Chapter 2

Radioisotope: Applications, Effects, and Occupational Protection

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Additional information is available at the end of the chapter

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Abstract

This chapter presents a brief introduction to radioisotopes, sources and types of radiation, applications, effects, and occupational protection. The natural and artificial sources of radiations are discussed with special reference to natural radioactive decay series and artificial radioisotopes. Applications have played significant role in improving the quality of human life. The application of radioisotopes in tracing, radiography, food preservation and sterilization, eradication of insects and pests, medical diagnosis and therapy, and new variety of crops in agricultural field is briefly described. Radiation interacts with matter to produce excitation and ionization of an atom or molecule; as a result physical and biological effects are produced. These effects and mechanisms are discussed. The dosimetric quantities used in radiological protection are described. Radiological protections and the control of occupational and medical exposures are briefly described.

Keywords: radioisotopes, sources of natural and artificial radiation, radiation dose, biological effect, dosimetric units, radiation protection, radiation application, environment

1. Introduction

Radiation and radioactivity existed long before life evolved on the earth and are *indispensable* parts of the environment. We are continuously exposed to natural and artificial radiations. In addition to these, some of the radionuclides such as polonium and radium are present in our bones; our muscle contains radiocarbon and radiopotassium, radon, thoron, and their progeny in our lungs, and they emit ionizing radiation. The radiation coming from the sun is due to the nuclear fusion; it is very essential for the existence of life on earth. Therefore we live in a natural radioactive world. All organisms including human beings on the earth are getting benefits

from radiation in a direct way without realizing it. Therefore, without radiation life does not exist. Scientific understanding of radiation and radioactivity and their benefits and effects on humans, that's back almost century to the pioneering work of Roentgen (1895) and Becquerel (1896). Further investigation by M. Curie and P. Curie (1898) and Rutherford (1911) showed that radioactivity is exhibited by heavy elements such as uranium, thorium, and radium. The discovery of isotope was one of the results of work on the radioactive elements. The name "isotope" was first suggested by Soddy in 1913. The radioactive decay law was also proposed by him. More than thousand natural radioisotopes are present in our nature. At present more than 200 radioisotopes were produced from nuclear reactors and accelerators. The application of radioisotopes in medical, industry, and research field has served human civilization over a several decades. The radioisotopes have been a valuable gift to many braches of medicine and biology. Shorter half-lives of radioisotopes are used in medicine because they decay quickly and they are suitable for medical diagnosis and therapy. The World Health Organization (WHO) and International Atomic Energy Agency (IAEA) jointly coordinated a research program on radioactive tracers in cardiovascular diseases and searched for clues to this widespread health problem [1]. There are numerous applications of radioisotopes in medical fields; one of the revolutionized techniques is radioimmunoassay; this is used to detect and quantify minute levels of tissues components such as hormones, enzymes, or serum proteins by measuring the components ability to bind to an antibody or other proteins in competition with a standard amount of the same component that had been radioactivity tagged in the laboratory. For this technique, Rosalyn Sussman Yalow was awarded Nobel Prize in 1977 [2]. The precise dose is a life-and-death matter; therefore the IAEA has several program components to assist institutions in the members of the countries and aspect of radiation therapy and diagnosis. The IAEA in cooperation with the WHO offers on intercomparison service to check and improve accuracy of radiation dosimetry due to increase in the effectiveness of the radiotherapy [1]. The release of radioisotopes from nuclear fuel cycles, naturally occurring radioactive materials (NORM) from mining activity, mishandling of radioisotopes in industries and laboratories, and accidental release of radioactive materials could enter into the atmosphere. Therefore, it is necessary to require an urgent decision for protective actions. Therefore, the main objective is to focus on the applications and effects of radioisotopes and radiological protection.

2. Radioisotopes and radiation

The atom is the basic building block of matter. The concept of atoms and molecules was first introduced by John Dolton in 1811, and he proposed the atomic theory. The atom consists of positively charged nucleus and surrounded by a number of negatively charged electron, so that atom as a whole is electrically neutral. The electron had been discovered by J. J. Thomson in 1897. The nucleus consists of positive-charged proton and neutral-charged neutron referred as nucleons. The nucleus and proton were discovered by Rutherford in 1911, and neutron was discovered by James Chadwick in 1932. The number of proton present in the nucleus is called atomic number (Z), and total number of neutrons and protons present in the nucleus is called mass number (A). The atomic number of an element is the same, but different mass numbers are called isotope of an element. If the nucleus contains either excess of neutrons or protons, the force between these constituents will be unbalanced leading to unstable nucleus. An unstable nucleus will continuously

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vibrate and will attempt to reach stability by undergoing radioactive decay. The number of neutrons determines whether the nucleus is radioactive or not. The radioactive isotopes of an element are called radioisotopes; they are natural and artificially produced by nuclear reactors and accelerators. The discovery of radioisotope was one of the result works on the radioactive element. The way in which isotope arises in the radioactive element can be understood in terms of effects of radioactive decay on the atomic number Z and mass number A. In the year 1902, Rutherford and Soddy established that radioactivity is directly connected to the state of atomic nucleus.

The unstable nuclei of an element can undergo the variety of processes resulting in the emission of radiation in two forms, namely, radioactivity and nuclear reactions. In a radioactive decay, the nucleus spontaneously disintegrates to different species of nuclei or to a lower energy state of the same nucleus with the emission of alpha (α), beta (β), and gamma (γ) radiation is called radioactivity. The radioactivity was discovered by Henry Becquerel in 1896. Alpha, beta, and their ionizing property were discovered by Rutherford in 1899, and gamma was discovered by Villard in 1900. In nuclear reaction, the nucleus interacts with another particle or nucleus with subsequently emission of radiation as one of its final products. In some cases, the final product is also radioactive. The radiation emitted in both these processes may be electromagnetic (X-rays and γ-rays) or particle-like α, β, and neutrons. The nuclear reactions were discovered by Rutherford in 1917.

2.1. The type of emission of ionizing radiations

The ionizing radiations such as α, β, and γ except neutron are originated from unstable nuclei of an atom in an element undergoing radioactive decay.

2.1.1. Alpha radiation

Some naturally occurring heavy nuclei with atomic number $82 < Z < 92$ and artificially produced transuranic element $Z > 92$ decay by alpha emission, in which the parent nucleus loses both mass and charge. The alpha particle is emitted in preference to other light particles such as deuteron (^{2}H), tritium (^{3}H), and helium (^{3}He). Because energy must be released in order for decay to take place at all. The alpha particle has very stable and high binding energy, has tightly bound structure, and can be emitted spontaneously with positive energy in alpha decay, whereas ^{2}H, ^{3}H, and ^{3}He decay would require an input energy. The parent nucleus (Z, A) is transformed via

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}X + \alpha \tag{1}$$

It has less penetrating and high ionizing power.

2.1.2. Beta radiation

Beta particles are fast electron or positron; these are originated from weak interaction decay of a neutron or proton in nuclei, which contains an excess of the respective nucleon. In a neutron-rich nucleus, neutron can transform itself in to a proton by emission of beta particles and antineutrino. Similarly, in the nuclei with rich proton, it transforms into neutron by emission of neutrino and positron. These radiations are high penetrating and less ionizing power:

$$n \rightarrow p + e^{-} + \nu^{-} \tag{2}$$

Similarly in the nuclei with rich proton, the decay is

$$p \rightarrow n + e^{+} + \nu \tag{3}$$

2.1.3. Gamma radiation

The emission of gamma rays is usually the most common mode of nuclear excitation and also occurs through internal conversion.

2.1.4. X-ray radiation

X-rays arises from the electron cloud surrounding the nucleus. They were discovered by Roentgen in 1895. X-rays are produced in X-ray tube by fast moving electron which is suddenly stopped by target.

2.1.5. Neutron radiation

It is a neutral particle that produces ionization indirectly by emission of γ-rays and charged particles when interacting with matter. These charged particles produce the ionization. It has more penetrating than gamma ray and can be stopped by thin concrete or paraffin barrier. They are produced by nuclear reaction and spontaneous fission in nuclear reactors. The characteristic emission of α, β, γ, and neutron sources is given in **Table 1** [3].

2.2. Classification of radiation

Depending on its effects on matter and its ability to ionize the matter, radiation is classified in two main categories: ionizing and nonionizing radiations.

2.2.1. Ionizing radiation

Radiation passing through the matter which breaks the bonds of atoms or molecules by removing the electron is called ionization radiation. It passes through the matter or living organisms, and it produces various effects.

Ionizing radiation is produced by radioactive decay, nuclear fission, and fusion, by extremely hot objects, and by particle accelerators. The emission of ionizing radiation is explained in Section 2.1. The ionizing radiation is again divided into two types: direct and indirect ionizing radiation.

2.2.1.1. Direct ionizing radiation

Directly ionizing radiation deposits energy in the medium through direct Coulomb interaction between the ionizing charged particles and orbital electrons of atoms in the medium, for example, α, β, protons, and heavy ions.

Source/isotope	Half-life	Energy (MeV)	
α			
^{241}Am	433 years	5.486	
^{210}Po	138 days	5.443	
^{242}Cm	163 days	5.305	
^{243}Am	7.4×10^3 years	6.113	
^{239}Pu	2.4×10^4 years	6.070	
β			
$^{3}_{1}H$	12.26 years	0.0186	
^{14}C	5730 years	0.156	
^{36}Cl	3.08×10^5 years	0.714	
^{63}Ni	92 years	0.067	
^{204}Tl	3.81 years	0.766	
γ			
^{60}Co	5.2 years	0.662	
^{137}Cs	30 years	1.277	
^{22}Na	2.6 years	1.173	
$^{60}_{27}C$	5.2 years	1.332	
X-rays			
^{41}Ca	8×10^5 years	3.690 keV	
^{44}Ti	48 years	4.508	
^{49}V	330 days	4.949	
^{55}Fe	2 k.6 years	5.895	
Source	**Half-life**	**Energy MeV**	**Yield × 10^6**
Neutron			
^{239}Pu/Be	24,000 years	5.14	65
^{210}Po/Be	138 days	5.30	73
^{238}Pu/Be	87.4 years	5.48	79
^{241}Am/Be	433 years	5.48	82

Table 1. Characteristics of some α, β, and γ emitters and neutron (sources).

2.2.1.2. Indirect ionizing radiation

Indirectly ionizing radiation deposits energy in the medium through a two-step process; in the first step, charged particles are released in the medium. In the second step, the released charged particles deposit energy to the medium through direct coulomb interaction with orbital electron of the atoms in the medium, for example, X-rays, photons, γ rays, and neutrons.

2.2.2. Nonionizing radiation

Nonionizing radiation is part of the electromagnetic radiation where there is insufficient energy to cause ionization. But it has sufficient energy only for excitation and not to produce

ions when passing through matter [4]. Radiowaves, microwaves, infrared, ultraviolet, and visible radiation are the examples of nonionizing radiations. Nonionizing radiation is essential to life, but excessive exposures will cause biological effects.

3. Sources of natural and artificial radiation

There are two important sources of radiation: they are natural and man-made.

3.1. Natural background radiation

The radiation that exits all around us is called natural background radiation. All living organisms including man have been continuously exposed to ionizing radiations emitted from different sources, which always existed around us. The sources of natural radiation are cosmic rays and naturally occurring primordial radionuclides such as ^{238}U, ^{232}Th, ^{235}U, and their decay products as well as the singly occurring natural radionuclides like ^{40}K and ^{87}Rb, which are present in the earth crust, soil, rocks, building materials, ore, and water in the environment [5, 6]. Background radiation is a constant source of ionizing radiation present in the environment and emitted from a variety of sources. Natural radiations originated from three major sources: terrestrial, extraterrestrial, and internal (intake of natural radionuclides and their daughter product) sources of radiation.

3.1.1. Terrestrial sources of radiations

Terra means earth; the radiation originated from the earth crust is called terrestrial radiation. The primordial radionuclides (^{238}U, ^{232}Th, and ^{40}K) present in varying amounts in soil, rocks, water, and atmosphere are the sources of terrestrial radiation. The bulk of the natural radiation is mainly due to ^{40}K and ^{238}U, ^{232}Th, and their decay products [7]. Natural uranium consists of three isotopes ^{234}U, ^{235}U, and ^{238}U. ^{238}U is present in an abundance of 99.28% with a half-life of 4.5×10^9 years and ^{235}U in abundance 0.72% with a half-life of 0.7×10^9 years. Thorium is one of the important natural primordial radionuclides with a half-life of 1.4×10^9 years. It is about four times more abundant in nature than uranium. Average crustal abundance of ^{232}Th is 7.2 ppm [7]. All substances found in the terrestrial system contain variable amounts of ^{238}U and ^{232}Th; they undergo radioactive decay until they become stable isotopes. The two main important radioactive series are given in **Tables 2** and **3**.

The bulk of natural radiation comes from the primordial radionuclides such as ^{238}U, ^{235}U and ^{235}Th. They decay into other radioactive isotope as a part of radioactive series. These series are naturally occurring radioactive series, which have existed since the earth was formed. The nuclei in each series decay by emitting α, β and γ particles until stable (lead). These radioisotopes are chemically bound to minerals in rocks and soils and pose no biological hazards except radon, thoron and its progeny. Radon and thoron are noble radioactive gases, the higher concentrations of these gases and progenies are inhaled to produce lung cancer. According WHO and UNSCEAR, radon and their progeny are the second leading lung cancer after tobacco smoking.

Parent nuclide	Half-life $T_{1/2}$	Decay mode (% branch)	Decay energy (MeV)	% Intensity	Daughter nuclide	γ-emission energy (keV)	% γ-emission intensity
^{238}U	4.5×10^9 years	α (100)	4.198	79.0	^{234}Th	49.55	0.063
			4.151	20.9		113.50	0.0102
^{234}Th	24.10 days	B (100)	0.199	70.3	^{234}Pa	63.28	4.1
			0.104	19.2		92.37	2.4
			0.103	7.6		92.79	2.39
^{234}Pa	1.17 m	β (99.84)	2.269	98.2	^{234}U	1001.03	0.837
			1.224	1.007		766.38	0.294
		IT (0.16)	*		^{234}Pa	73.92	*
^{234}Pa	6.70 h	β (100)	0.642	19.4	^{234}U	131.30	0.029
			0.472	33.0		946.00	0.021
^{234}U	2.5×10^5 years	α (100)	4.7746	71.38	^{230}Th	53.20	0.123
			4.7224	28.42		120.90	0.0342
^{230}Th	7.5×10^4 years	α (100)	4.6870	76.3	^{226}Ra	67.672	0.373
			4.6205	23.4		143.872	0.0483
^{226}Ra	1600 years	α (100)	4.7843	94.45	^{222}Rn	186.21	3.59
			4.601	5.55		262.27	0.0050
^{222}Rn	3.8235 days	α (100)	5.4894	99.92	^{218}Po	511.00	0.076
^{218}Po	3.10 m	α (99.98)	6.0024	100.0	^{214}Pb	**	
		β (0.02)	*		^{218}At		
^{218}At	1.60 s	α (100)	6.0024	100.0	^{214}Bi	*	
^{214}Pb	26.8 m	β (100)	0.671	48.9	^{214}Bi	351.93	35.1
			0.728	42.2		295.22	18.2
			1.023	6.3		241.99	7.12
^{214}Bi	19.9 m	β (99.98)	3.272	18.2	^{214}Po	609.31	44.6
			1.542	17.8		1764.50	15.1
			1.507	17.02		1120.29	14.7
		α (0.02)	5.452	53.9	^{210}Tl	1238.11	5.78
			5.516	39.2		2204.21	4.98
^{214}Po	164.30 μs	α (100)	7.6868	99.99	^{210}Pb	799.7	0.0104
^{210}Tl	1.30 m	β (100)	4.209	30.0	^{210}Pb	*	
			1.863	24.0			
^{210}Pb	22.3 years	β (100)	0.0166	0.0631	^{210}Bi	46.54	4.25
			0.0631	16.0			
^{210}Bi	5.013 days	β (100)	1.1615	100	^{210}Po	**	
^{210}Po	138.376 days	α (100)	5.3043	99.99	^{206}Pb	803.10	0.00122
^{206}Pb	Stable end product						

**No gamma rays observed.

Table 2. Decay series of uranium (^{238}U) [8].

3.1.1.1. Uranium decay series

The decay series of uranium and the type of radiation and range of energy of decay products are shown in **Table 2** [8]. The important daughter product of uranium series is radon and its progenies. Radon is a naturally occurring radioactive gas. This was discovered by F.E. Dorn in 1900. It is found everywhere as part of our environment (i.e., in soil, water, and air). The ubiquitous radioactive gas is formed by radioactive decay of radium (^{226}Ra), which is the daughter product of uranium decay series (**Table 2**). The half-life of radon is 3.82 days; it decays by emission of alpha particle to form radon decay products or progeny, which are divided into short-lived and long-lived progeny. These are the significant contributor of natural radiation [9]. On the basis of the epidemiological studies, it has been established that the enhanced levels of indoor radon in dwellings can cause health hazards and may lead to serious diseases like lung cancer in human beings [5, 10].

3.1.1.2. Thorium decay series

The decay series of thorium and types of radiation with range of energies of decay products are as shown in **Table 3** [11]. The important daughter products in this series are thoron and its progenies. The thoron progeny has relatively long half-life than that of radon progeny; therefore thoron progeny would give a significant dose to the lungs [11–13]. The decay of thorium ^{232}Th leads to the subsequent formation of thoron (^{220}Rn), its half-life 55 seconds. It is more abundant than ^{238}U, but the short half-life of ^{220}Rn allows only a fraction to escape into the atmosphere. The ^{222}Rn is the one of the most significant isotope and it contributes significant dose to publics as ionizing radiation.

3.1.1.3. Potassium

Potassium is the most common of the naturally occurring non-series, singly occurring primordial radionuclides. Natural potassium comprises three isotopes ^{39}K (93.3%), ^{40}K (0.012%), and ^{41}K (6.7%). Among the three naturally occurring potassium isotopes, only ^{40}K is radioactive with a half-life of 1.28×10^9 years and having a specific activity of 31.4 Bqg^{-1} for natural potassium. ^{40}K decays through β-decay to stable ^{40}Ca 89% of the time. The remaining 10.72% of ^{40}K undergoes decay by electron capture to stable ^{40}Ar. This latter decay branch also emits a characteristic gamma ray at 1.461 MeV. This line is very useful to identify and quantify ^{40}K by gamma spectrometry [14].

Potassium is present in the earth crust with varying amounts and also present in almost all plant and animal tissues. Most of the potassium occurs in earth crust as minerals such as feldspar, orthoclase, muscovite, and biotite micas. Human beings require potassium to sustain their biological processes. A person who weighs 70 kg has about 140 g of potassium in his body which has activity of 4 kBq, most of which is located in the muscle. The absorbed dose per year is about 0.2 mSv in the bone. ^{40}K can be taken into the body by drinking water, eating food, or breathing air. Upon ingestion, ^{40}K then moves quickly from the gastrointestinal track into the bloodstream. The ^{40}K quickly enters the bloodstream and distributed to all organs and

Parent nuclide	Half-life $T_{1/2}$	Decay mode (% branch)	Decay energy (MeV)	% Intensity	Daughter nuclide	γ-emission energy (keV)	% γ-emission intensity
^{232}Th	1.4×10^{10} years	α (100)	4.0123	78.2	^{228}Ra	63.81	0.263
			3.9472	21.7		140.88	0.021
^{228}Ra	5.75 years	β (100)	0.0392	40.0	^{228}Ac	13.52	1.6
			0.0128	30.0		16.24	0.72
			0.0257	20.0		12.75	0.30
^{228}Ac	6.15 h	β (100)	1.158	29.9	228Th	911.20	25.8
			1.731	11.66		968.97	15.8
			2.069	8.0		338.32	11.27
^{228}Th	1.9116 years	α (100)	5.4232	72.2	^{224}Ra	84.373	1.22
			5.3404	27.2		215.98	0.254
^{224}Ra	3.66 days	α (100)	5.6854	94.92	^{220}Rn	240.99	4.10
			5.4486	5.06		292.70	0.0062
^{220}Rn	55.6 s	α (100)	6.2881	99.87	^{216}Po	549.76	0.114
^{216}Po	0.145 s	α (100)	6.7783	100	^{212}Pb	804.9	0.0019
^{212}Pb	10.64 h	β (100)	0.335	82.5	^{212}Bi	238.63	43.3
			0.574	12.3		300.09	3.28
			0.159	5.17		115.18	0.592
^{212}Bi	60.55 m	β (64.06)	2.248	86.57	^{212}Po	727.33	6.58
			1.521	6.81		1620.50	1.49
			0.627	2.92		785.37	1.102
		α (35.94)	6.0508	69.19	^{208}Tl	39.86	1.06
			6.0899	27.12		288.20	0.337
			5.7675	1.78		452.98	0.363
^{212}Po	0.299 μs	α (100)	8.7849	100.0	^{208}Pb	**	
^{208}Tl	3.053 m	β (100)	1.796	48.7	^{208}Pb	2614.53	35.64
			1.286	24.5		583.19	30.4
			1.519	21.8		510.77	8.13
^{208}Pb	Stable end product						

**No gamma rays observed.

Table 3. Decay series of thorium (^{232}Th) [8].

tissues. Each year, this isotope delivers doses of about 18 millirem (mrem) to soft tissues of the body and 14 mrem to the bone. ^{40}K can present both external and internal health hazards [9].

3.1.2. Extraterrestrial radiations (cosmic radiations)

The extraterrestrial radiations or cosmic radiations are high energetic radiations or subatomic particles, mainly originated from the sun, stars, collapsed stars (such as neutron stars), quasars, and the hot galactic and intergalactic plasma. The earth and all living things on it are constantly bombarded by these radiations from space. The galactic cosmic radiation coming at the upper atmosphere is made up of about 98% baryons and 2% electrons [15]. Cosmic ray radiation consists of 85% protons, 14% alpha particles (helium ions), and about 1% nuclei of atomic number between 4 and 26. The cosmic ray particles incident on the earth's atmosphere are the mixture of charged particles such as electrons, protons, α-particle, and a just detectable amount of heavier nuclei. These radiations have extremely high energies that vary from 10^2 MeV to more than 10^{14} MeV [16]. The cosmic ray shower (typically beta and gamma radiation) is obtained due to interaction of cosmogenic charged particles with the earth's atmosphere and magnetic field. The dose from cosmic radiation varies in different parts of the world due to differences in elevation and to the effects of the earth's magnetic field. The cosmic radiations are much more intense in the upper troposphere. Cosmic radiation dose increases with altitude; at 2.5 km, it is about 0.55 $mSv.y^{-1}$, and during their flights, airline crews typically get an extra dose on the order of 2.2 $mSv.y^{-1}$. Therefore, the annual effective doses from cosmic ray radiation around the world are estimated to range between 0.26 and 2.00 $mSv.y^{-1}$ [17].

The cosmic radiation interacts with the atoms and molecules in the atmosphere (mainly nitrogen and oxygen), are the dominant mechanism of interaction resulting in a cascade of interactions, and produces a number of secondary radiation in the form of protons, neutrons, and charged/uncharged pions of various energies which intern produce a various radioisotopes such as ^{3}H, ^{7}Be, ^{14}C, ^{22}N, ^{32}P, ^{35}S, and ^{35}Cl through nuclear reactions known as cosmogonic radionuclides [18]. These cosmogonic nuclides eventually reach the earth's surface and can be incorporated into living organisms and also contribute to the natural radiation exposures. The equivalent annual effective dose from cosmogonic radionuclides is estimated to be 12 μSv for ^{14}C, 0.15 μSv for ^{22}Na, 0.01 μSv for ^{3}H, and 0.03 μSv for ^{7}Be, and the most significant of these is due to ^{14}C [15].

3.1.3. Internal sources of radiation

The radioactive material gets inside the body by eating, drinking, breathing, or injection (from certain medical procedures and radon/thoron and their progeny). The alpha and beta radiation emitted by these radioactive materials poses serious health threat if significant quantities are inhaled or injected.

3.2. Artificial or man-made radiation

In addition to natural background radiation, human beings are exposed to man-made radiation obtained from nuclear installations, nuclear explosions, nuclear fuel cycle, radioactive

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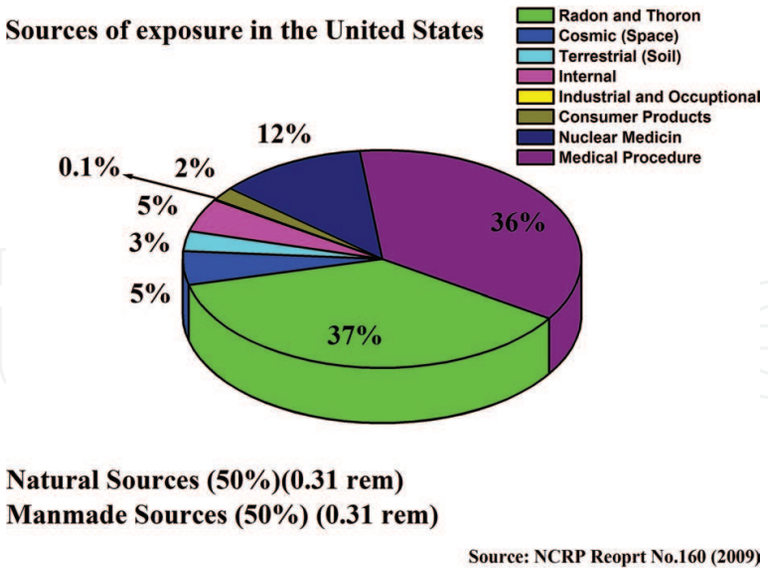

Figure 1. Sources of radiation exposure in the United States.

waste releases from nuclear reactor operations, and accidents and other industrial, medical, and agricultural uses of radioisotopes. The most significant sources of exposure, which gives the largest contribution to the public is from medical diagnostic X-rays, nuclear medicine, and nuclear therapy. This is also generated from consumer products such as combustible fluids (gas and coal), TV, luminous watches and dials, and electron tubes. The public are exposed to the radiation from the nuclear fuel cycle, which includes the entire sequence from mining and milling of uranium, the actual production of power at a nuclear power plant, and residual fall-out from nuclear weapon testing and accident. The public are not exposed to all the sources of radiation, for example, patients who are treated with the medical irradiation or the workers of nuclear industry may receive higher radiation exposure than the public [19]. The sources of radiation exposure in the United States were given in **Figure 1**.

4. Applications of radioisotope

The applications of radioisotopes have played a significant role in improving the quality of life of human beings. The whole world is aware of the benefits of the radiation, but the phobia of nuclear weapons on Hiroshima and Nagasaki (August 6 and 9, 1945) and the nuclear accidents occurred in Chernobyl in Russia (April 25–26, 1986) and Fukushima in Japan (March 2011) was so deep in the mind of the common man that we can still struggle to come out of it. Major problems arrived by workers in nuclear fields are due to lack of legalization, shortage of resources, and knowledge about nuclear society and safe guards. To minimize these problems the international organization such as International Atomic Energy Agency (IAEA) and International Commission on Radiation Protection (ICRP), identify requirements and provide the infrastructure that can support nuclear technology [20].

4.1. Radiotracer (radioisotopes)

Radiotracers are widely used in medicine, agriculture, industry, and fundamental research. Radiotracer is a radioactive isotope; it adds to nonradioactive element or compound to study the dynamical behavior of various physical, chemical, and biological changes of system to be traced by the radiation that it emits. The tracer principle was introduced by George de Hevesy in 1940 for which he was awarded the Nobel prize.

4.1.1. Radioisotope production

The sustainability of radioisotope production is one of the critical areas that receive great attention. There are more than 160 different radioisotopes that are used regularly in different fields; these isotopes are produced either in a medium or in high-flux research reactors or particle accelerators (low or medium energy) [21]. Some of the radioisotopes produced by the reactor and particle accelerators and their applications are given in **Table 4**.

Reactor radioisotope	Half-life	Applications
Radioisotopes produced by reactors		
Bismuth-213	45.59 min	It is an alpha emitter (8.4 MeV). Used for cancer treatment, e.g., in the targeted alpha therapy (TAT)
Cesium-131	9.7 days	It emits photon radiation in the X-ray range (29.5–33.5 keV). Used in brachytherapy of malignant tumors
Cesium-137	30 years	Used in medical devices (sterilization) and gauges (661.64 keV)
Chromium-51	28 days	Used in Diagnosis of gastrointestinal bleeding and to label platelets (320 keV)
Cobalt-60	5.27 years	Used for controlling the cancerous growth of cells (1173.2 keV)
Dysprosium-165	2 h	Used for synovectomy treatment of arthritis (95 keV)
Erbium-169	9.4 days	Used for relieving arthritis pain in synovial joints (8 keV)
Holmium-166	26 h	Diagnosis and treatment of liver tumors (81 keV)
Iodine-125	60 days	Used in cancer brachytherapy and radioimmunoassay (35 keV)
Iodine-131	8 days	Widely used in treating thyroid cancer and in imaging the thyroid, diagnosis, and renal blood flows (284 keV)
Iridium-192	74 days	Used as an internal radiotherapy source for cancer treatment. Strong beta emitter for high-dose rate brachytherapy (317 keV)
Iron-59	46 days	Used in studies of iron metabolism in the spleen (1095 keV)
Lead-212	10.6 h	Used in TAT for cancers (239 keV)
Molybdenum-99	66 h	Used as the parent in a generator to produce technetium-99 m (740 keV)
Palladium-103	17 days	Used to make brachytherapy permanent implant seeds for early-stage prostate cancer. Emits soft X-rays (362 keV)
Potassium-42	12.36 h	Used for potassium distribution in bodily fluids and to locate brain tumors (1524 keV)
Radium-223	11.4 days	Used to treat prostate cancers that have spread to the bones

Reactor radioisotope	Half-life	Applications
Rhenium-186	3.71 days	Used for therapeutic purpose to relief pain in bone cancer. Beta emitter with weak gamma for imaging (137 keV)
Samarium-153	47 h	Effective in relieving the pain of secondary cancers lodged in the bone, sold as Quadra met. Beta emitter (103 keV)
Selenium-75	120 days	Used to study the production of digestive enzymes (265 keV)
Sodium-24	15 h	Used for studies of electrolytes within the body (2754 keV)
Ytterbium-169	32 days	Used for cerebrospinal fluid studies in the brain (63 keV)
Radioisotopes produced by accelerators		
Cobalt-57	272 days	Used as a marker to estimate organ size and for in vitro diagnostic kits (122 keV)
Copper-64	13 h	Used for PET imaging studies of tumors and also cancer therapy (511 keV)
Copper-67	2.6 days	Beta emitter, used in therapy
Fluorine-18	110 min	Used as fluorothymidine (FLT)
Gallium-67	78 h	Used for tumor imaging and locating inflammatory lesions (infections)
Indium-111	2.8 days	Brain studies, infection, and colon transit studies
Iodine-123	13 h	Used for diagnosis of thyroid function
Rubidium-82	1.26 min	Convenient PET agent in myocardial perfusion imaging
Strontium-82	25 days	Used as the parent in a generator to produce Rb-82
Thallium-201	73 h	Used for location of low-grade lymphomas

Table 4. Some of the radioisotopes produced by the reactor and particle accelerators and their applications.

4.2. Medicine

Nowadays radiotracer has become an indispensable and sophisticated diagnostic tool in medicine and radiotherapy purposes.

4.2.1. Diagnostic purpose

The most common radioactivity isotope used in radioactive tracer is technetium (^{99}Tc). Tumors in the brain are located by injecting intravenously ^{99}Tc and then scanning the head with suitable scanners.

^{131}I and most recently ^{132}I and ^{123}I are used to study malfunctioning thyroid glands. Kidney function is also studied using compound containing ^{131}I. ^{33}P is used in DNA sequencing. Tritium (^{3}H) is frequently used as a tracer in biochemical studies. ^{14}C has been used extensively to trace the progress of organic molecule through metabolic pathways.

A most recent development is positron emission tomography (PET), which is a more precise and accurate technique for locating tumors in the body. A positron emitting radionuclide (e.g., ^{13}N, ^{15}O, ^{18}F, etc.) is injected to the patient, and it accumulates in the target tissue. As it

emits positron which promptly combines with nearby electrons, it results in the simultaneous emission of two γ-rays in opposite directions. These γ-rays are detected by a PET camera and give precise indication of their origin, that is, depth also. This technique is also used in cardiac and brain imaging.

Compound X-ray tomography or CT scans. The radioactive tracer produces gamma rays or single photons that a gamma camera detects. Emissions come from different angles, and a computer uses them to produce an image. CT scan targets specific area of the body, like the neck or chest, or a specific organ, like the thyroid [22].

4.2.2. Therapeutic

The most common therapeutic use of radioisotopes is ^{60}Co, used in treatment of cancer. Sometimes wires or sealed needles containing radioactive isotope such as ^{192}Ir or ^{125}I are directly placed into the cancerous tissue. The radiations from the radioisotopes attack the tumor as long as needle/wire is in place. When the treatment is complete, these are removed. This technique is frequently used to treat mouth, breast, lung, and uterine cancer. ^{131}I is used to treat thyroid for cancers and other abnormal conditions of thyroid. ^{32}P is used to treat excess of red blood cells produced in the bone marrow.

4.3. Agricultural research

Development of high yielding varieties of plants, oil seeds, and other economically important crops and protection of plant against the insects are the thrust area of agricultural research.

4.3.1. New varieties of crops

The irradiated seeds of wheat, rice, maize, cotton, etc., are undergoing profound genetic changes in order to improve crop varieties and mutation breeding. These varieties of crops are more disease resistant and have high yields. Several countries all over the world produce new variety of crops from radiation-induced mutants [23].

4.3.2. Eradication of insect and pests

The best technique for the control of insects and pests is sterile insect technique (SIT). Irradiation is used to sterilize mass-reared insects so that, while they remain sexually competitive, they cannot produce offspring. As a result, it enhances the crop production and preservation of natural resources.

4.4. Food preservation and sterilization

As per WHO reports, about 25–35% of world food production is susceptible to the attack by pests, insects, bacteria, and fungi causing a great loss of the economy of the country. Food irradiation has more advantages than conventional methods. All types of radiations are not recommended for food irradiation; only three types of radiation are recommended by CODEX general standard for food irradiation which are ^{60}Co or ^{137}Cs, X-rays, or electron beams from particle accelerators [24]. The food products are exposed to γ-radiations from the intense

controlled sources to kills pests, bacteria, insects, and parasites and extends shelf-life but also reduces the food's nutritional value somewhat by destroying vitamins A, B_1 (thiamin), C, and E. No radiation remains in the food after treatment.

Depending on the radiation dose and its application, radiations are classified into three categories: they are low dose (<1 kGy), medium dose (1–10 kGy), and high dose (>10 kGy) [24].

4.4.1. Low-dose applications

4.4.1.1. Sprout inhibition in bulbs and tubers

Irradiated potato can be stored at higher temperature of around 15°C. This not only conserves energy but also prevents sweetening of potato, commonly occurring at low temperatures. It gives advantage to the manufacturers of chips as low-sugar potato gives desired lighter color to fries and chips.

4.4.1.2. Delayed ripening of fruits

Irradiated fruits (all kinds of mangoes) of these at hard mature pre-climacteric stage at 0.25–0.75 kGy delay the ripening process by about 7 days, thus improving shelf-life. These doses are also effective in destroying quarantine pests. Irradiated fresh fruits can be stored for longer duration, sometimes up to 30 days at 12–14°C and in modified atmospheres.

4.4.2. Medium-dose applications

Under ice, sea food such as fish and prawns, fish-like Bombay duck, pomfret, Indian salmon, mackerel, and shrimp can be stored for about 7–10 days. Studies have demonstrated that irradiation at 1–3 kGy followed by storage at melting ice temperatures increases its shelf-life nearly threefold.

Meat and meat products including poultry have a shelf-life of about a week at 0–3°C, which could be extended up to 4 weeks by applying a dose of 2–5 kGy, which inactivates spoilage bacteria. Radiation treatment has been employed to enhance the shelf-life of intermediate moisture meat products.

4.4.3. High-dose applications

While transporting the spices, due to inadequate handling and processing conditions, spices get contaminated with insect eggs and microbial pathogens. When incorporated into semi-processed or processed foods, particularly, after cooking, the microbes, both spoilers and pathogens, in spices can outgrow causing spoilage and posing risk to consumers. Many of the spices develop insect infestation during storage, and unscrupulous traders convert them into spice powders. A dose of 10 kGy brings about near sterility or commercial sterility while retaining the natural characteristics of spices.

Irradiation at higher doses can also be employed for total sterilization of diets for immuno-compromised patients, adventure sports, military, and astronauts.

4.5. Industry and civil engineering

Radioisotopes are commonly used in industry for checking blocked water pipes and detecting leakage in oil pipes. For example, small quantity of radioactive ^{24}Na is placed in a small enclosed ball and is allowed to move in pipe with water. The moving ball containing radioisotope is monitored with a detector. If the movement of ball stops, it indicates the blocked pipe. Similarly, radioisotope ^{24}Na is mixed with oil flowing in an underground pipe. With radiation detector, the radioactivity over the pipe is monitored. If there is a leakage place, the radiation detector will show large activity at that particular place. Radioisotopes are also used to monitor fluid flow and filtration, detect leaks, and gauge engine wear and corrosion of process in equipment.

Radioactive materials are used to inspect metal parts and the integrity of welds across a range of industries. The titanium capsule is a radioactive isotope which is placed on one side of the object being screened, and some photographic film is placed on the other side. The gamma rays pass through the object and create an image on the film. Gamma rays show flaws in metal castings or welded joints. The technique allows critical components to be inspected for internal defects without damage. Radiotracer is also used to inspect for internal defect without damage.

In industries, the production methods need to be constantly monitored in order to check the quality of products and to control the production process. The monitoring is carried out by quality control devices using the unique properties of radiation; such devices are called nuclear gauges. They are more useful in extreme temperature, harmful chemical process, molten glass, and metals. The gauges are also used to measure the thickness of sheet materials, including metals, textiles, paper, and plastic production.

5. Effects of exposure to radioisotope

Radiation passing through the material breaks the bonds by removing the electron of an atom or molecules; this induces physical, chemical, and biological changes. Ionizing radiation focuses large amount of energy into a highly localized areas of irradiated materials. Damage is caused by the interaction of this energy with nuclei or orbiting electrons. The material structure may be modified through this energy interaction; as a result the mechanical property of bulk material changes.

5.1. Radiation effects on metals

Radiation creates a point defect in metals; this had been recognized by Wigner in 1946. The radiation effects on metals depend on type and duration of the radiation. Ionizing radiation can affect the metal in two ways, (1) lattice atoms are removed from their regular lattice sites, that is, displacement damage production and (2) chemical composition of the target can be changed by ion implantation or transmutation.

Neutron-irradiated metals at room temperature show increase in electrical and thermal resistance, hardness, and tensile strength and higher yield strength along with decrease ductility in metals [25]. At higher temperature it is found that the strength and ductility return to the same values as before irradiation. A metal under stress at higher temperature exhibits the phenomenon

of creep, that is, the gradual increase in strain with time. The thermal neutrons have less significant effect on the mechanical properties of metals. They can be captured by nuclei of irradiated material which will become radioactive.

5.2. The radiation effects on nonmetals

Radiation causes the viscosity of oil and grease to increase as gummy, tar-like polymers are formed. Radiation causes soap-oil-type greases to become more fluid. Plastics undergo drastic changes when exposed to radiation. The rubber may become harder or softer depending on its types. Concrete under radiation exposure heats up. This drives the water out of its internal structure. Swelling, cracking, and spalling result [25].

5.2.1. Radiation effects on polymers

Ionizing radiation can alter the molecular structure and macroscopic properties of the polymer. The polymers are exposed to the radiation; as a result excitation and ionization of target/molecules are produced. These processes in the target molecules lead to breaking of original bonds, production of ionized and excited species, bond rearrangement, chain scission, radical formation, etc. All these processes are responsible for the modification of chemical, electrical, mechanical, and optical properties of polymers leading to their applications in different scientific and technological fields [25].

5.2.2. Cross-linking

During radiation polymerization, the interaction takes place between two free radical monomers which combine to form intermolecular bond leading to three-dimensional network of cross-linked high molecular polymer. These cross-linked polymers show high thermal resistance and strong mechanical strength [26].

5.2.3. Radiation grafting

Grafting is a method wherein monomers are covalently bonded (modified) onto the polymer chain. Irradiation on polymers by γ-radiation is useful for the functionalization of surfaces with stimuli–response polymers. This method involves the formation of free radical sites near the surface of polymers on to the polymeric backbone as a result of irradiation. Hence microenvironment suitable for the reaction among monomer or polymer and the active site is formed, leading to propagation to form side chain grafts. Radiation grafting changes the surface of polymeric materials by chemically bonding polar or nonpolar monomers having functional groups such as –COOH, -OR, $-NH_2$, $-SO_3H$, –R, and their derivatives, to affect surface properties. The radiation-induced grafting is used in variety of applications such as biomedical, environmental, and industrial uses [26–28]. The radiation grafting can be performed by two major methods: pre-irradiation technique and mutual or simultaneous method [29].

5.2.4. Degradation

Radiation-induced degradation technology is a new application to develop viscose, pulp, paper, food preservation, pharmaceutical production, and natural bioactive agent industries. Controlling

the degree of degradation of polymers in industries is very important. Irradiation of polymers induces molecular chain branching, cross-linking, and molecular degradation or scissioning. Chain branching increases the molecular weight of the polymer. Cross-linking forms the insoluble three-dimensional polymer network, while degradation or scissioning causes a reduction of initial molecular weight [30, 31]. The polymer irradiated in air by solar radiation results in the formation of free radicals and can also react with oxygen, giving rise to oxidative degradation. All these molecular modifications can modify the properties of polymers. The study of degradation of polymer is important in using polymeric materials in radioactive environments such as in nuclear power plants, space, or the sterilization of polymeric medical disposals or food plastic packaging [32]. The splitting of polymeric macromolecules to form free radicals is employed for synthesizing modified polymers. At the same time, polymer degradation may often be considered as an undesirable side reaction occurring during the chemical transformation, fabrication, and usage of polymers.

5.3. Biological effects of radiations

The harmful effects that are produced in human beings who are exposed to radiations are called health effects. The result of all the physical interaction processes between incident radiation and the tissue of a cell is a trail of ionized atoms and molecules. The radiation is directly interacting with sensitive critical sites of the tissue (DNA) to produce damage by breaking chemical bonds. The chemically active free radicals are indirectly produced by interaction of primary radiation with DNA of the tissue. Both direct and indirect damages produced in DNA by radiation are shown in **Figure 2**.

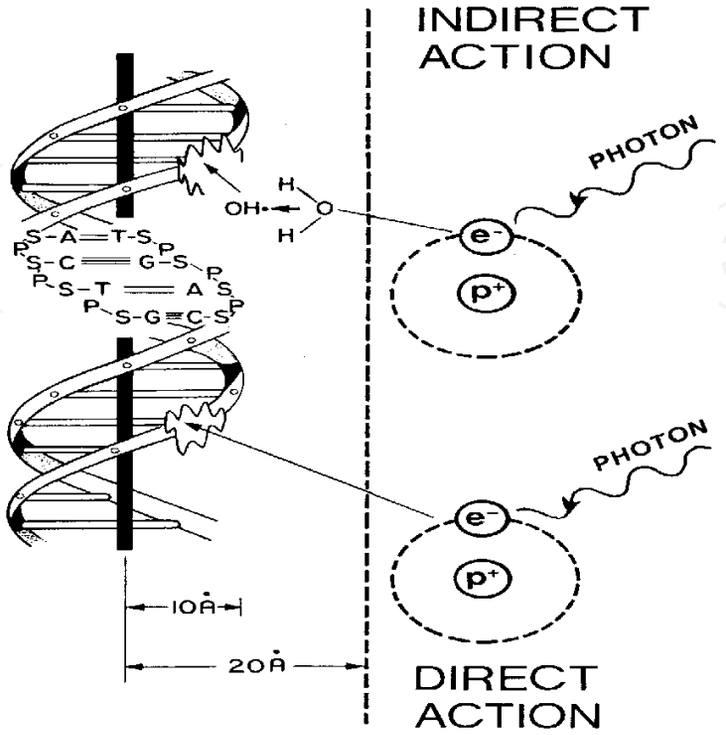

Figure 2. The mechanism by which damage occurs in the cell by direct and indirect action of radiation.

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5.3.1. Direct action

Radiation attacks DNA molecule directly (**Figure 2**); as a result the ionization is produced and the bond is disrupted within a few nanometers of the DNA molecule.

5.3.2. Indirect action

Indirect action is due to the chemical radicals which are produced by radiation that interact with water molecule; it comprises about 80% of tissue. Free radicals are important since they can diffuse far enough to reach and induce chemical changes at critical sites in biological structures. The chemical damage produced by the breaking of DNA by the action of free radicals. The formation and action are as follows:

Ionization of a water molecule produces a free electron and a positively charged molecule:

$$H_2O + Radiation \rightarrow H_2O^+ + e^- \tag{4}$$

The released electron is most likely to be captured by another water molecule converting it into a negative ion:

$$H_2O + e^- \rightarrow H_2O^- \tag{5}$$

Both these ions are unstable and dissociate which are as follows:

$$H_2O^+ \rightarrow H^+ + OH^0 \tag{6}$$

$$H_2O \rightarrow H^0 + OH^- \tag{7}$$

Formation of free radicals is denoted by OH^0 and H^0. These free radicals interact with organic biomolecules (RH) again to produce organic free radicals denoted by R^0:

$$RH + OH^0 \rightarrow R^0 + H_2O \tag{8}$$

$$RH + H^0 \rightarrow R^0 + H_2 \tag{9}$$

These free radicals interact with DNA to produce the damage. DNA is made up of double-helix structure; if the radiation/free radical breaks only one strands, it is easily repaired by opposite strand as a template. If double strand breaks the repair of the cell is not possible; as a result mutations or changes in DNA code this leads to a cell death or cancer. To a certain extent, these molecules are repaired by natural biological processes, and this ability to self-heal or self-repair depends on the extent of damage. The biological effect of radiation on living cell may result in three outcomes:

1. Death of the cells
2. Impairment in the natural functioning of cell leading to somatic effects such as cancer
3. A permanent alteration of the cell which is transmitted to later generation, that is, genetic effect.

Oxygen effect is another effect produced by organic free radicals. The amplification of the Chemical action of free radicals due to the presence of oxygen in tissue is called oxygen effect.

It has consequences that irradiated cell have a lower chance of survival in tissue rich in oxygen than in tissue less rich in oxygen.

Biological effects of radiation are broadly classified into deterministic effect and stochastic effects.

5.3.3. Deterministic effect

These effects of damage from the radiation can be long term or short term. The large amount of radiation which is exposed to short interval of time is called acute radiation effects. Small amount of radiation dose exposed to longer period is called delayed effect or chronic effect. Deterministic effects are severe, if dose exceeds a threshold level (500 mSv). The severity of these effects in an exposed individual increases with the dose above the threshold as shown in **Figure 3(b)**. The acute effect above the threshold at different time intervals is given **Table 5**.

5.3.4. Stochastic effect

These effects are associated with long-term low-level exposure. They have no apparent threshold. The risk from the exposure increases with increasing the dose, but the severity of the effect is independent of the dose as shown in **Figure 3(a)**. In stochastic effect (**Figure 3(a)**) the effect rate increases with increase in the dose rate. But in deterministic effect (**Figure 3(b)**), there is apparent threshold, thereafter the effect rate increases rapidly with increase in the dose.

With the chronic exposure, there is a delay between the exposure and observed health effects. These effects include cancer and other health outcomes such as benign tumor, cataracts, and potentially harmful genetic effects. Cancer and genetic effects are recognized as stochastic effects.

5.3.5. Genetic effect

These effects are not immediate. They are produced in the future generation. The experimental evidences from animal studies show that the radiation can cause genetic effects, but the studies of the survivors of Hiroshima and Nagasaki gives no indication of these effects on human beings [33].

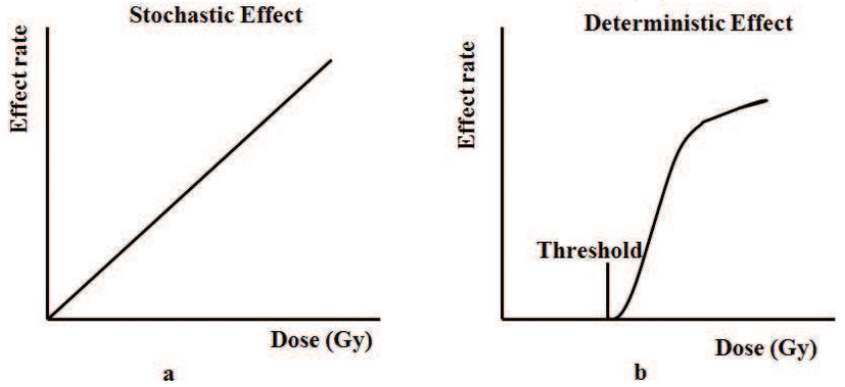

Figure 3. Deterministic effect and stochastic effects of radiation.

Effective dose	Time of exposure	Effects
<1 Sv	Weeks	Decrease white blood cell levels
	Short period	Recovery
Around 2 Sv	1 h	Nausea, headache, or vomiting
	Within a week	50% of lymphocyte decreases and 50% thrombocyte level decreases
	3–4 weeks	Quick recovery is possible
3 Sv	Hours to days	Radiation sickness: nausea, vomiting, fatigue, loss of appetite, infections, infections, dehydration, and hair loss
	After few days	Patient may feel better
	Within a week or months	Good recovery
4 Sv	Few weeks	Damage to the mucous membrane of the intestines and bone marrow tissue
5–6 Sv	—	A strong possibility of death
>6 Sv	—	The chance of surviving longer than a few weeks is slim
>10 Sv	Within 2 weeks	The mucous membrane of the intestines will be damaged beyond repair causing death
50 Sv	Within hours	The central nervous system will be damaged, loss of consciousness
	Within a day	Death

Table 5. Deterministic effect with different doses [37].

There is a considerable uncertainty about the low dose is beneficial or harmful. In the published literature, data and reports regarding health effects of low doses are two classes of thoughts. The first thought favors in linear no-threshold (LNT) hypothesis adopted by major scientific, official, and governmental organizations such as ICRP, NCRP, NAS-NRC, WHO, and UNSCEAR for risk assessment and states that the low radiation is harmful. The other school of thought believes in the beneficial features (hormesis hypothesis) of such a low-level exposure. According to this hypothesis, very low dose of radiation is beneficial, that is, to stimulate repair mechanism and induce activity of DNA region (UNSCEAR 94, NRPP 95) [27]. Over 3000 research papers show that low-dose irradiation is stimulatory and beneficial in a wide variety of microbes, plants, invertebrates, and vertebrates [34, 35]; this was excepted by France, Japan, and China. The epidemiological studies of irradiated population exhibit reduced risk of cancer from low dose of radiation [36].

Radiation is not only the cause of cancer. Cancer is always a cancer. Lung cancer caused by smoking tobacco is medically identical to lung cancer caused by inhalation of radioactive gas. If a patient suffers from cancer, there is no absolute certainty that the reason was radiation. Even if a cancer patient has received a lifetime dose of 500 mSv which is many times higher than the annual dose limit for professional radiation workers, then it is ten times more likely that his or her cancer was caused by another reason than radiation.

6. Quantities and units used in radiation protection

The physical quantity and radiation protection quantities are used in radiation protection. For the estimation of the effects of radiation and for their control, it is necessary to define

a suitable unit for the measurement of radiation dose. Exposure to radiation or radioactive materials results in the irradiation of people. The exposure may be external from the sources outside the body or internal from the sources inside the body. The energy absorbed from ionizing radiation per unit mass of the materials at the point of interest is called "radiation dose."

6.1. Absorbed dose (D)

The amount of energy is deposited in the medium per unit mass. The unit of absorbed dose is gray. The activity is defined as rate of disintegration per second.

In addition to the physical quantity, other units related to the quantities have been introduced to account for biological effects of radiation upon the tissue. The quantities are organ dose, equivalent dose, effective dose, committed dose, and collective dose.

6.2. Organ dose

The mean dose D_T in specified tissue or organ T of the human body is given by

$$D_T = \frac{E_T}{m_T} \tag{10}$$

where E_T is the total energy deposited by radiation to the organ and m_T is the mass of the organ.

6.3. Equivalent dose (H_T)

The ionizing power of different radiations are different; their biological effects on living cells are also different. Biological damage caused by the radiation is a strong function of the specific radiation and its energy. For the same dose to organ, α and neutron will cause more effect compared to γ and β radiation. The difference lies in the linear energy transfer of different particles. To account of this effect, each radiation type is assigned a radiation weighting factor (W_R) or relative biological effectiveness (RBE). The equivalent dose is the product of radiation weighting factor and absorbed dose. The unit equivalent dose is Sievert (Sv):

Equivalent dose (H_T) = average absorbed dose × radiation waiting factor.

$$H_T = \sum W_R D_{T,R} \tag{11}$$

The radiation weighting factor for X-rays and γ and β particle is 1 and for α is 20 and neutron is 5–20.

6.4. Effective dose (E)

The relation between the probabilities of developing the biological effect depends on specific organ or tissue receiving radiation. To accounts for this, a tissue weighting factor W_T, defined for different organs of the body. It is independent on type of radiation and energy. The unit of effective dose is also Sievert. The tissue weighting factors for some organs are given in **Table 6**.

Sl. no.	Tissue or organ	Tissue weighting factor W_T
1	Gonads	0.20
2	Bone marrow	0.12
3	Colon	0.12
4	Lung	0.12
5	Stomach	0.12
6	Bladder	0.05
7	Breast	0.05
8	Liver	0.05
9	Esophagus	0.05
10	Thyroid	0.05
11	Skin	0.01
12	Bone surface	0.01
13	Remainder	0.05
14	Whole body	1

Table 6. Tissue weighting factors [ICRP 1990 recommendations].

$$E = \sum_T W_T H_T \tag{12}$$

6.5. Committed dose

The radionuclide delivers the dose to the tissue or organ in the body which remains in the body called committed dose. The unit is Sievert (Sv).

6.6. Collective dose

This refers to the group of people, who are exposed to radiation from the source and the period of exposure. It is calculated by the product of number of people exposed with average dose from the source. The unit is ManSv.

7. Categories of exposure

ICRP considers three types of exposure [38]:

1. Occupational exposure, which is the exposure incurred at work and principally as a result of work. Exposure to natural sources in the workplace would not normally come under occupational exposure. Exceptions are exposures to high levels of radon in specific workplaces such

as uranium mines, space as identified by the regulatory agency, and exposure of the crew of jet aircraft and space flights to higher levels of radiation from cosmic rays and solar flares.

2. Medical exposure, which refers to exposures incurred by (a) individuals as part of their own diagnosis or treatment, (b) exposures incurred knowingly and willingly by individuals helping in support of such patients, and (c) exposures incurred by volunteers as part of a program of biomedical research.
3. Public exposure, which comprises all other exposures. (The component of public exposure due to natural sources is by far the largest of the total.)

In practices and in intervention, it will often be virtually certain that exposures will occur and their magnitude will be predictable, albeit with some degree of error. However, in "potential exposures," there will be potential for exposure but no certainty that it will occur.

8. Radiation protection, safety, and dose limits

Radiation protection and safety standard sources for occupational and public radiation exposure are established by Basic Safety Standards (BSS) and ICRP recommendations. The system is based on the following general principles:

1. Justification: The practices or a source of radiation exposure is to provide the benefit for the exposed individuals or to the society; otherwise it cannot be considered.
2. Optimization: In relation to any particular source within a practice, the magnitude of individual's doses, the number of people exposed, and the likelihood of incurring potential exposures should be minimum, and dose is as low as reasonably achievable (ALARA). The economic and social factors are being taken into account with the restriction that the doses to the individuals delivered by the source be subject to dose constraints.
3. Dose limitation: The exposure of individuals resulting from the normal and all the relevant practices should be subject to dose limits. In any normal circumstances, the individuals

	Occupational exposure	**Exposure to apprentices 16–18 years of age**	**Public exposure**
Effective dose (whole dose) (mSv)	20, averaged over 5 consecutive years 50 in a single year[a]	6	1, averaged over 5 consecutive years in a single year[b]
Equivalent dose (eye lens) (mSv)	150	50	15
Equivalent dose (hands, feet, skin) (mSv)	500	150	50

[a]Provided that the average effective dose over 5 consecutive years does not exceed 2 mSv/a.

[b]Provided that the average effective dose over 5 consecutive years does not exceed 1 mSv/a.

Table 7. Annual dose limits according to BSS schedule II and ICRP report 60.

should not be exposed to more than the specified dose limits. Not all sources are susceptible to control by action at the source, and it is necessary to specify the sources to be included as relevant before selecting a dose limit.

According to Basic Safety Standards, the dose limit is defined as the value of effective dose or equivalent dose to individuals from controlled practices that shall not be exceeded [39]. The latest recommended limits were specified in the ICRP (60), 1990, and is given in **Table 7**.

9. Control of occupational and public exposure

According the International Labor Office (ILO), the occupational exposure refers to the exposure of a worker that is received or committed during the period of work [40]. Radiation protection of workers is essential for the same and acceptable use of radiation, radioactive materials, and nuclear energy. The IAEA and ICRP frame a norm and regulations to protect the workers. The dose limits for occupational and public exposure are given in **Table 7**.

In medical professionals, to minimize the radiation exposure, one can follow as low as reasonably achievable (ALARA) and personnel shielding options (e.g., two-piece wraparound aprons, thyroid shields, and eye protection) which should be used to effectively attenuate scattered X-ray levels. For medical exposure of patients, dose limit is not appropriate to apply. Therefore medical radiation does not have dose limits and generally used diagnostic reference level (DRL) as a reference value.

To decrease radiation exposure risks, any medical radiation exposure must be justified, and the examinations which use ionizing radiation must be optimized. Justification means that the examination must be medically indicated and useful. Optimization means that the imaging should be performed using doses that are as low as reasonably achievable (ALARA), consistent with the diagnostic task.

The control of public exposure is normally exercised by the application of controls at the source rather than in the environment. According to ICRP recommendations, the dose limits should not exceed 1 $mSvy^{-1}$ (excluding normal background radiation). However, in special circumstances, a higher value can be allowed in a single year, provided that the average over 5 years does not exceed 1 $mSvy^{-1}$.

For controlling the occupational exposure, the following three parameters are considered:

1. Distance: The distance between the source and exposing worker should be large to reduce the amount of radiation received by the workers.
2. Time: The radiation dose is directly proportional to the time spent in the radiation. Therefore the time of exposure should be as small as possible.
3. Shielding: Depending upon the type of radiation, different materials are used for shielding. For gamma radiation high-atomic-numbered elements are used, because the rate of

energy loss is directly proportional to Z^5. For neutron, high absorption cross section and low-atomic-numbered elements are used for shielding; hydrogen and hydrogen-based materials are well suited for neutron shielding. The plastic can be used to form an efficient barrier for dealing with high-energy beta radiation.

10. Conclusions

Radiation is present everywhere, and it is a permanent feature of the environment; thus the risk associated with the radiation can only be restricted and not eliminated entirely. Applications of radioisotopes are growing in industry, agriculture, medicine, and many other fields of industry and research, benefiting humanity. Irradiation is used around the world to preserve food staffs and reduce wastage, and sterilization techniques have been used to eradicate disease-carrying insects and pests. The activities involving radiation exposure are subject to certain standards of safety in order to protect the individuals exposed to radiation, be it occupationally, for medical diagnostic or therapeutic purposes or as the member of the public. Higher radiation dose produces harmful effects; the severity of effect increases with increasing the dose. There is a considerable uncertainty whether the low-dose radiation (LDR) is beneficial or harmful; some scientific groups favor the low dose is harmful, and other scientific groups argued that low dose is beneficial to mankind. At the present low-dose radiation is the thrust area for research.

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Conflict of interest

There is no conflict of interest.

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