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# Radiations- Types and Significance

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**ABSTRACT:** There are four major types of radiation: alpha, beta, neutrons, and electromagnetic waves such as gamma rays. They differ in mass, energy and how deeply they penetrate people and objects.

The first is an alpha particle. These particles consist of two protons and two neutrons and are the heaviest type of radiation particle. Many of the naturally occurring radioactive materials in the earth, like uranium and thorium, emit alpha particles. An example most people are familiar with is the radon in our homes.

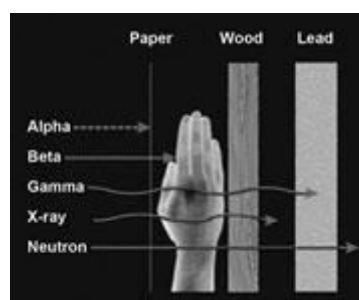
The second kind of radiation is a beta particle. It's an electron that is not attached to an atom. It has a small mass and a negative charge. Tritium, which is produced by cosmic radiation in the atmosphere and exists all around us, emits beta radiation. Carbon-14, used in carbon-dating of fossils and other artifacts, also emits beta particles. Carbon-dating simply makes use of the fact that carbon-14 is radioactive. If you measure the beta particles, it tells you how much carbon-14 is left in the fossil, which allows you to calculate how long ago the organism was alive.

The third is a neutron. This is a particle that doesn't have any charge and is present in the nucleus of an atom. Neutrons are commonly seen when uranium atoms split, or fission, in a nuclear reactor. If it wasn't for the neutrons, you wouldn't be able to sustain the nuclear reaction used to generate power.

**KEYWORDS-**alpha, beta, neutrons, gamma, electromagnetic, reactor

## I.INTRODUCTION

The last kind of radiation is electromagnetic radiation, like X-rays and gamma rays. They are probably the most familiar type of radiation because they are used widely in medical treatments. These rays are like sunlight, except they have more energy. Unlike the other kinds of radiation, there is no mass or charge. The amount of energy can range from very low, like in dental x-rays, to the very high levels seen in irradiators used to sterilize medical equipment.



As mentioned, these different kinds of radiation travel different distances and have different abilities to penetrate, depending on their mass and their energy.

Neutrons, because they don't have any charge, don't interact with materials very well and will go a very long way. The only way to stop them is with large quantities of water or other materials made of very light atoms.

On the other hand, an alpha particle, because it's very heavy and has a very large charge, doesn't go very far at all. This means an alpha particle can't even get through a sheet of paper. An alpha particle outside your body won't even penetrate the surface of your skin. But, if you inhale or ingest material that emits alpha particles, sensitive tissue like the lungs can be exposed. This is why high levels of radon are considered a problem in your home. The ability to stop alpha particles so easily is useful in smoke detectors, because a little smoke in the chamber is enough to stop the alpha particle and trigger the alarm.[1,2,3]

Beta particles go a little farther than alpha particles. You could use a relatively small amount of shielding to stop them. They can get into your body but can't go all the way through. To be useful in medical imaging, beta particles must be released by a material that is injected into the body. They can also be very useful in cancer therapy if you can put the radioactive material in a tumor.

Gamma rays and x-rays can penetrate through the body. This is why they are useful in medicine—to show whether bones are broken or where there is tooth decay, or to locate a tumor. Shielding with dense materials like concrete and lead is used to avoid exposing sensitive internal organs or the people who may be working with this type of radiation. For example, the technician who does my dental x-rays puts a lead apron over me before taking the picture. That apron stops the x-rays from getting to the rest of my body. The technician stands behind the wall, which usually has some lead in it, to protect him or herself.

Radiation is all around us (called background radiation), but that is not a reason to be afraid. Different types of radiation behave differently, and some forms can be very useful.

## II.DISCUSSION

Radiation is the process by which energy is emitted as either particles or waves. Broadly, it can take the form of sound, heat, or light. However, most people generally use it to refer to radiation from electromagnetic waves, ranging from radio waves, though the visible light spectrum, and up through to gamma waves.

Most of the discussion about radiation, how it works, and what its effects are boil down to the interaction of radiation with atoms (and molecules) that it comes into contact with. Atoms form the basic building blocks of all matter. They consist of a nucleus, made of positively-charged protons (and sometimes neutrally-charged neutrons), and an outer cloud of electrons, which have a negative charge. The positive charge of a single proton is equal to the negative charge of a single electron.[4,5,6]

Protons and neutrons have a relatively large size and atomic weight, whereas electrons are extremely small and light by comparison. Due to the nature of opposite charges attracting, atoms tend to have an equal number of protons and electrons, leaving the atom as a whole having a net charge of zero. However, if the atom either loses or gains an electron, it becomes an ion, and carries a charge.

It will seek bonds with other charged particles in order to regain a neutral balance, potentially leading to new molecules being formed.

### Ionizing Vs Non-Ionizing Radiation

Radiation is generally classified ionizing or non-ionizing, based on whether it has enough energy to knock electrons off atoms that it interacts with, as well as being able to do lower-energy damage such as breaking chemical bonds in molecules. Ionizing radiation, which is caused by unstable atoms giving off energy to reach a more stable state, is more of a health threat to humans because it involves changing the basic makeup of atoms in cells, and more specifically the DNA molecules inside of cells. It does, of course, take a very strong dose of radiation to substantially damage a cell's structure, as there can be trillions of atoms in a single cell.

The scale of electromagnetic radiation, broken down into categories of ionizing and non-ionizing radiation

The scale of electromagnetic radiation, broken down into categories of ionizing and non-ionizing radiation

Most non-ionizing radiation, such as radio and microwave energy, is considered harmful only to the extent of the amount of heat energy it transfers to whatever it hits. This is, in fact, the way that microwaves cook food. UV light is unique in that while it is non-ionizing, it does have the capacity to cause harmful effects similar to what ionizing radiation can create, such as an increased risk of cancer due to damage to DNA molecules.

How is radiation measured?

The radioactivity of a substance, or how "active" it is radioactively, is measured in either curies (Ci) or Becquerel's (Bq). Both are measures of the number of decays per second, or how often an atom in a given sample will undergo radioactive decay and give off a particle or photon of radiation. The curie (1 Ci equals about 37,000,000,000 decays per

second) is named after Marie and Pierre Curie, and is equal to roughly the activity of one gram of radium, which they studied. The Becquerel is the SI unit for radioactivity. One Bq equals one decay per second. The Bq is the SI unit, though the curie remains widely used throughout the US in both government and industry.

### III.RESULTS

The substances we call elements are composed of atoms. Atoms in turn are made up of neutrons, protons and electrons: neutrons and protons in the nucleus and electrons in a cloud of orbits around the nucleus. Nuclide is the general term referring to any nucleus along with its orbital electrons. The nuclide is characterized by the composition of its nucleus and hence by the number of protons and neutrons in the nucleus. All atoms of an element have the same number of protons (this is given by the atomic number) but may have different numbers of neutrons (this is reflected by the atomic mass numbers or atomic weight of the element). Atoms with different atomic mass but the same atomic numbers are referred to as isotopes of an element.[7,8,9]

The numerical combination of protons and neutrons in most nuclides is such that the nucleus is quantum mechanically stable and the atom is said to be stable, i.e., not radioactive; however, if there are too few or too many neutrons, the nucleus is unstable and the atom is said to be radioactive. Unstable nuclides undergo radioactive transformation, a process in which a neutron or proton converts into the other and a beta particle is emitted, or else an alpha particle is emitted. Each type of decay is typically accompanied by the emission of gamma rays. These unstable atoms are called radionuclides; their emissions are called ionizing radiation; and the whole property is called radioactivity. Transformation or decay results in the formation of new nuclides some of which may themselves be radionuclides, while others are stable nuclides. This series of transformations is called the decay chain of the radionuclide. The first radionuclide in the chain is called the parent; the subsequent products of the transformation are called progeny, daughters, or decay products.

In general there are two classifications of radioactivity and radionuclides: natural and artificial (man-made). Naturally-occurring radioactive material (NORM) exists in nature and no additional energy is necessary to place this material in an unstable state. Natural radioactivity is the property of some naturally-occurring, usually heavy elements, that are heavier than lead. Radionuclides, such as radium and uranium, primarily emit alpha particles. Some lighter elements such as carbon-14 ( $^{14}\text{C}$ ) and tritium ( $^3\text{H}$ ) primarily emit beta particles as they transform to a more stable atom. Natural radioactive atoms heavier than lead cannot attain a stable nucleus heavier than lead. Everyone is exposed to background radiation from naturally-occurring radionuclides throughout life. This background radiation is the major source of radiation exposure to humans and arises from several sources. The natural background exposures are frequently used as a standard of comparison for exposures to various artificial sources of ionizing radiation.

Artificial radioactive atoms are produced either as a by-product of fission of uranium or plutonium atoms in a nuclear reactor or by bombarding atoms with particles (such as neutrons, protons, or heavy nuclei) at high velocity via a particle accelerator. Goals of these efforts can include producing medical isotopes or new elements. These artificially produced radioactive elements usually decay by emission of particles, such as alpha particles, positive or negative beta particles, and one or more high energy photons (gamma rays). Unstable (radioactive) atoms of any element can be produced.

Both naturally-occurring and artificial radioisotopes find application in medicine, industrial products, and consumer products. Some specific radioisotopes, called fall-out, are still found in the environment as a result of nuclear weapons use or testing, or nuclear power plant accidents (e.g., Three Mile Island Unit 2, Chernobyl, and Fukushima Dai-ichi).

The stability of an atom depends on the balance of forces within the nucleus. An atom that is unstable (a radionuclide) will release energy (decay) in various ways and transform to stable atoms or to intermediate radioactive species called progeny or daughters, often with the release of ionizing radiation. If there are either too many or too few neutrons for a given number of protons, the resulting nucleus may undergo transformation. For some elements, a chain of progeny decay products may be produced until stable atoms are formed. Radionuclides can be characterized by the type and energy of the radiation emitted, the rate of decay, and the mode of decay. The mode of decay indicates how a parent compound undergoes transformation. Radiations considered here are primarily of nuclear origin, i.e., they arise from nuclear excitation, usually caused by the capture of charged or uncharged nucleons by a nucleus, or by the radioactive decay or transformation of an unstable nuclide. The type of radiation may be categorized as charged or uncharged particles, protons, and fission products) or electromagnetic radiation (gamma rays and x rays).[10,11,12]



For any given radionuclide, the rate of decay is a first-order process that is constant, regardless of the radioactive atoms present, and is characteristic for each radionuclide. The process of decay is a series of random events; temperature, pressure, or chemical combinations do not affect the rate of decay. While it may not be possible to predict exactly which atom is going to undergo transformation at any given time, it is possible to predict, on average, the fraction of the radioactive atoms that will transform during any interval of time.

The activity is a measure of the quantity of radioactive material. For these radioactive materials it is customary to describe the activity as the number of disintegrations (transformations) per unit time. The unit of activity is the curie (Ci), which was originally related to the activity of one gram of radium, but is now defined as the disintegration or transformation rate occurring in a quantity of radioactive material. The definition is:

1 curie (Ci) =  $3.7 \times 10^{10}$  disintegrations (transformations)/second (dps) or  $2.22 \times 10^{12}$  disintegrations (transformations)/minute (dpm).

The SI unit of activity is the becquerel (Bq); 1 Bq = that quantity of radioactive material in which there is 1 transformation/second. Since activity is proportional to the number of atoms of the radioactive material, the quantity of any radioactive material is usually expressed in curies, regardless of its purity or concentration. The transformation of radioactive nuclei is a random process, and the number of transformations is directly proportional to the number of radioactive atoms present. For any pure radioactive substance, the rate of decay is usually described by its radiological half-life ( $t_{1/2}$ , i.e., the time it takes for a specified source material to decay to half its initial activity). The specific activity is an indirect measure of the rate of decay, and is defined as the activity per unit mass or per unit volume. The higher the specific activity of a radioisotope, the faster it is decaying.

The activity of a radionuclide at time  $t$  may be calculated by:

$$A = A_0 e^{-0.693t/t_{1/2}}, A = A_0 e^{-0.693t/t_{1/2}},$$

where

- $A$  = the activity in dps or curies or becquerels,
- $A_0$  = the activity at time zero,
- $t$  = the time at which measured, and
- $t_{1/2}$  = the radiological half-life of the radionuclide ( $t_{1/2}$  and  $t$  must be in the same units of time).

The time when the activity of a sample of radioactivity becomes one-half its original value is the radioactive half-life and is expressed in any suitable unit of time.

Table D-1: Characteristics of Nuclear Radiations

Radiation	Rest mass <sup>a</sup>	Charge	Typical energy range	Path length <sup>b</sup>		Comments
				Air	Solid	
Alpha ( $\alpha$ )	4.00 amu	+2	4–10 MeV	5–10 cm	25–80 $\mu$ m	Identical to ionized He nucleus
Negatron ( $\beta^-$ )	$5.48 \times 10^{-4}$ amu; 0.51 MeV	-1	0–4 MeV	0–10 m	0–1 cm	Identical to electron
Positron ( $\beta^+$ )	$5.48 \times 10^{-4}$ amu; 0.51 MeV	+1	0–4 MeV	0–10 m	0–1 cm	Identical to electron except for sign of charge
Neutron	1.00866 amu; 939.565 MeV	0	0–15 MeV	b	b	Half-life: 10.183 min
X ray (e.m. photon)	—	0	5 keV–100 keV	b	b	Photon from transition of an electron between atomic orbits
Gamma ( $\pi$ ) (e.m.)	—	0	10 keV–3	b	b	Photon from nuclear transformation



Radiation	Rest mass <sup>a</sup>	Charge	Typical energy range	Path length <sup>b</sup>		Comments
				Air	Solid	
photon)			MeV			

a

The rest mass (in amu) has an energy equivalent in MeV that is obtained using the equation  $E=mc^2$ , where 1 amu = 932 MeV.

b

Path lengths are not applicable to x- and gamma rays since their intensities decrease exponentially; path lengths in solid tissue are variable, depending on particle energy, electron density of material, and other factors.

amu = atomic mass unit; e.m. = electromagnetic; MeV = MegaElectron Volts

The specific activity is a measure of activity, and is defined as the activity per unit mass or per unit volume. This activity is usually expressed in curies per gram and may be calculated by

$$\text{curies/gram} = 1.3 \times 10^8 / (t_{1/2})(\text{atomic weight}) \quad \text{or} \quad [3.577 \times 10^5 \times \text{mass(g)}] / [t_{1/2} \times \text{atomic weight}]$$

where  $t_{1/2}$  = the radiological half-life in days.

In the case of radioactive materials contained in living organisms, an additional consideration is made for the reduction in observed activity due to regular processes of elimination of the respective chemical or biochemical substance from the organism. This introduces a rate constant called the biological half-life ( $t_b$ ) which is the time required for biological processes to eliminate one-half of the activity. This time is virtually the same for both stable and radioactive isotopes of any given element.[13,14,15]

Under such conditions, the time required for a radioactive element to be halved as a result of the combined action of radioactive decay and biological elimination is the effective clearance half-time:

$$t_{\text{eff}} = (t_b \times t_{1/2}) / (t_b + t_{1/2})$$

Table D-2 presents representative effective half-lives of particular interest.

Table D-2: Half-Lives of Some Radionuclides in Adult Body Organs

Radionuclide	Critical organ	Half-life <sup>a</sup>		
		Physical	Biological	Effective
Uranium 238	Kidney	4,460,000,000 y	4 d	4 d
Thorium 232	Liver, bone	14,000,000,000 y	2.6 y	2.6 y
Hydrogen 3 (Tritium) <sup>b</sup>	Whole body	12.3 y	10 d	10 d
Iodine 131	Thyroid	8 d	80 d	7.3 d
Strontium 90	Bone	28 y	50 y	18 y
Plutonium	Bone surface	24,400 y	50 y	50 y
	Lung	24,400 y	500 d	500 d
Cobalt 60	Whole body	5.3 y	99.5 d	95 d
Iron 55	Spleen	2.7 y	600 d	388 d
Iron 59	Spleen	45.1 d	600 d	42 d
Manganese 54	Liver	303 d	25 d	23 d
Cesium 137	Whole body	30 y	70 d	70 d

a

d = days, y = years

b

Mixed in body water as tritiated water

#### Interaction of Radiation with Matter

Both ionizing and nonionizing radiation will interact with materials; that is, radiation will lose kinetic energy to any solid, liquid, or gas through which it passes by a variety of mechanisms. The transfer of energy to a medium by either electromagnetic or particulate radiation may be sufficient to cause formation of ions. This process is called ionization. Compared to other types of radiation that may be absorbed, such as radio waves or microwave radiation, ionizing radiation deposits a relatively large amount of energy into a small volume.

The method by which incident radiation interacts with the medium to cause ionization may be direct or indirect. Electromagnetic radiations (x-rays and gamma photons) and neutral particles (neutrons) are indirectly ionizing; that is, they give up their energy in various interactions with cellular molecules, and the energy is then utilized to produce a fast-moving charged particle such as an electron, which may then react with and transfer energy to a target molecule. This particle is called a primary ionizing particle. Charged particles, in contrast, strike tissue or media and directly react with target molecules, such as oxygen or water. These particulate radiations are directly ionizing radiations. Examples of directly ionizing particles include alpha and beta particles. Indirectly ionizing radiations are always more penetrating than directly ionizing particulate radiations.[16,17]

Mass, charge, and velocity of a particle, as well as the electron density of the material with which it interacts, all affect the rate at which ionization occurs. The higher the charge of the particle and the lower the velocity, the greater the propensity to cause ionization. Heavy, highly charged particles, such as alpha particles, lose energy rapidly with distance and, therefore, do not penetrate deeply. The result of these interaction processes is a gradual slowing down of any incident particle until it is brought to rest or “stopped” at the end of its range.

#### Characteristics of Emitted Radiation

**Alpha Emission.** In alpha emission, an alpha particle consisting of two protons and two neutrons is emitted with a resulting decrease in the atomic mass number by four and reduction of the atomic number by two, thereby changing the parent to a different element. The alpha particle is identical to a helium nucleus consisting of two neutrons and two protons. It results from the radioactive decay of some heavy elements such as uranium, plutonium, radium, thorium, and radon. All alpha particles emitted by a given radioisotope have the same energy. Most of the alpha particles that are likely to be found have energies in the range of about 4 to 8 MeV, depending on the isotope from which they came.

The alpha particle has an electrical charge of +2. Because of this double positive charge and size, alpha particles have great ionizing power and, thus, lose their kinetic energy quickly. This results in very little penetrating power.

In fact, an alpha particle cannot penetrate a sheet of paper. The range of an alpha particle (the distance the charged particle travels from the point of origin to its resting point) is about 4 cm in air, which decreases considerably to a few micrometers in tissue. These properties cause alpha emitters to be hazardous only if there is internal contamination (i.e., if the radionuclide is inside the body).

**Beta Emission.** A beta particle ( $\beta$ ) is a high-velocity electron ejected from a disintegrating nucleus. The particle may be either a negatively charged electron, termed a negatron ( $\beta^-$ ) or a positively charged electron, termed a positron ( $\beta^+$ ). Although the precise definition of “beta emission” refers to both  $\beta^-$  and  $\beta^+$ , common usage of the term generally applies only to the negative particle, as distinguished from the positron emission, which refers to the  $\beta^+$  particle.

**Beta Negative Emission.** Beta particle ( $\beta^-$ ) emission is another process by which a radionuclide, with a neutron excess achieves stability. Beta particle emission decreases the number of neutrons by one and increases the number of protons by one, while the atomic mass number remains unchanged.<sup>1</sup> This transformation results in the formation of a different element. The energy spectrum of beta particle emission ranges from a certain maximum down to zero with the mean energy of the spectrum being about one-third of the maximum. The range in tissue is much less. Beta negative emitting radionuclides can cause injury to the skin and superficial body tissues, but mostly present an internal contamination hazard.

**Positron Emission.** In cases in which there are too many protons in the nucleus, positron emission may occur. In this case a proton may be thought of as being converted into a neutron, and a positron ( $\beta^+$ ) is emitted.<sup>1</sup> This increases the

number of neutrons by one, decreases the number of protons by one, and again leaves the atomic mass number unchanged. The gamma radiation resulting from the annihilation (see glossary) of the positron makes all positron-emitting isotopes more of an external radiation hazard than pure  $\beta$  emitters of equal energy.[18]

Gamma Emission. Radioactive decay by alpha, beta, or positron emission, or electron capture often leaves some of the energy resulting from these changes in the nucleus. As a result, the nucleus is raised to an excited level. None of these excited nuclei can remain in this high-energy state. Nuclei release this energy returning to ground state or to the lowest possible stable energy level. The energy released is in the form of gamma radiation (high energy photons) and has an energy equal to the change in the energy state of the nucleus. Gamma and x rays behave similarly but differ in their origin; gamma emissions originate in the nucleus while x rays originate in the orbital electron structure or from rapidly changing the velocity of an electron (e.g., as occurs when shielding high energy beta particles or stopping the electron beam in an x-ray tube).

#### IV.CONCLUSION

When biological material is exposed to ionizing radiation, a chain of cellular events occurs as the ionizing particle passes through the biological material. A number of theories have been proposed to describe the interaction of radiation with biologically important molecules in cells and to explain the resulting damage to biological systems from those interactions. Many factors may modify the response of a living organism to a given dose of radiation. Factors related to the exposure include the dose rate, the energy of the radiation, and the temporal pattern of the exposure (e.g., protracted or fractionated exposures). Biological considerations include factors such as species, age, sex, and the portion of the body exposed. Several excellent reviews of the biological effects of radiation have been published, and the reader is referred to these for a more in-depth discussion (Brodsky 1996; Klaassen 2001; Hobbs and McClellan 1986; ICRP 1984; Mettler and Moseley 1985; Rubin and Casarett 1968).[19]

##### Radiation Effects at the Cellular Level

According to Mettler and Moseley (1985), at acute doses up to 10 rad (100 mGy), single strand breaks in DNA may be produced. These single strand breaks may be repaired rapidly. With doses in the range of 0.5-5 Gy (50–500 rad), irreparable double-stranded DNA breaks are likely, resulting in cellular reproductive death after one or more divisions of the irradiated parent cell. At large doses of radiation, usually greater than 5 Gy (500 rad), direct cell death before division (interphase death) may occur from the direct interaction of free-radicals with essentially cellular macromolecules. Morphological changes at the cellular level, the severity of which are dose-dependent, may also be observed.

The sensitivity of various cell types varies. According to the Bergonie-Tribondeau law, the sensitivity of cell lines is directly proportional to their mitotic rate and inversely proportional to the degree of differentiation (Mettler and Moseley 1985). Rubin and Casarett (1968) devised a classification system that categorized cells according to type, function, and mitotic activity. The categories range from the most sensitive type, “vegetative intermitotic cells,” found in the stem cells of the bone marrow and the gastrointestinal tract, to the least sensitive cell type, “fixed postmitotic cells,” found in striated muscles or long-lived neural tissues.

Cellular changes may result in cell death, which if extensive, may produce irreversible damage to an organ or tissue or may result in the death of the individual. If the cell recovers, altered metabolism and function may still occur, which may be repaired or may result in the manifestation of clinical symptoms. These changes may also be expressed at a later time as tumors, cellular mutations, or transformed tissue (scar tissue) which may result in abnormal tissue or compromised function.

##### Radiation Effects at the Organ Level

In most organs and tissues, injury and the underlying mechanism for that injury are complex and may involve a combination of events. The extent and severity of this tissue injury are dependent upon the radiosensitivity of the various cell types in that organ system. Rubin and Casarett (1968) describe and schematically display the events following radiation in several organ system types. These include: a rapid renewal system, such as the gastrointestinal mucosa; a slow renewal system, such as the pulmonary epithelium; and a nonrenewal system, such as neural or muscle tissue. In the rapid renewal system, organ injury results from the direct destruction of highly radiosensitive cells, such as the stem cells in the bone marrow. Injury may also result from constriction of the microcirculation and from edema



and inflammation of the basement membrane, designated as the histohematic barrier (HHB), which may progress to fibrosis. In slow renewal and nonrenewal systems, the radiation may have little effect on the parenchymal cells, but ultimate parenchymal atrophy and death over several months result from HHB fibrosis and occlusion of the microcirculation.

#### Low Level Radiation Effects

Cancer is the major latent harmful effect produced by ionizing radiation and the one that most people exposed to radiation are concerned about. The ability of alpha, beta, and gamma radiation to produce cancer in virtually every tissue and organ in laboratory animals has been well-demonstrated, while radiogenic cancer has not been observed in some human tissues and organs. The development of cancer is not an immediate effect. In humans, radiation-induced leukemia has the shortest latent period at 2 years, thyroid cancer after Chernobyl showed up in children about four years after the accident, while other radiation induced cancers have latent periods >20 years. For the non-radiogenic cancers, it has been hypothesized either that repair mechanisms effectively protect the individual or that the latency period exceeds the current human life span (Raabe 2010). The mechanism by which cancer is induced in living cells is complex and is a topic of intense study. Exposure to ionizing radiation can produce cancer; however, some sites, such as the breast, lung, stomach, and thyroid, appear to be more common than others.

DNA is a major target molecule during exposure to ionizing radiation. Other macromolecules, such as lipids and proteins, are also at risk of damage when exposed to ionizing radiation. The genotoxicity of ionizing radiation is an area of intense study, as damage to DNA is ultimately responsible for many of the adverse toxicological effects ascribed to ionizing radiation, including cancer. Damage to genetic material is basic to developmental or teratogenic effects, as well.

There is limited evidence of non-cancer human effects at low radiation doses. Non-cancer effects that have been reported are associated with the Japanese atomic bomb survivor population and include neurological and cardiovascular effects. Neurological effects were observed in fetuses exposed to prompt radiation during the detonations while they were in gestation weeks 8–15, less so for weeks 16–25, and were not observed for other developmental time frames. Cardiovascular effects have been reported for atomic bomb survivors following 60 years of follow-up. These include a statistically significant increase in heart disease (% elevated relative risk per Gy with 95% confidence interval = 14 [6–23] %/Gy,  $p < 0.001$ ) and a non-statistically significant increase in stroke (9 [1–17]%/Gy,  $p = 0.02$ ) above a dose of 0.5 Gy. These radiation-induced circulatory effects may be increased by other factors such as smoking, microvascular damage in the kidney and associated hypertension, high serum cholesterol, diabetes, and infection.[20]

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