Radiation and Its Effect on Living Organisms

Eiichiro Ochiai
April 4, 2014

Eiichiro Ochiai is Professor Emeritus, Department of Chemistry, Juniata College

The following expands on my presentation "Radiation Issues—Some Fundamentals" on April 4, 2014, given at Juniata College. The focus of my talk was how basic chemistry and physics concepts and theories students learn in the first two years of college shed light on the health effects of radiation. Because the time allotted was insufficient for me to tell fully what I intended, I have expanded the presentation a little here in order to give wider audiences some ideas as to why radiation is detrimental to living organisms on this earth.[1]

WHAT'S HAPPENING DUE TO RADIATION?

Nuclear Weapons, Nuclear Power Reactors, and Radioactive Material

Since the discovery of atomic structure, radiation, and nuclear reactions (such as nuclear fission in 1938), the human race has been excited about the potential use of this knowledge, particularly of nuclear fission and nuclear fusion. A 1939 report that the German government had started to develop a weapon based on nuclear fission reaction prompted Dr. Albert Einstein and Dr. Leó Szilárd to appeal to U.S. President Franklin Delano Roosevelt that the U.S. should produce such a weapon before Germany could succeed. This led to the formation of the secret Manhattan Project, which succeeded in producing three atomic bombs by mid-1945. After a successful test, the U.S. dropped one bomb based on uranium (U) on Hiroshima on August 6, 1945, and another based on plutonium (Pu) on Nagasaki three days later. The devastation and human casualties these atomic bombs caused are widely known.

This success and subsequent development led to commercial nuclear power plants in the U.S. and persuaded the Japanese to build nuclear power plants as a "peaceful" use of nuclear energy. The U.S. now has 104 nuclear power reactors on its soil, and Japan has fifty-four on its tiny islands.

Let us focus on the nuclear fission reaction of the uranium isotope U-235. Upon absorbing a slow neutron, U-235 becomes U-236, which then decays in one of several ways. For example, it may split into barium (Ba)-142, krypton (Kr)-92, and two neutrons. (See the appendix for an explanation of mass number such as that of U-235 and the idea of isotope.) This is a nuclear fission reaction and will produce an enormous amount of energy. This energy is used to kill people and destroy everything in the case of nuclear weapons, but to produce electricity in nuclear power plants. The energy itself dissipates eventually as heat, though killing or being converted into electricity in the process. It is not well recognized that the nuclear fission reaction produces an enormous amount of radioactive fission products; this happens both in the use of nuclear weapons and in electricity production. This has increased the amount of radioactive material on this planet enormously since about 1945.

A very strong earthquake and its subsequent huge tsunami devastated a vast area of the northeastern part of the Japanese main island on March 11, 2011. This caused severe accidents at Fukushima Daiichi Nuclear Power Plant (Fk-1NPP of the Tokyo Electric Power Company). The nuclear fuel rods in Reactors No. 1-3 melted because of the failure of the cooling systems, and several explosions took place. As a result, a large amount of radioactive material was released. Accidents at nuclear facilities have occurred in the past, including serious ones at the Three Mile Island Nuclear Generation Station (TMINPP) in Harrisburg, Pennsylvania, in 1979 and at the Chernobyl Nuclear Power Plant (ChNPP) in Ukraine (then the USSR) in 1986. Hence the Fk-1NPP accident is not unique, but it would turn out to be the most severe and most difficult one to deal with that the human race has experienced. The Japanese have now suffered from a number of nuclear related events, and hence I wrote a book, *Hiroshima to Fukushima: Biohazards of Radiation*, in order to tell the world the danger of radioactive material created on this earth, from a Japanese perspective. [2]

Effects of Radiation in the Case of Atomic Bomb Explosions

The radiation doses that people were exposed to at the atomic bomb explosions both in Hiroshima and Nagasaki have been investigated by many means, and the estimates obtained from studies have been published several times. The most recent one is known as DS02, which took account of γ and neutron radiation from the atomic bomb explosions.[3] DS02 estimates that the dose at the epicenter was 165 Gy (Sv) in Hiroshima and 350 Gy (Sv) in Nagasaki. At 1 km and 2 km from the epicenter, the dose estimates were 8.7 Gy and 0.14 Gy, respectively, in Nagasaki, and 4.5 Gy and 0.07 Gy, respectively, in Hiroshima. At doses higher than about 10 Gy (Sv), people died instantly or within a few weeks to months. These deaths are separate from those caused by the heat and the very strong wind blasts. Please refer to a later section (Half-life/Bq/Sv (Gy)) for the meaning of Sv/Gy and others.

I would like to quote an eyewitness account by a medical doctor about what happened within a few days after the blast in Hiroshima. Dr. Shuntaro Hida happened to be in the outskirts of Hiroshima on that day.

> Until the fourth morning we assumed that all those that died had succumbed to their burns. However, beginning that morning, patients began to die who had not suffered serious burns…..But what sort of symptoms were they afflicted with? First a high fever of 40 degrees [Celsius]….they

> began to bleed from their eyes, nose and mouth….We attempted to examine the inside of their mouths, but could not. It was not simply bad breath, it was the smell of decay. A smell so bad, we could not put our faces near their mouths….even though these people were still alive, the insides of their mouths were decaying.[4]

This observation tells us how radiation affects the human body. But there is one factor that is not quite obvious but nonetheless quite important in interpreting radiation effects. The question is this: whether the observed effects were due to the radiation from outside of the body, like that coming from the exploded bomb, or due to radioactive material somehow coming into the human body. The former is called external exposure, and a typical such exposure is a diagnostic X-ray. The latter is called internal exposure.

We will look again at a different part of Dr. Hida's talk:

> What next surprised us was the patient who claimed, "Doctor, I'm not sick from the 'pika' [the atomic bomb explosion]." "What makes you say that?" I queried, and he answered "Well, I wasn't in Hiroshima on that day!" He continued, "I didn't come to Hiroshima until two days after the August 6th bombing. You see, one of my children did not return home after the bombing, so I traveled to the city to look for him. It wasn't until after walking around the ruins for two days that I began to feel ill, and that's when I thought I should come here and get checked out by you…." Soon after he began to display a number of odd symptoms and passed away….[5]

This latter type of effect is very likely due to inhaled radioactive material, which caused destruction of inner tissues; that is, internal exposure. Exposure to what? The U.S. authorities maintained that radiation effects came from only the bomb explosion itself, ignoring the effects of radioactive fallout. It is very likely that even people who came to Hiroshima (or Nagasaki) later could have inhaled floating radioactive minute particles or somehow ingested radioactive material.[6] The fallout can also affect bodies from the outside, that is, through external exposure.

An official estimate that does not incorporate internal exposure is that exposure below 0.25 Gy (Sv) has no immediate visible health effects. The truth of the matter is that many people with exposure less than 0.25 Gy (Sv) did experience a number of ill health effects even right after the blast. This fact has not been recognized as such by the authorities until recently. Another low-exposure effect is seen in the fact that people who survived the atomic bomb have suffered long from a whole variety of illnesses, including various cancers. Some of them are still suffering.

Fallout from Accidents at Nuclear Facilities

The No. 2 reactor of the Three Mile Island (TMI) nuclear power plant near Harrisburg, Pennsylvania, had its nuclear fuel partially melted due to malfunctions and some operational mistakes in the spring of 1979. It caused the release of radioactive material, but officially no health effects due to radiation have been reported. A careful analysis of the official data, however, revealed that statistically significant increases were observed in various diseases, including childhood cancer, birth defects, and breast cancer, among the people living in ten counties around TMI, as compared with the Pennsylvania average and the U.S. average.[7] It took twenty years to clean up the melted fuel.

Another more serious disaster took place at the Chernobyl Nuclear Power Plant (ChNPP) in the former Soviet Union (today's Ukraine) in 1986. The fallout from the explosion of Reactor No. 4 of ChNPP spread as far west as France, as far southwest as Greece, and to northern parts of Sweden and Norway, as well as to Ukraine, Belarus, and Russia. The severe health effects from the fallout on the people in Ukraine, Belarus, Russia, and some Western European countries are known, as well as the direct effects on the people who dealt with the damaged reactors immediately after the accident. These people are called liquidators, and 800,000 of them were eventually recruited and involved in various aspects of cleaning the area and making a sarcophagus for the damaged reactor. Liquidators have suffered from a variety of ill health effects. The rate of disease among the liquidators in 1993 was significantly higher than their rate of disease just before the accident in 1986. Some numbers are as follows: a 70-fold increase in diseases of the digestive organs; 40-fold in those of the nervous system and sense organs, the endocrine system, and the urogenital system; 30-fold in tumors; 12- to 20-fold in the circulatory system and blood producing organs; and so on.[8]

Y. I. Bandazevsky, a Belarusian doctor, studied several hundred corpses of people killed by radiation contamination.[9] He measured radioactivity due to cesium (Cs)-137 in individual organs. These studies showed that the radioisotope Cs-137 tends to be concentrated in certain organs and tissues. It is most concentrated in the thyroid gland, followed by skeletal muscle, the small intestine, the myocardium, the brain, the spleen, the kidneys, and the liver. It tends to accumulate more in children than in adults.

It is important to note that people are still suffering from various diseases even twenty-eight years later, and that in some contaminated Belarusian regions only about 20% of children are healthy, and the remaining 80% are suffering from various illnesses. Thyroid gland cancer is usually quite rare among children, but it showed a slow increase after the incident and started an accelerated increase four to five years later and is still increasing among children. The immunological system has been weakened, and as a result, a phenomenon called Chernobyl AIDS has been prevalent. Type I diabetes also increased among children. Malformed children were born. The intellectual capacity seems to have been affected negatively. An enormous amount of data on the health effects from the ChNPP accident is collected in Yablokov et al., 2009.[10] Their estimate is that as of 2004, as many as one million people have died from the radioactive contamination due to the accident, though the officials have admitted only several thousand due to thyroid cancers and leukemia.

The Fk-1NPP disaster is only three years old and is far from being settled. Even the locations of the melted fuel rods have not been identified because the radiation levels are so high that no human being can stay long in critical places to investigate. They are developing many robots to do the work. The health effects of radioactive material released from the accidents have been reported sporadically but not systematically investigated yet. The only official data so far are on the thyroid gland abnormalities among children in Fukushima Prefecture. In the first three years, 75 thyroid gland cancers were found among them; this is about 29 per 100,000 people over the first three years.[11] The Chernobyl data were 1~2 per 100,000 people per year in the first three years, increased rapidly after four years, went up about 10 per 100,000 people per year in 2010, and seem to be still increasing.[12] The number in Fukushima is enormously higher than these values only three years after the disaster. The Japanese official opinion is that those thyroid gland cancers are not related to the radiation from Fk-1NPP accident, based on the data from Chernobyl.

There have been many other accidents at nuclear facilities, serious or maybe not too serious. Except for the case of Fk-1NPP, they were not due to natural disasters, implying that the nuclear power reactors are vulnerable to many minor or major structural deficiencies and also to human errors. The facilities are indeed very complicated and the operation is very difficult, as a nuclear fission reaction needs to be controlled very delicately. Otherwise it can lead to a nuclear explosion.

Radiation Effects Observed in the United States and Other Countries

There are many other indications that radiation from many different sources is affecting human health. We will look at some data on the soil of the U.S. It must be noted that human health is affected by many factors: bacteria, viruses, toxic chemicals, cancer-causing chemicals, weather, and others. Because radiation is only one of those many factors, it is usually difficult to establish a cause-effect relationship involving low-level radiation. It requires a careful analysis of data, and often the amount of data is insufficient to determine unequivocally the cause-effect relationship in the case of radiation.

Let us start with the effect of the first atomic bomb test conducted in Nevada in 1951. There was a sudden increase in the percentage of low-birth weight children born right after the test.[13] The majority of those affected were in the Las Vegas area, which is downwind from the test site. Then the tests were changed so that no wind blew from the test toward Las Vegas. This had an immediate effect, such that the low birth-weight rate returned to the normal level in Las Vegas area, though it remained high in other areas of Nevada. This time sequence testifies fairly well to the cause-effect relationship; i.e., the fallout from the atomic test caused the low birth weight phenomenon.

The term “downwinders” has recently become widely recognized. The people living downwind from the Nevada test site have suffered from various cancers and many have died from them. Some of them have now been recognized to be victims of the test by the government.[14] The Hanford reactor located in Washington State was the first nuclear reactor to produce plutonium used for the Nagasaki atomic bomb. It started to operate in 1944. The infant mortality in Benton County, where it is located, went up by 160% from 1943 to 1945.[15]

Jay M. Gould details studies on the effects of radiation on breast cancer in the vicinity of nuclear facilities under normal operating conditions.[16] It has been shown with most facilities that indeed the breast cancer rate has increased since the facility went into operation. One example is the Dresden nuclear power plant in Illinois, one of the earliest nuclear power plants in the U.S. The breast cancer death rate in 1985-89 was higher in the counties surrounding the facility than it was in 1950-54; for example, there was a 62% increase in Grundy County, 83% in Kendall, 46% in Livingston, 34% in Will, and 23% in Kankakee. In the same time interval, Illinois as a whole saw a decrease of 2% and the U.S. an increase of 1%.

It has been noted that the incidence of thyroid cancer is increasing more rapidly than any other type of malignancy, rising about threefold from 4.33 per 100,000 to 11.03 per 100,000 from 1980 to 2006 in the U.S.[17] Similar trends have also been observed in many other developed countries, and the causes have been debated. J. J. Mangano looked at the data for forty-six states (including Washington, D.C.) representing 276 million Americans and analyzed data from 500 counties involving 202 million people.[18] In the period of 2001-2005, thyroid cancer rates per 100,000 ranged from a low 5.4 in Arkansas to a high of 12.8 in Pennsylvania; this value of 12.8 is 44% above the national average. Among the highest beside Pennsylvania are Massachusetts, New Jersey, Connecticut and Rhode Island; all are in the Northeast, though New Mexico, Utah, and Montana are among the highest as well. At the county level, the highest was 21.4 in Lehigh County, PA, 18.8 in Northampton County, PA, 18.3 in Rockland County, NY, and other counties in eastern Pennsylvania and adjacent counties in New York. This is to be contrasted with the fact that Pennsylvania's thyroid cancer rate in the mid-1980s was 40% below the national average. There are nine nuclear reactors in this area, the highest concentration of reactors in the U.S.

Many other data, not only from the U.S. but also any country that has operating nuclear facilities, indicate that even under normal operating conditions, radioactive material may be emitted from nuclear power plants and affect people living nearby. In 2002 the German government contracted with the German Childhood Cancer Registry at the University of Mainz to conduct a study of childhood cancers and leukemia in the area around the country's sixteen nuclear power plants. They carried out a thorough epidemiological study for 1980-2003. The study is known as KiKK.[19] Addresses (including distances from the likely spot of radioactive emission) of all children younger than five years old with leukemia or other malignancies at the time of diagnosis (1592 cases) were compared to those of three times as many randomly selected children of the same age and sex, residing in the same region, who did not have either of these diseases (4735 controls). The only parameter was the distance from the likely source of radiation. A logarithmic regression analysis showed a rise of all cancer cases with the decrease in distance, with the sharpest rise within 5 km. It turned out that the leukemia risk of the children younger than five years old and living within 5 km of a nuclear power plant was twice as high as the risk for those living farther than 5 km away. The increase in leukemia risk remained significant when comparing children living within 10 km of the plant to children living farther than 10 km away.

Another sophisticated analysis of incidence and mortality rates of childhood leukemia near 136 nuclear facilities in the UK, Canada, U.S., Germany, Japan, and Spain showed statistically significant increases between 14% and 21% of leukemia incidence in children younger than nine years old near many of these sites.[20]

RADIATION EFFECTS ON LIVING ORGANISMS – SCIENTIFIC BASES

In order to understand the effects of radiation on living organisms, we need to look at radioactive particles, at molecules, and at cells and their components. We need to understand the interactions of the nuclear world and the chemical world.

Radiation

Radiation includes electromagnetic waves as well as radioactive particles such as α–particles, β-particles, and neutrons. Electromagnetic waves include radio waves, microwaves, infrared light (sensed as heat), visible light, ultraviolet light, X-rays and γ-rays. When an electromagnetic wave interacts with a chemical system, it behaves like a particle, and hence it is called a photon. The energy of a photon is determined by its frequency, as a wave is characterized by its frequency or wavelength. The wavelength of visible light ranges from about 800 to 320 nm (nanometer). The midrange wavelength 500 nm corresponds to an energy of 2.5 eV. This is in the range of chemical reaction energy, as seen below, and this fact means that light of this wavelength range can interact with chemical systems and biological systems. On the other hand, all other radiation including radio wave and radiation coming from nuclear decay is out of the range of chemical energy and hence cannot be sensed by living organisms' sense organs.

Radiation and the Nuclear World—The Basics

An atom consists of a nucleus and surrounding electrons. A nucleus is made of protons (positively charged) and neutrons (electrically neutral) and can be stable or unstable. A stable nucleus remains as it is forever, whereas an unstable nucleus cannot remain as it is and spontaneously changes into a more stable form. If it results in a stable form, it stops there. The process by which an unstable nucleus changes into a more stable form is termed nuclear decay or disintegration, and the energy of change is emitted as radiation. Radiation can be in the form of either particles (α, β, or neutron) or electromagnetic waves (γ). Such an unstable entity is hence called a radioactive substance. ("Isotope" is the technical term.)

There are only a few naturally occurring radioactive isotopes on this planet. They are remnants of the original heavenly bodies that formed the earth. Radioactive isotopes disappear as time goes on; how fast one does so depends on the half-life of its decay process. (See the next section for an explanation of half-life). Only entities with very long half-life are still present on the earth; such examples include U-235, U-238, potassium (K)-40, thorium (Th)-230, and their decay products, including radium (Ra)-226, radon (Rn)-222, and polonium (Po)-210.

The human race has invented ways to produce more radioactive substances in the process of developing nuclear energy, though producing radioactive material was not intended. They come out inevitably anyway, and none of those have any use for humans, except for plutonium, which can be used to produce nuclear weapons. They are unwelcome byproducts, and we have not found safe disposal methods for these dangerous materials yet.

Now, we need to take a look at the issue of the stability of the nucleus and radiation. This is in the realm of elementary particle physics, and I am not too familiar with it. I would say only that there are certain ratios of neutrons/protons (n/p ratio) and certain particle distributions in quantum states necessary for a nucleus to be stable.

Any isotopes of elements with proton numbers higher than 84 are unstable and typically emit α-particles in the decay process. The α-particle is a helium nucleus, which consists of two protons and two neutrons. An emitted α-particle has a very high kinetic energy, typically 5 MeV or higher. (See the appendix for energy units, including eV.) Its speed is close to the velocity of light.

A nucleus with too high an n/p ratio tends to be unstable, and one way for it to become more stable is to emit an electron by turning a neutron to a proton, thus reducing the n/p ratio. The emitted electron has a high energy, typically ranging from 0.5 KeV to 2 MeV or so. This is a β-particle. On the other hand, if the n/p ratio is too low, then a proton can change into a neutron and hence a positron (another type of β-particle) will be emitted. Often the end result of α- or β-decay may not be the most stable form; it is called a metastable state. The metastable state then decays into the most stable state, and in the process electromagnetic radiation in the form of γ-rays will be emitted. The energy of γ-radiation is also up to 2 MeV or so.

All these processes occur with changes in nuclear states and are governed by the strong nuclear force. (The weak nuclear force is also involved in β-emission). By the way, it may not be necessary to point out that according to the standard theory, there are four forces operating in this universe: gravity, electromagnetic force, the strong nuclear force, and the weak nuclear force. I call the world in which nuclear changes take place the nuclear world, which is governed by the strong nuclear force. The energy changes involved are very large, typically of the order of MeV in the case of nuclear decay and several hundred MeV in nuclear fission reactions.

Let us look at the fission reaction. A typical fission reaction of U-235 is expressed as U-235 + n (neutron) → Ba-142 + Kr-92 + 2n. In this process, a U-235 atom acquires a neutron and becomes U-236. It is very unstable and splits into two smaller nuclei. In this reaction, a little mass is lost, and the mass lost is converted into energy according to Einstein's famous equation $E = mc^2$ (E = energy, m = mass, c = speed of light). This is the basis for nuclear energy.

In the case of the Hiroshima atomic bomb (nicknamed "Little Boy"), it is estimated that about 1 kg of U-235 contained in the bomb was split and produced about 6.3×10^{13} J of energy. In comparison, 1 kg of gasoline, a typical chemical, produces about 4.8×10^{7} J. So with the same quantity (1 kg), uranium produces a million times more energy than gasoline.

A typical nuclear power plant producing one million KW (or 1000 MW=10^9 W) reacts about 3 to 4 kg of U-235 a day. That 10^9 W amounts to 8.6×10^{13} J/day, so 3.5 kg/day of U-235 will produce about 2.3×10^{14} J/day. Little Boy produced about 6.3×10^{13} J. Therefore, a 1000 MW nuclear power plant will produce the amounts of energy and radioactive material equivalent to three to four Hiroshima atomic bombs per day or 1000 Hiroshima atomic bombs per year. These data also indicate that only 8.6×10^{13} J/day out of the total heat of 2.3×10^{14} J/day is converted to the electric energy; that is, the efficiency of energy use in a nuclear power plant is about one third. The remaining two-thirds of the heat is released to the environment as waste. This contributes directly to heating the planet. Nuclear power is not a green energy.

The most difficult issue beside the health effects of radioactive material produced in the nuclear industry is how to dispose of or store safely the dangerous material. It contains a whole variety of radioactive isotopes with short, long, and very long half-lives. It has been estimated it takes a thousand years for a set of radioactive waste produced in the nuclear industry to return to almost the normal state (something like one thousandth of the initial value), though small quantities of trans-uranium isotopes would persist longer. No country including the U.S. has yet figured out adequate methods to store this waste. This is due to the dangerous nature of the material and the geological conditions of the storage. How can we store them safely over that long period?

Half-life/Bq/Sv(Gy)

As mentioned in the previous section, a radioisotope decays or disintegrates spontaneously. How fast it does so is determined by the nuclear conditions and is specific to each individual radioisotope. It decays as a first order reaction or exponentially; i.e., $N = N_0 \exp(-kt)$, where N is the number of nuclei at time t, and N_0 is the initial number of nuclei, and k is the reaction constant or the probability of decay per second. The time duration in which N becomes half of the initial value is called the half-life. How fast a radioisotope decays depends on the value of k, but it is often defined in terms of half-life instead. A shorter half-life implies a faster decay.

Radioactivity is measured in becquerels (Bq), where 1 Bq represents the decay of 1 nucleus per second. This measurement also equals kN and hence is proportional to the amount of radioactive material present in a sample as well.

The absorbed dose of ionizing radiation on an object is measured in gray (Gy), which is the energy received from radiation per kilogram of the body; that is, 1 Gy = 1 J/kg. Since different types of ionizing radiation have different effects on the human body, the impact of such radiation on humans is measured in sieverts (Sv), where 1 Sv = Q x Gy. The constant Q is known as the radiation weighting factor and quantifies the biological impact of different types of radiation on live tissue; specifically, Q is 20 for α-particles, 1 for β-particles and γ-rays, and 10-20 for neutrons (depending on velocity), as determined by the International Commission on Radiological Protection (ICRP).

The severity of radiation cannot be adequately expressed by Sv (Gy). As mentioned earlier, an exposure higher than 10 Sv means almost instant death. Let's do some calculations with 100 Sv (Gy). According to the definition, it means 100 J/kg of body mass. Now100 J = 24 cal, which will raise the body temperature by 0.024 degrees Celsius. Would a rise in temperature by this amount kill the body? No way. Yet the fact is that it kills instantly. Why? Here is a chance to look into the mechanism of radiation effects on living organisms. We need to look at the chemical world of living organisms in order to solve this mystery.

Living Organisms as a Part of the Chemical World

We, living organisms, are made of chemicals.[21] Chemicals are made of atoms, and chemical reactions involve movements of electrons around nuclei. These processes are governed by the electromagnetic force. No change in the nuclei takes place, and hence chemical processes involve no strong nuclear force. The electromagnetic force is quite weak compared with the nuclear force, and it operates over a longer distance. I use the term "chemical world" for the scale that involves only chemical reactions, and all the material and all the processes on this earth constitute the chemical world. Water in a river erodes a rocky mountain; fish eat plankton and live and grow; human beings produce, say, a chemical DES, which then enters a human body and disrupts the endocrine system: all these are chemical processes.

Living organisms are made of cells, from the simplest single-celled organisms like bacteria to multi-cellular organisms like human beings. Most cells are tiny but contain a lot of chemicals: water, proteins, lipids (fat), DNA, etc. One kilogram of human body consists of about one trillion (10^{12}) cells.

Now, we need to know what forces cause changes in chemicals. Let us look at the simple reaction of removing an electron from a hydrogen atom, which consists of a nucleus with a positive charge and a negatively charged electron surrounding the nucleus. The electron is attracted by the nucleus by electromagnetic force, and to move the electron away from the nucleus requires energy to overcome this attractive force. This kind of calculation is learned in the first year of chemistry, and the value is known as ionization energy. It is 1310 kJ/mole in the ionization of a hydrogen atom. One mole consists of 6.023 x 10^{23} entities, hydrogen atoms in this case. (By the way, this number is called Avogadro's number.) Therefore, the energy to remove an electron from a single hydrogen atom is
$(1.31 \times 10^6 \text{ J})/(6.023 \times 10^{23}) = 2.175 \times 10^{-18} \text{ J} = 13.6 \text{ eV}$. Another example of chemical energy is the bond energy of a C-H bond; it is 412 kJ/mole, which corresponds to 4.27 eV. Chemical energy typically ranges from of the order of 0.1 to 100 eV.

Compare these values with the energy of nuclear reactions and radiation energy. The latter is typically of several tens of KeV to several MeV, i.e., of the order of 10^4 to 10^6 eV. That is, radiation energy is several orders of magnitude greater than chemical energy.

Interaction of the Nuclear World with the Chemical World – Radiation Effects

The effect of radiation is based on the interaction of radiation with chemical systems. Radiation of visible to ultraviolet light typically excites the energy state from the lowest level to a higher level in a molecule, and it will be absorbed by the chemical system. This can cause it to be colored and hence visible. If the absorbed energy is larger than that of visible range, the chemical system looks colorless.

What would happen if a radioactive particle with high energy hit an assembly of chemical compounds? Several possibilities exist, but a typical one is that an electron would be kicked out from the chemical compound, resulting in the formation of an ionic species or the breakage of a chemical bond. To kick out an electron or break a bond would require something like 30 eV, The radioactive particle would lose some energy, but it would still carry a lot of energy. So it would go on to kick out electrons or break bonds from a large number of molecules, perhaps up to several thousands. It depends on the nature of the radioactive particle and its energy. This is the basis of the adverse effects of radiation on chemical systems, including biological ones.

Effects of Radiation on Living Organisms – External *vs.* Internal Exposure

Living organisms are of course made of chemicals, but they have several levels of structure. The body of a multi-cellular organism consists of cells, tissues, and organs. In a cell, there are a large number of chemicals present which are constantly undergoing chemical reactions that are intimately coordinated with each other, constituting living conditions. Disruption of the cell's living condition can be brought about by many factors, including toxic chemicals, bacteria, viruses, temperature, and radiation. Some mechanisms have evolved to rectify some disruptions. Important mechanisms include immunity, several mechanisms to repair damaged DNA, and apoptosis if the repair of DNA fails.

What about radiation? Radiation goes through several tens to several hundred cells, depending on the nature of the radiation and its energy. As it goes through one cell after another, it keeps destroying molecules it encounters. Radiation coming from the outside of a body goes through skin and then into the tissue cells in the body. An α-particle cannot go far into the body, as it cannot go even through thin paper. A β-particle can go a little deeper but only in the surface area. But γ-rays and neutrons go deep into the body and typically can come out from the opposite side of the body. This is the situation with external exposure.

However, radioactive material can get into a body through inhalation of minute particles or ingestion of contaminated food or drink. It can settle in a location and then radiate the immediate surrounding area. This is internal radiation. In this case, all types of radiation (α, β, γ, and others) have immediate effects. Direct evidence for internal radiation was recently reported. Samples of the bodies of those who perished in Hiroshima and Nagasaki were secretly stored in the U.S. but returned to Japan recently. A group of scientists led by K. Shichijo of Nagasaki University succeeded in photographing traces of α-particles in a kidney sample taken from a person who died of acute radiation effects in Nagasaki. This photo has been shown on the Internet but has not been published in a journal yet. The sample is more than sixty years old, but it still contains radioactive material that is still emitting radiation. The source of the radiation has been identified as plutonium. The Nagasaki atomic bomb was made of plutonium, and the fact that it was found in a dead body implies that minute particles of the fallout somehow got into the body and have been radiating internally.

As seen above, no biological system can protect itself against high-energy radiation. There are some repair mechanisms for the damage done to DNA, and there are some chemical entities available to reduce the reactivity of free radicals produced by radiation. Are these remedies sufficient to defend against radiation? No. There is no adequate repair mechanism for molecules other than DNA, particularly critical molecules like proteins. Some kinds of damage done to DNA seem to be un-repairable by existing mechanisms. In certain situations, DNA repair mechanisms cannot cope with the frequency of damage done by radiation. Overall, living organisms are ill-prepared against radiation effects. Though they have survived against background radiation throughout evolution, they are having difficulty now in coping with the heightened radiation level caused by human activities in the last three-quarters of a century.

Two Important Issues Regarding the Effects of Radiation on Human Health

Two main issues are how to explain (a) the apparent severity of 10 Sv and (b) the effect of low-level radiation. Problem (b) is often addressed by the authorities by saying that no negative effects (e.g., cancer) have been substantiated below 100 mSv. And then they say that the radioactivity in the contaminated area, for example, Fk-1NPP, is relatively low and does not exceed 100 mSv, and that therefore people do not have to worry about the negative radiation effects on health. It is widely believed that there is no need to worry about low-level exposure to radiation.

Let's look at question (a). A dose of 100 Sv kills a person instantly while raising the body temperature by only 0.024 degree Celsius, according to a direct way of interpreting the meaning of 100 Sv, as mentioned earlier. Obviously this rise of temperature would not kill a person. Why is this so? Not many people have questioned this. (I have not seen one myself.) We need to look at the particle-wise interactions of radiation with chemical reaction systems in cells. A dose of 100 Sv = 100 J/kg; i.e., 1 kg of a human body received radiation particles equivalent to 100 J. Let's assume that a particle has a typical energy of 1 MeV, which is 1.6×10^{-13} J. Then it requires $100/(1.6 \times 10^{-13}) = 6 \times 10^{14}$ particles to carry100 J. (This is a simple assumption, but basically true: dose = (energy of a radioactive particle)*(number of radioactive particles)). This many particles enter 1 kg of body mass, which consists of 10^{12} cells. So, each cell receives about 600 radioactive particles. Each particle destroys about 100 molecules. (This is a low estimate; it could be up to several thousands.) Therefore, each cell has 6×10^{4} molecules destroyed. If the radiation does not distribute equally in the 1 kg and is concentrated in a smaller area, the effect is more severe at one location. It is very likely that some of the molecules destroyed are critical for the functions of some tissues or organs and may result in the death of cells of these tissues or organs, which would lead to the death of the entire body. By the way, in the case of exposure to the atomic bomb explosion, this entire process would have happened in a matter of a few seconds to a few minutes, and the bodily repair mechanisms would not have been able to cope with the destructive force of radiation so fast.

Low-level exposure is the most complicated issue. First let us distinguish between external and internal exposure. Low-level external radiation (let's assume lower than 100 mSv) could be relatively harmless, though not without ill effects. Ill effects caused by low-level external exposure would be difficult to identify as such. This is simply because millions of different effects, chemical, biological or otherwise, cause various illnesses.

One difficult example to characterize as either external or internal is nose bleeding. Many reports regarding the Fk-1 incident say that many people have had unusual nose bleeding. It is likely that minute radioactive particles may attach themselves to sensitive blood vessels and could disrupt the cell membrane of the blood vessels. In this sense it can be characterized as internal. Nose bleeding can be caused by many factors, physical or otherwise. Hence, the nose bleeding, though more frequent and severe than usual, has been dismissed as nothing to do with radiation by the officials and scientists associated with the nuclear industry.[22]

Internal exposure would be serious even at a low level, as it directly affects the cells that surround the place the radioactive material settled. It can come into the respiratory system through inhalation and can be deposited in the passages into the lungs and eventually in the lungs themselves. In external exposure, α and β radiation have little effect because they don't penetrate into the body, but they are very effective radiators once they settle in certain organs or tissues. In terms of exposure dose, expression in Gy or Sv is quite inadequate to indicate its severity. For example, 0.2 mSv (J/kg) in the ordinary expression may not affect the entire 1 kg; it is more likely that it affects only a small range around its deposited area in the case of α– and β–particles. Suppose it affects only 10 g of tissue. Then the effective dose would be 0.2 mJ/0.01 kg=20 mJ/kg=20 mSv (Gy). In the case of γ-radiation, the effective range may be larger.

With this uncertainty in mind, we need to see how low-level radiation can harm living organisms. The two alternative views are: (1) there is a threshold dose level below which radiation has no ill effect or (2) there is no threshold and the ill effect is proportional to the dose down to a zero dose; this is called the LNT (linear no threshold) hypothesis. A Japanese organization called RERF (Radiation Effect Research Foundation) has been studying approximately 1,200,000 atomic bomb survivors of Hiroshima and Nagasaki since 1950. The latest results are published as LSS-14.[23] They calculated a value defined as ERR (extra relative risk), which represents atomic bombs' effects on various illnesses the survivors died from. The illnesses include various cancers as well as a variety of non-cancerous diseases. The data obtained from this study indicate that LNT holds true down to a zero dose in the cases of various solid cancers. What's more, the ERR values are actually higher at very low doses (<0.3 mSv) than the values extrapolated from the higher dose data. This is very likely related to the issue of internal *vs.* external exposure. Indeed, no internal exposure is taken into consideration in this study, which is regarded to be the most authoritative regarding the relationship of ill effects and dosage. They refuse to incorporate the idea of internal radiation, though the dose value used in the study is the dose on a certain organ (colon rectum; it is too long to explain here how the estimate is done).

Other data have come out indicating that LNT is indeed the case. One such set of data is the effect of diagnostic x-ray radiation on cancer.[24] By the way, only cancers, particularly leukemia and thyroid gland cancer, have officially been recognized to be related to radiation. Yet, the authoritative study determined the correlation between various non-cancerous disease and radiation dose, implying that they are admitting a cause-effect relationship with regard to non-cancerous disease as well. [25]

The LNT relationship may be theorized as follows. First, the ERR is the probability that radiation's effects would be manifested. Second, such a probability will increase with more radioactive particles. The ERR is then proportional to N, the number of radioactive particles. That is, ERR = aN for some constant a. On the other hand, it was shown that Gy (Sv) = NE, where E is the energy of a radioactive particle. Therefore, ERR = (a/E)Gy; i.e., ERR is linearly related to Gy (Sv).

The assertion made by the nuclear industry that you don't to have to worry about radiation levels below 100 mSv/year is not true. Yet the industry still maintains such an assertion in order to persuade people to live under fairly contaminated conditions, such as 20 mSv/year. The way they calculate this kind of dose estimate is usually not particularly reasonable, and besides, is based on often-unreliable measurements of Sv/h, and of course does not account for the possibility of internal exposure.

There are many other unreasonable assertions and estimations promulgated by the authorities associated with the nuclear industry. Just one more example is the method to estimate the Sv value one will receive throughout an entire life once one has ingested a certain amount of radioactive substance (expressed in Bq); this is the conversion factor from Bq to Sv given by the ICRP. It is based on an arbitrary assumption called biological half-life. In other words, it is assumed that a radioactive substance will leave a human body in an exponential manner and the half-life may be determined by observations. In their calculation they use a certain value of biological half-life for each radioisotope. These assumptions make possible the estimation of the dose value in Sv from Bq. However, it has been shown in many ways that excretion of a radioisotope from living organisms does not follow such an exponential law, and hence the conversion factors they elaborately calculated are not meaningful. They used these assumptions in order to convince the laymen that their way of calculation is very scientific. Even many scientists seem to have been convinced. It is simply a deception. Besides, their Sv value is a nominal value and does not reflect the true dose in the internal exposure; actually it is always an underestimate by the order of two or three.

It might be pointed out here that the World Health Organization (WHO, a part of the United Nations) is under the control of the nuclear industry. An ultimate strategy to suppress the truth about radiation effects was to bring WHO under the influence of the nuclear industry complex. ICRP organized an unofficial gathering of all the agencies concerned: IAEA (International Atomic Energy Agency), UNSCEAR (United Nations Scientific Committee on the Effect of Atomic Radiation), WHO, UNESCO (United Nations Educational, Scientific and Cultural Organization), ILO (International Labor Organization), FAO (Food and Agricultural Organization of the United Nations), and a few others in Switzerland in 1958. In 1959 WHO made an agreement with IAEA in which WHO was required to get permission from IAEA in order to publish anything associated with radiation issues due to the nuclear industry and associated industries.

CONCLUDING REMARKS

The intention of this talk and my book was to show that radiation of high energy originating from nuclear decay is incompatible with living organisms. Most living organisms simply do not have adequate defenses against radiation, no matter how low the dose might be. They have instead some mechanisms for repairing damaged DNA, but no proper mechanisms to repair other molecules including proteins, RNA, and cellular membranes. In other words, the repairing capacity of living organisms for the damage done by radiation is quite limited. There are also indigenous chemicals that may reduce the reactivity of dangerous free radicals produced by radiation. How effective and sufficient these chemicals are against a whole variety of damaged chemical entities are not well studied, though they can be supplemented artificially.

These points, however, could not have been argued in sufficient detail in this article. Some more details are found in the book,[26] and a few diagrammatic representations of data and arguments will be found in a power point presentation of the talks given by this author at other venues.[27] It might also be pointed out that NPP is not economically advantageous, and that it is not a green technology, though often advertised so by the industry.

I would dare to say that nuclear power reactors as well as nuclear weapons have to be abolished as soon as possible, based on these arguments; it is a matter of the survival of living organisms on this planet.

APPENDIX

An atom consists of a nucleus and surrounding electrons. A nucleus is made of protons and neutrons, and the total number of protons and neutrons is called the mass number. It is expressed, for example, as Cs-137, which is a cesium isotope of mass number 137. The chemical behavior of an atom is determined by the number of protons in the nucleus. Hence, atoms with the same number of protons but possibly several different numbers of neutrons are the same element, and atoms with a different number of neutrons but the same number of protons are called isotopes. For example, the isotopes of uranium include U-233, U-235, and U-238, with 92 protons and 141, 143, and 146 neutrons, respectively.

The most familiar unit of energy is calories (cal), and the scientific standard international unit is the joule (J). We need to use a very small energy unit, the electron volt (eV) in an inquiry at the atomic-molecular level. The relationships between them are 1 cal = 4.184 J and 1 eV = 1.60218×10^{-19} J.

NOTES

1. The content of this essay is based on my recent publication, Eiichiro Ochiai, *Hiroshima to Fukushima: Biohazards of Radiation* (New York: Springer Verlag, 2013).
2. Ochiai, *Hiroshima to Fukushima*.
3. R.W. Young, S.D. Egbert, H.M. Cullings, G.D. Kerr, H.M. Cullings, and T. Imanaka, "Survivor Dosimetry," in *Reassessment of the Atomic Bomb Radiation Dosimetry for Hiroshima and Nagasaki—Dosimetry System 2002* (RERF, 2006).
4. S. Hida, talk given at the opening press conference of the Association for Citizens and Scientists Concerned about Internal Radiation Exposure (ACSIR), January 27, 2012.
5. Ibid.
6. S. Sawada, "Estimation of residual nuclear radiation effects on survivors of Hiroshima atomic bombing, from incidence of the acute radiation disease," *Bulletin of Social Medicine*, 29 (2011): 1-15.
7. J. Gould, *The Enemy Within, The High Cost of living near Nuclear Reactors* (New York, NY: Four Walls Eight Windows, 1996); J. Gould and B. Goldman, *Deadly Deceit, Low-level Radiation and High-Level Cover-up* (New York, NY: Four Walls Eight Windows, 1990).
8. S. Pflugbeil, A. Claussen, and I. Schmitz-Feuerhake, "Health Effects of Chernobyl," Gesellshaft für Strahlenschutz (2011), http://www.chernobylcongress.org/fileadmin/user_upload/pdfs/chernob_report_2011_en_web.pdf.
9. Y.I Bandazhevsky, *Medical and Biological Effects of Radiocesium Incorporated into the Human Organism* (Minsk: The Institute of Radiation Safety "BELRAD," 2000); Y.I. Bandazhevsky, "Chronic Cs-137 incorporation in children's organs," *Swiss Medical Weekly*, 133 (2003): 488-490.
10. A.V. Yablokov, V.B. Nestrenko, and A.V. Nestrenko, *Chernobyl: Consequences of the Catastrophe for People and the Environment* (Hoboken, NJ: Wiley-Blackwell, 2010).
11. Ochiai, *Hiroshima to Fukushima.*
12. It has been revealed and confirmed by a number of persons directly involved that adequate (ultrasound) instruments were not available in the USSR at the time of Chernobyl accident, and that such instruments were donated to the USSR only four to five years after the accident. Hence it may not be a fact that thyroid cancers among children started to increase only four years after the accident; it is possible that they simply could not be diagnosed in the first four years or so because of the lack of instruments.
13. Gould, *The Enemy Within*; Gould and Goldman, *Deadly Deceit.*
14. U.S. Department of Health and Human Services, Health Resources and Services Administration, http://www.hrsa.gov/gethealthcare/conditions/radiationexposure/downwinders.html; Downwinders, http://www.downwinders.info/.
15. E. Sternglass, *Secret Fallout – Low-level Radiation from Hiroshima to Three-Mile Island* (New York: McGraw-Hill Book Co., 1972, 1981).
16. Gould, *The Enemy Within;* Gould and Goldman, *Deadly Deceit.*
17. J.J. Mangano, "Geographic variation in U.S. thyroid cancer incidence, and a cluster near nuclear reactors in New Jersey, New York and Pennsylvania," *Internat. J. Health Services*, 39 (2009): 643.
18. Ibid.
19. "German KiKK Study: Higher Cancer Risc [sic] next to Atomic Power Plants & unofficial Belarussian Children Cancer data – updated." Last modified December 17, 2007, http://tekknorg.wordpress.com/2007/12/17/german-kikk-study-higher-cancer-risc-next-to-atomic-power-plants-unofficial-belarussian-children-cancer-data/; R.H. Nussbaum, "Childhood leukemia

and cancers near German reactors: significance, context, and ramifications of recent studies," *Int. J. Occup. Environ. Health*, 15 (2009): 318-323.

20. P.J. Baker and D.G. Hoel, "Meta-analysis of standardized incidence and mortality rates of childhood leukemia in proximity to nuclear facilities," *Eur. J. Cancer Care*, 16 (2007): 355-363.
21. E. Ochiai, *Chemicals for Life and Living* (New York: Springer Verlag, 2011).
22. A very noisy controversy erupted in regard to nose bleeding, which was described to be attributable to radiation to Fukushima in a manga titled "Oishinbo" in May 2014 in Japan. A review of this controversy is described here: E. Ochiai, "The Manga 'Oishinbo' Controversy: Radiation and Nose Bleeding in the Wake of 3.11," *The Asia-Pacific Journal*, Vol. 11, Issue 25, No. 4, June 23, 2014. http://japanfocus.org/-Eiichiro-Ochiai/4138.
23. K. Ozasa, Y. Shimizu, A. Suyama, F. Kasagi, M. Soda, E.J. Grant, R. Sakata, H. Sugiyama, and K. Kodama, "Studies of the mortality of atomic bomb survivors, Report 14, 1950-2003: An overview of cancer and noncancer diseases," *Radiat. Res*., 177 (2012): 229-243.
24. M.J. Eisenberg, J. Afilalo, P.R. Lawler, M. Abrahamowicz, H. Richard, and J. Pilote, "Cancer risk related to low-dose ionizing radiation from cardiac imaging in patients after acute myocardial infarction," *Can. Med. Assoc. J*., 183 (2011): 430-436.
25. Ozasa et al., "Studies of the mortality of atomic bomb survivors."
26. Ochiai, *Hiroshima to Fukushima.*
27. Vancouver Save Article 9, last modified August 10, 2014, http://vsa9.blogspot.ca.