and develop into the more organized tissues seen later at maturity. For the purposes of describing teratogenic and other effects of *inutero* exposure, gestation is divided into three major periods: preimplantation, 0-2 weeks, major organogenesis, 2-8 weeks, and the fetal period, 8-40 weeks (Brent, 1980). Central nervous system (CNS) injury of radiological importance results from exposure in the early fetal period.

Sensorimotor effects

Norton and Kimler (1987) also investigated the early postnatal behaviours involving sensorimotor integration and the thickness of the sensorimotor cortex in prenatally irradiated rats which received a dose of 100 rad (1 Gy) from a 137Cs source (Acevedo et al., 2008). Cortical thickness of the cerebral mantle was not significantly altered. The number of pyknotic cells, the number of macrophages, the nuclear area, and the number of mitotic cells were altered in a dose-related way. The number of mitotic figures in the ventricular zone was significantly reduced and the number of macrophages was significantly increased in fetuses from the 50-, 75- and 100 rad (0.5, 0.75, and 1 Gy) treatment groups. The number of macrophages in the ventricle and in the cortical mantle was significantly increased at 12 and 24 hours in fetuses prenatally exposed to 50 rad (0.5 Gy).

Respiratory and cardiovascular effects

The respiratory tract has long been known to be a target organ of both internal and external radiation. Respiratory effects have been reported in humans (Stavem et al., 1985) who had received radiotherapy for breast cancer and those who had been accidentally overexposed, as well as in laboratory animals (Rezvani et al., 1989; Salovsky and Shopova, 1992). No harmful effects have been seen in the millions of people who receive occasional diagnostic x-rays of the chest (Wall et al., 2006). Local injury is tolerated much more than diffuse injuries. Irradiation of large portions of one or both lungs initially results in alterations in blood flow, initially manifested as edema, and later as pneumonitis and pulmonary fibrosis, depending on the total dose received. Radiation pneumonitis, followed by pulmonary fibrosis (i.e., fibrosis of alveolar structures involving changes in the ratios of some pulmonary collagens), are two of the most commonly reported aberrations in laboratory animals following an inhalation of large activities of radioactive material (Brooks et al. 1971, 1992; Hahn et al. 1975, 1981; Benjamin et al. 1978, 1979; Lundgren et al. 1980, 1991).

Ocular effects

The lens of the eye is not among the most radiosensitive tissues in the body, but it has less efficient repair capabilities than many other tissues. This allows radiation damage to build up with less repair, even when doses are fractionated or delivered at low dose rates (Botkin and Keller, 2011). Exposure of the lens to sufficient doses of ionizing radiation results in cataract formation, which can range from minimally detectable opacities that do not impair vision to blindness. The effects of ionizing radiation on the eye have been reported in some human exposure cases. Ham (1953) described the radiogenic cataracts in cyclotron physicists from mixed gamma-neutron doses of 700-1,000 rad (70-100 Gy) to the lens (Ross *et al*., 1990). Klener *et al.* (1986) reported on a human case study in which a male technician was accidentally irradiated by a sealed 60Co source he had been installing. His health status was followed for 11 years after the accident. A film dosimeter worn during the accident indicated it received an exposure of 159 rad (1.59 Gy), but the dose to his eye was not reported. Changes in the lens of the left eye began to appear gradually, leading to the deterioration of visual acuity. Later, opacities of the lens of the right eye were also found. In dogs exposed on ppd 2, retinal degeneration was evident in all dogs sacrificed at 70 days, 2 years, or 4 years of age. Retinal dysplasias were evident in all dogs sacrificed at 70 days of age and in 4 of the 13 dogs sacrificed at 2 years. Retinal dysplasia was not evident in dogs sacrificed at 4 years.

Genotoxic effects

The genotoxicity of ionizing radiation is an area of intense study, as damage to the DNA is ultimately responsible for many of the adverse toxicological effects described so far in this chapter. Cells depend on their DNA for coding information to make specific enzymes, proteins, hormones, vasoactive substances, and a host of other essential chemicals (Shapiro, 2002). When the genetic information containing the "blueprint" for these substances is disturbed, cellular homeostasis is disrupted, resulting in a wide-range of immediate and/or delayed toxicological effects in a number of organ systems, as described earlier in this chapter. Disruptions and changes of the cellular genome are also thought to be responsible for the formation of cancer in both humans and laboratory animals.

Radiation induced cellular DNA damage

DNA double strand breaks (DSB) play a critical role in the carcinogenesis process. It takes the form of an electromagnetic wave, with the frequency of the electromagnetic wave determining its position in the electromagnetic spectrum. Low-frequency waves such as radio waves lie at one end of the spectrum and high-energy, high-frequency X-rays/Gamma rays at the other end. This high-frequency, high-energy waves are termed "ionizing" (as opposed to non-ionizing) radiation because they contain sufficient energy to displace an electron from its orbit around a nucleus. The most important consequence of this displaced electron on human tissue is the potential damage it can inflict on DNA, which may occur directly or indirectly. Direct damage occurs when the displaced electron hits and breaks a DNA strand. Indirect damage occurs when the electron reacts with a water molecule, creating a powerful hydroxyl radical which then damages the cell's DNA (Chavez *et al*., 2019).

Damage to a cell's DNA in either of these ways can have several consequences. A single-strand DNA break is usually repaired appropriately by the cell with no subsequent deleterious sequelae. However, a break affecting both strands of DNA allows the potential for abnormal reconnection of the strands, which likely accounts for all the adverse biological effects ionizing radiation has on humans. First, DNA may rejoin itself incorrectly, rendering the cell nonviable with cell death taking place. Second, it may rejoin as a symmetrical translocation with the potential expression of an oncogene during division (and development of subsequent malignancy) or with abnormal division in gonads, giving rise to potential hereditary disorders. Radiosensitivity is the probability of a cell, tissue, or organ suffering an effect per unit dose of radiation (Akleyev, 2016). Radiosensitivity is highest in cells which are highly mitotic or undifferentiated. For this reason the basal epidermis, bone marrow, thymus, gonads, and lens cells are highly radiosensitive. Muscle, bones, and nervous system tissues have a relative low radiosensitivity.

Conclusion

Low level ionizing radiation, including background radiation, is a cause of cancer, heritable mutations, and probably other significant health effects. Deregulation of radioactive wastes would lead to exposures of transport workers, environmental releases, and exposures to the general population to low level radiation in a highly complex and difficult to predict pattern. The waste could not be recalled and much of it would continue to release radiation for many generations. Long term epidemiological studies of populations exposed to radiation, have demonstrated that exposure to radiation have potential for the delayed induction of malignancies. It is therefore essential that activities involving radiation exposure, such as the production and use of radiation sources and radioactive materials, and the operation of nuclear installations, including the management of radioactive waste, be subjected to certain standards of safety in order to protect those individuals exposed to radiation.

References

Acevedo, S.F., McGinnis, G. and Raber, J. 2008. Effects of 137Cs γ irradiation on cognitive performance and measures of anxiety in Apoe-/-and wild-type female mice. *Radiation Research* **170**: 422-428.

Akleyev, A.V. 2016. Normal tissue reactions to chronic radiation exposure in man. *Radiation Protection Dosimetry* **171**(1): 107-116.

Benjamin, S.A., Boecker, B.B. and Cuddihy, R.G. 1979. Nasal carcinomas in Beagles after inhalation of relatively soluble forms of beta-emitting radionuclides. *Journal of the National Cancer Institute* **63**: 133-139.

Benjamin, S.A., Hahn, F.F. and Boecker, B.B. 1978. Effects of chronic pulmonary irradiation on peripheral lymphocytes and their function in the dog. *Radiation Research* **75**: 133-139.

Birioukov, A., Meurer, M., Peter, R.U., Braun-Falco, O. and Plewig, G. 1993. Male reproductive system in patients exposed to ionizing irradiation in the Chernobyl accident. *Archives of Andrology* **30**(2): 99-104.

Botkin, D.B. and Keller, E.A. 2011. Radiation doses and health. In Environmental science - earth as a living planet, 8th edition, Wiley, New York.

Brent, R.L. 1980. Radiation teratogenesis. *Teratology* **21**(3): 281-298.

Brooks, A.L., Guilmette, R.A. and Hahn, F.F. 1992. Distribution and biological effects of inhaled $^{239}Pu(NO_3)_4$ in Cynomolgus monkeys. *Radiation Research* **130**: 79-87.

Brooks, A.L., Mead, D.K. and Peters, R.F. 1971. Effect of chronic exposure to 60Co on the frequency of metaphase chromosome aberrations in the liver cells of the Chinese hamster (*in vivo*). *International Journal of Radiation Biology* **20**: 599-604.

Chavez, C., Cruz-Becerra, G., Fei, J., Kassavetis, G.A. and Kadonaga, J.T. 2019. The tardigrade damage suppressor protein binds to nucleosomes and protects DNA from hydroxyl radicals. *Chromosomes and Gene Expression* **8**: e47682.

Chen, M. 2014. Radiation protection and regulations for the nuclear medicine physician. *Elsevier* **44**: 215-228.

Edwards, A.A. and Lloyd, D.C. 1996. Risk from deterministic effects of ionising radiation. *Docs NRPB* **7**(3): 1-31.

Frischknecht, R., Braunschweig, A., Hofstetter, P. and Suter, P. 2000. Human health damages due to ionizing radiation in life cycle impact assessment. *Elsevier* **20**: 159-189.

Hahn, F.F., Barnes, J.E. and Hobbs, C.H. 1975. Effect of 90Y inhaled in fused clay particles on the gastrointestinal tract of Beagles. *Radiation Research* **61**: 444-456.

Hahn, F.F., mewhinney, J.A. and Merickel, B.S. 1981. Primary bone neoplasms in Beagle dogs exposed by inhalation to aerosols of Plutonium-238 dioxide. *Journal of the National Cancer Institute* **67**: 917-927.

Ham, W.T. 1953. Radiation cataracts. *Archives of Ophthalmology* **50**:618

Hamada, N. and Fujimichi, Y. 2014. Classification of radiation effects for dose limitation purposes: history, current situation and future prospects. *Journal of Radiation Research* **55**(4): 629-640.

Klener, V., Tuscany, R. and Vejlupkova, J. 1986. Long-term follow-up after accidental gamma-irradiation from a 60Co source. *Health Physics* **51**(5): 601-607.

Little, M.P. and Muirhead, C.R. 1996. Evidence for curvilinearity in the cancer incidence dose–response in the Japanese atomic bomb survivors. *International Journal of Radiation Biology* **70**: 83-94.

Lundgren, D.L., Hahn, F.F. and McClellan, R.O. 1980. Influence of age at the time of inhalation exposure to aerosols of 144 CeO_2 on 144 Ce retention, dosimetry and toxicity in mice. *Health Physiology* **38**: 643-655.

Lundgren, D.L., McClellan, R.O. and Thomas, R.L. 1974. Toxicity of inhaled 144 CeO2 in mice. *Radiation Research* **58**: 448-461.

Mosse, I.B. 2012. Genetic effects of ionizing radiation – some questions with no answers – Low radiation doses. *Elsevier* **112**: 70-75.

Moulder, J.E. 1999. Electromagnetic Fields and Human Health. An Assessment of the Evidence Relating to Radio-frequency Radiation and Cancer.

Norton, S. and Kimler, B.F. 1987. Correlation of behavior with brain damage after in utero exposure to toxic agents. *Neurotoxicology and Teratology* **9**: 145-150.

Pierce, D.A. and Preston, D.L. 2000. Radiation-related cancer risks at low doses among atomic bomb survivors. Radiation Research **154**: 178-186.

Rezvani, M., Heryet, J.C. and Hopewell, J.W. 1989. Effects of single doses of gamma-radiation on pig lung. *Radiotherapy and Oncology* **14**(2): 133-142.

Ross, W.M., Creighton, M.O. and Trevithick, J.R. 1990. Radiation cataractogenesis induced by neutron or gamma irradiation in the rat lens is reduced by vitamin E. *Scanning Microscopy* **4**(3): 641-650.

Salovsky, P.T. and Shopova, V.I. 1992. Early biological effects of whole body irradiation on rat lungs. *Radiation and Environmental Biophysics* **31**(4): 333-341.

Shapiro, J. 2002. Radiation protection - a guide for scientists, regulators, and physicians, gamma rays—a major class of uncharged ionizing particles. 4th edition, Harvard University Press, Massachusetts.

Stavem, P., Brogger, A., Devik, F. 1985. Lethal acute gamma radiation accident at Kjeller, Norway. Report of a case. *Acta Radiologica: Oncology* **24**(1): 61-63.

Streffer, C. 2008. Radiological protection: challenges and fascination of biological research, strengthening radiation protection worldwide: highlights-global perspective and future trends. Paper presents at: 12th Congress of the International Radiation Protection Association (IRPA12); October 19–24; Buenos Aires, Argentina.

Valentin, J. 2002. Proceedings of an international conference on ICRP principles for the radiological protection of workers – occupational radiation protection: protecting workers against exposure to ionizing radiation, Geneva, 26-30 August.

Wahl, L.E. and Berkeley, L. 2010. Health effects of background. In: Environmental radiation, HPS, McLean.

Wall, B.F., Kendall, G.M., Edwards, A.A., Bouffler, S., Muirhead, C.R. and Meara, J.R. 2006. What are the risks from medical X-rays and other low dose radiation? *The British Journal of Radiology* **79**: 285-294.