chapter 3

Effects of Radiation on Humans

CASE STUDY CONTINUED: Francine Has More Questions

Francine had gone through various diagnostic procedures, confirming not only a neck injury involving two fractured vertebrae, but a thyroid tumour as well. Francine asked her doctor whether her neck injury had caused the tumour to grow. The doctor said that was not the case. The MRI merely picked up something that was already there before the injury occurred. Francine was lucky to have had the MRI when she did, because the tumour otherwise may not have been discovered in time to prevent metastasis (spreading to other regions of the body). The doctor told Francine that once treatment was complete, regular thyroid checkups using ultrasound (shown in *Figure 3-1*) would be necessary. Though Francine knew she would have many questions about the types of treatment available and the technology used for ongoing checkups, she first wanted more details on what effects the CT and x-ray scans would have on her for the long term. The MRI did not involve radiation, but the other two diagnostic procedures did. "What exactly was this ionizing radiation all about?" she inquired within herself.

Figure 3-1

Non-Ionizing Radiation

Any type of electromagnetic radiation that does not carry enough energy to ionize an atom is called **non-ionizing radiation**. An atom becomes ionized when it loses or gains an electron. Ionizing radiation causes a chemical change and thus causes more damage than non-ionizing radiation. Still, observable effects can be tracked from non-ionizing radiation.

Visible light, infrared light, microwaves, and radio waves are some examples of non-ionizing radiation. The light from the sun that reaches Earth is largely non-ionizing radiation, yet some ultraviolet rays (which have the ability to ionize) do reach the surface of Earth as well.

Infrared or laser light can cause burns to skin and damage to eyes, depending on the levels of energy they carry. Laser light energy levels can also be controlled to avoid skin and eye damage. Typical household laser pointers are designed to do no damage to skin. **Microwaves** carry enough energy to heat surfaces, which is why they are used in microwave ovens. Some sources say that the energy levels found near low-frequency electrical fields by power lines can cause nerves and muscles to respond erratically.

Figure 3-2

Did You Know

Many people have concerns concerns about the safety and use of commercially-available laser products. These include DVD players, smoke detectors, being near laser light shows, and laser pointers. A common fallacy is that laser light is in fact amplified sound waves, and constitutes a form of ionizing radiation that can do harm even at the cellular level of tissues. This false reasoning can result in an unwarranted fear of lasers. The better choice is to use laser light under safe, controlled conditions and that means finding out more about the physics behind laser phenomena as a good first step.

activity

SunSense

Check out the information you can get from **SunSense** provided online by the **Canadian Cancer Society**. This resource includes helpful information about "sun exposure myths". To obtain a free package for yourself (or for your whole class), go to *www.cancer.ca* and click on the tab that says "Publications." Scroll down in the list to find the SunSense link.

Figure 3-3

Cancer Connection

Ultraviolet Radiation

In Canada, sunlight is strong enough to cause premature aging of the skin and skin cancer. As the ozone layer becomes thinner due to increasing levels of pollution and chemicals, it protects us less from harmful UV rays and we are exposed to more of them. Thankfully, the production of ozone-thinning chlorofluorocarbons was banned in 1996, helping to protect the ozone layer.

There are three types of UV rays:

- Ultraviolet A rays (UVA) form most of the sun's natural light. They can penetrate deep into the skin and cause wrinkles and aging.
- Ultraviolet B rays (UVB) cause the most damage to our skin. They are the main cause of sunburns as they are nearly 1000 times stronger than UVA rays.
- Ultraviolet C rays (UVC or short-wave radiation) never reach the earth's surface: the atmosphere filters them out.

UV rays cannot be stopped by haze, fog or clouds. Water, sand, concrete and especially snow can reflect, and sometimes increase, the effect of the sun's burning rays. The head, face, neck, hands and arms are areas that are typically left uncovered. It is in these uncovered areas where most skin cancers start. Your risk of getting skin cancer increases if you have had several blistering sunburns as a child; if you regularly work, play, or exercise in the sun for extended periods of time; if you have light-coloured skin, eyes and hair; or if you take medication that makes you more sensitive to UV light (such as birth control pills).

Ionizing Radiation

The nucleus of an atom can decay or transform releasing energy in the form of either particles or waves. **Alpha decay** occurs when the nucleus of a radioactive element, such as uranium, uses the strong nuclear force to release an alpha particle. **Alpha particles** occur naturally, yet have enough energy to participate in nuclear reactions. Alpha particles are exactly the same as helium nuclei, containing two protons and two neutrons each.

When an unstable atom spontaneously decays or transforms, its nucleus releases a **beta particle** and a **neutrino**. The beta particle can be either a positively charged particle (**positron**) or a negatively charged beta particle similar to an **electron**. The neutrino released is electrically neutral. This process of beta decay occurs when the nucleus of an atom has either too many protons or too many neutrons. The weak nuclear force then causes a neutron to be converted into a proton (or vice versa) in order to become stable. In general, beta particles are a form of ionizing radiation. There are some low-energy beta particles that do not cause ionization, however.

Gamma radiation is a form of ionizing radiation, and thus produces a chemical change in the substance through which it passes. Elements with high atomic numbers such as lead have the density to be able to absorb gamma rays and prevent them from penetrating. Note, however, that attenuation coefficients can vary with atomic number. Researchers need to take into account more than just atomic number to determine whether an element will block gamma rays.

All forms of ionizing radiation can destroy or cause damage to **DNA** in cells. Large doses of ionizing radiation have been shown to cause mutations in radiation victims' descendants. Dr. David Boreham, of McMaster University, believes that low levels of ionizing radiation may help protect cells against DNA damage from other causes and help decrease cancer risk. His ideas are controversial and are based on studies done on laboratory mice. Most radiation researchers do statistical analysis of cancer victims from such catastrophic events as the Hiroshima and Nagasaki atomic bombs, the Three Mile Island disaster, and the Chernobyl

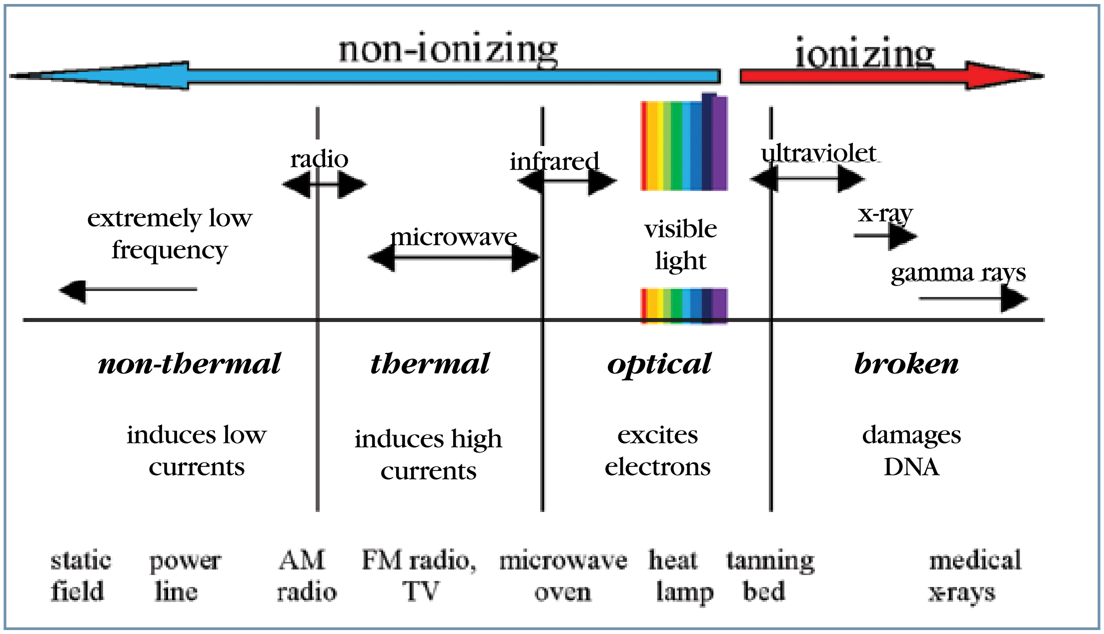

Figure 3-4
The relationship between types of radiation and the electromagnetic spectrum is shown on the chart above.

disaster. Boreham wishes to challenge the notion that sweeping conclusions can be made solely on large-scale radiation dosage statistics.

There is a way to mathematically determine the amount of **gamma radiation** a substance will absorb: the probability of absorption is proportional to the thickness of the substance. This relationship can be expressed as a formula:

Gamma Radiation Absorption Equation: $I(d) = I_0 e^{-\mu d}$

In this equation, I_0 represents the original number of gamma rays (or incident intensity), I(d) represents the number of gamma rays which do pass through a substance of thickness d (measured in cm), e is the mathematical constant 2.71828183 and μ is the linear absorption coefficient. The linear absorption coefficient is a measure of how effectively gamma radiation passes through a material, and will be a function of the kind of material used to block gamma rays. In particular, it strongly depends on the material's density. That is why lead has such a high value when compared to aluminium, and so is a good protective layer for the body in blocking the penetration and transmission of ionizing radiation.

Source: The American Physical Society. "Gamma Ray Absorption Coefficients at 6.13 MeV." Physical Review Online Archive 7 September 1954. 29 July 2008 www.prola.aps.org/abstract/PR/v96/i6/p1563_1

Substance	μ	Substance	μ
Carbon	0.0244	Cadmium	0.035
Aluminium	0.0264	Uranium	0.0459
Water	0.0284	Lead	0.436
Sodium Iodide	0.0350		

Sample Calculation:

A worker has just been irradiated with gamma rays. HazMat teams are on hand to determine whether the levels of radiation were high enough to cause long-term damage. They base their calculations on the assumption that the gamma rays carried 100 keV of energy. At this energy level, $\mu=0.1692$. If the arm muscle of the potentially injured worker is 4 cm thick, compare how much gamma radiation passes through this muscle to a situation where the worker was exposed to x-rays whose energy levels were 30 keV and thus $\mu=0.3651$.

Solution:

First scenario: $I(d) = I_0 e^{-\mu d}$
$I(d) = I_0 e^{(-0.1692x4)} = I_0 (0.5082)$

Second scenario: $I(d) = I_0 e^{-\mu d}$
$I(d) = I_0 e^{(-0.3651x4)} = I_0 (0.2321)$

0.5082/0.2321 = more than twice as much gamma radiation passes through the worker in first scenario compared to the x-radiation in second scenario.

Figure 3-5

Reality Check

Question | Does radiation have a green glow?

Origin: Comic book "logic" encourages us to believe that if you are exposed to radiation, you have a green glow and you become radioactive. Perhaps this stems from the early part of the 20th century, when green glow-in-the-dark watches contained paint that was radium-based. Factory workers who spent many months on the job licking their paintbrushes to form a tip sharp enough to paint the tiny numbers on watch faces eventually suffered from radiation-related illnesses.

Reality: The radium-based paint used for those early 20th century watches contained a phosphor (a transition metal element with glow-in-the-dark properties) that caused the green glow. Radium is both phosphorescent and radioactive, but phosphorescence is what causes the glow. Humans can only register a small portion of the electromagnetic spectrum through sight—the visible light spectrum. Radiation, in all its forms, falls nowhere near that section of the spectrum (with either wavelength or frequency). So, unless the human eye is genetically manipulated to be able to register wave interference from alpha, beta, gamma or x-rays, we will never be able to see a "radioactive glow"…green or otherwise!

Practice Questions:

1. Compare the number of non-absorbed gamma rays for a substance with a thickness of 30 cm, and absorption coefficients of 0.000025 for an energy level of 1000 keV and 0.00027 for an energy level of 120 keV.
2. If a substance that is 10 cm thick has 35 times as much gamma radiation passing through it when the rays carry 90 keV compared to 30 keV, determine the absorption coefficient for the higher energy gamma ray scenario. Assume $\mu = 0.018$ for 30 keV.

Somatic Effects

Radiation damage to living organisms is divided into two categories: somatic and genetic. **Somatic damage** by radiation is damage to any part of the body except the reproductive organs. Somatic damage directly affects the individual exposed to the radiation, and does not deal with after-effects in future generations. Skin that is damaged by excessive radiation radiation exposure may develop cancer later on. Irradiated bone marrow can cause anaemia (low red blood cell count) and therefore fatigue and muscle weakness. Poor digestion and absorption of nutrients can stem from an irradiated gastrointestinal tract. Large doses of radiation cause hair loss and dryness of skin. Over time, large doses of radiation can cause cancer and the formation of cataracts on the lenses of the eyes. The risk of developing these types of somatic damage is usually consistent with the level of exposure to radiation beyond a certain threshold amount.

Did You Know

Hiroshima and Nagasaki, Japan and WWII

On August 6, 1945, the first atomic bomb was dropped on Hiroshima, Japan by the United States. Three days later, another atomic bomb was dropped on Nagasaki. The devastation that was caused by the bombs was far-reaching. Both cities were reduced to ashes and rubble. Thousands of people were killed instantly by the blasts. Doctors who survived the blast and attempted to treat surviving victims were overwhelmed by the magnitude of the injuries. A PBS documentary titled *"The Day After Trinity"* includes interviews with the scientists who participated in the construction of the atomic weapons, and explains the nature of the widespread radiation sickness caused by these explosions.

One day after the Nagasaki bombing, photographer Yosuke Yamahata began to record the devastation in photographs. A painter and a writer traveled with him on this odyssey, recording their reactions. Fifty years after the journey began, these memories in pictures and print are displayed on the Internet for all to see and remember. It is worth your while to ponder this event in world history, and discuss it with friends.

NAGASAKI JOURNEY can be found at www.exploratorium.edu/nagasaki/index.html

Figure 3-6
Nagasaki, August 1945

Genetic Effects

Radiation that causes **genetic damage** directly damages the reproductive organs, and therefore affects any offspring that individual may have after the damage has occurred. Radiation damage is done to genes and chromosomes, which can be passed on to future generations. Studies of survivors of the Hiroshima and Nagasaki bombings and of the Chernobyl survivors in Ukraine have shown that there are increased rates of stillbirths, miscarriages, and infant deaths. If the children survive past the first few years of life, they tend to develop leukemia or microcephaly (slower cranial development), have birth defects (limbs missing, large growths), or mental impairments.

If exposure to radiation was not acute, then genetic effects may be minor or may not appear at all. However, Health Canada acknowledges that exposure to even minute doses of radiation from medical procedures such as x-rays or CT scans can have repercussions on the unborn fetus and therefore it is recommended that no procedures involving ionizing radiation be performed during pregnancy.

Cancer Warrior

www.pbs.org/wgbh/nova/cancer/program.html

Originally broadcast in February 2001, the one-hour NOVA documentary entitled "Cancer Warrior" can be viewed entirely online. The program follows **Dr. Judah Folkman** of the Children's Hospital in Boston, who spent more than 30 years researching ways to curb cancer by cutting off the blood supply to tumours. Follow the growth of a **malignant tumour** from its origin as a single cell until it becomes grape-sized. Learn about the **ground-breaking discoveries** Folkman and his research team made over the years. Though Folkman died in January of 2008, his research forms the basis for many new projects on the cutting edge of cancer research.

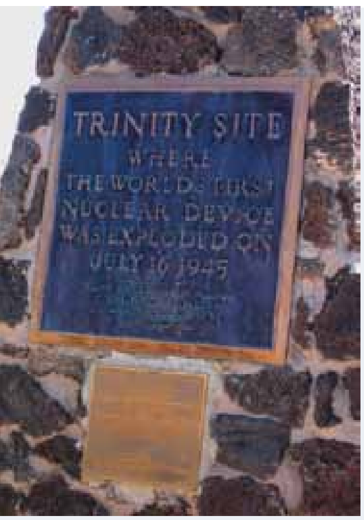

Figure 3-7
Plaque at the original atomic bomb test site in New Mexico

In The Media

"Fat Man and Little Boy" – the Winnipeg Connection

In 1989, Paramount Pictures released the movie Fat Man and Little Boy, which re-enacts the Manhattan Project. The Manhattan Project was a secret wartime initiative that the U.S. government set up (primarily at Los Alamos in New Mexico) with the purpose of creating the world's first atomic bomb. More than 6000 scientists and engineers were involved in the effort in laboratories across the United States.

One of the lead characters in the drama, Michael Merriman, is played by John Cusack. Though the movie makes no mention of it, this character is based on an actual, real-life scientist from Winnipeg. Louis Slotin, a Manitoban and one of a few Canadians participating in the Manhattan Project, was born in 1910. He obtained science degrees at the University of Manitoba, winning gold medals for both physics and chemistry.

One of his duties as part of the Los Alamos research team was to perform experiments with uranium and plutonium cores, determining their critical masses. While performing one of these experiments on May 21, 1946 (almost a full year after the bombings of Hiroshima and Nagasaki), Slotin was involved in a serious accident that occurred in his laboratory that released massive quantities of radiation into the surroundings. Others of the research team were nearby. Nine days after the accident, Slotin died of his injuries derived from a massive radiation dose. Posthumously, he was praised for his own, selfless actions that prevented the death of his colleagues. His family has set up a monetary award for researchers that use safe laboratory procedures.

The Story of Manitoba's Radiation Physicist - Louis Slotin

The Canadian Nuclear Society has an archive publication available that provides a very readable and understandable account of the scientific life and contributions of Winnipegger Dr. Louis Slotin. Thankfully, a reviewer of this site has taken the time to clear up a few errors that have surrounded the criticality incident that claimed Slotin's life.

Check it out at: www.cns-snc.ca/history/pioneers/slotin/slotin.html

Questions:

1. How accurately does the movie portray the criticality incident?
2. How accurately does the movie portray Louis Slotin?

Francine's Case Study Continued

After doing some research, Francine was reassured that though her x-ray and CT scan involved radiation exposure, there would be no long-term somatic or genetic effects. Had she been pregnant, the unborn foetus may have been affected – but her doctor would not have performed the diagnostic procedures in that case. Her next step was to obtain a biopsy of the tumour to determine whether or not it was cancerous. A surgeon would remove a small piece of it for laboratory analysis.

See Chapter 5 page 41 *for a chart of examples for both natural and synthetic (human produced) radiation.*

EXTENSION: Units of Measurement - A Historical Approach

Because ionizing radiation can cause biological damage to both the person exposed to it and to the offspring of that individual, scientists have devised ways to quantify radiation. There are three main measurement methods used: exposure, absorbed dose, and biologically equivalent dose.

Exposure measures the amount of ions produced by x-rays or gamma rays in air. It was the first radiation method to be defined, with the unit of measurement named after one of the scientists studying radiation effects. Though the roentgen (R) is still used today, the Systeme Internationale (SI) unit of measurement for exposure is defined as coulombs per kilogram (C/kg). This unit stems from the method of measurement, whereby a beam of x-rays or gamma rays is sent through a given mass (kg) of dry air at standard temperature and pressure. This beam produces positive ions with a total measurable charge (C). To convert from roentgens to coulombs per kilogram:

Exposure (in roentgens) = 2.58×10^{-4}m

In other words, 1 R = 2.58×10^{-4} C/kg

The units of measurement for exposure do not connect radiation effects to living tissue, however. For living tissue, absorbed dose is the energy absorbed from radiation per unit of mass of absorbing material (or living tissue):

$$\text{Absorbed dose} = \frac{\text{Energy absorbed}}{\text{Mass of absorbing material}}$$

The SI unit for absorbed dose is the **gray (Gy)**, which is equivalent to **joules per kilogram** (J/kg). Another unit, not part of the Systeme Internationale, is the **rad (rd)**. The word "rad" stands for radiation absorbed dose. To convert from rads to grays, 1 rad = 0.01 gray

Questions:

1. What is standard temperature and pressure? How might the amount of ionization in air due to radiation change as temperature increases? How might the amount of ionization in air due to radiation change as pressure increases?
2. In human tissue, one Roentgen of gamma radiation exposure results in about one rad of absorbed dose. Why is this number (1 rad) an approximation?

The absorbed dose unit was an improvement on the exposure units developed earlier, however researchers soon realized that the amount of damage to living tissue by ionizing radiation varied with differing forms of radiation. The absorbed dose units gave no indication of those differences. To compare damage caused by different types of radiation, the relative biological effectiveness (RBE) or quality factor (QF) is used.

The relative biological effectiveness of a specific form of radiation compares the dose of 200 keV x-rays needed to produce a certain amount of damage to the dose of the specific form of radiation needed to produce the same amount of damage:

$$\text{Relative biological effectiveness (RBE)} = \frac{\text{The dose of 200 keV x-rays that produces a certain biological effect}}{\text{The dose of radiation that produces the same iological effect}}$$

The RBE depends on the type of ionizing radiation and its energy, as well as the type of tissue being irradiated. The RBE for gamma rays and negative beta particles (electrons) is 1, whereas the RBE for protons is 10. The larger RBE value for protons indicates that more tissue damage is done than by gamma rays or beta particles. Alpha particles, protons, and neutrons all have larger RBE values than gamma rays and beta particles.

Sometimes, the RBE and the absorbed dose in rads are combined to form what is called the **biologically equivalent dose**:

$$\text{Biologically equivalent dose} = \text{Absorbed dose (in rads)} \times \text{RBE}$$

The unit of measurement for the biologically equivalent dose is the **rem**, "short for roentgen equivalent, man". Occupational radiation exposure is measured in rems. Typically, there are no observable biological effects if an individual is exposed to up to 25 rems of radiation. (Note that there are government-imposed limits on the amount of radiation workers are exposed to in the workplace – no more than 5 rem is allowable.) To gain some perspective on the rem and the millirem (1/1000th of a rem), here are some statistics: you can increase your total amount of exposure to radiation by one millirem by watching an average amount of television for one year. That is the same amount of radiation you would receive by going on a coast-to-coast flight.

The SI unit for biologically equivalent dose is the **Sievert (Sv)**. One Sievert equals 100 rem.

If exposure to radiation occurs over a period of time, then this exposure is expressed as a **dose rate**, measured in millirems per hour (mrem/hr).

Research Questions:

1. Fiestaware was a popular style of dishes in the 1960s. However, we now know that Fiestaware releases low levels of radiation. Research why, and how much radiation (in rems) is released.
2. How many rems of radiation was Switzerland exposed to when the toxic cloud of radiation blew over their country from the Chernobyl event in Ukraine?

Calculation Questions:

1. An individual is exposed to the following forms of radiation: 20 mrad of gamma rays, 35 mrad of electrons, 10 mrad of protons, and 5 mrad of slow neutrons (RBE = 2). Rank the types of radiation from highest to lowest, according to their biologically equivalent dose.

2. If an individual is exposed to two different types of radiation where the absorbed doses are the same but RBEs are different, which type of radiation—the one with the larger RBE or the smaller RBE—will cause the greater damage?

3. The typical biologically equivalent dose for a chest x-ray is 2.5×10^{-2} rem. If the mass of exposed tissue is 19 kg and the energy absorbed is 5.9×10^{-3} J, what is the RBE for this type of radiation on chest tissue? How does this compare to the RBE for gamma rays?

4. If you stand in an area where the dose rate for an unknown source of radiation is 40 mrem/hr for half an hour, what would your total dose of radiation be? If this radiation was aimed at your chest (as in question #3), with the same mass of exposed tissue and the same amount of energy absorbed, what is the RBE for this unknown source of radiation?

Units of Measurement... another approach

Imagine you are standing outside in the rain. If we were to use SI units for radiation and radioactivity and connect them to something about the rain:

- the number of dust particles that become raindrops would be comparable to exposure, measured in **coulombs per kg**
- the amount of rain hitting you would be like the a**bsorbed dose**, measured in **grays**
- how wet you get would be like the **biologically equivalent dose**, measured in **Sieverts**

CASE STUDY CONTINUED: Francine's Surgical Procedures

The surgery to remove the two bone fragments was a success. Though Francine was quite tired from the whole ordeal, she knew she was one step closer to being completely healed. The biopsy of the tumour was done while she was in surgery for the bone fragments, and she soon found out from her doctor that the results were indeed malignant (cancerous). Now she needed to discuss treatment options and potential side effects with her doctor.

Figure 3-8

Career Moves

Environmental Consultant

Career opportunities exist in any field or industry using radiation technologies—nuclear reactor energy plants, research laboratories, hospitals, and defence plants. Environmental consultants perform work for both government and industry to ensure that standards are maintained that will protect both the environment and the population. When issues like decontamination and decommissioning of reactors are required, environmental consultants are there to ensure that adequate procedures are followed with both cleanup and storage of waste materials.

Career Connection Website – Eco Canada: www.eco.ca

Figure 3-9

Chapter 3 Review: Concepts and Terms

Concepts: Electromagnetic radiation that does not carry enough energy to ionize an atom is called non-ionizing radiation. Examples of this are visible light, infrared light, microwaves, and radio waves.

When the nucleus of an atom decays, energy is released in the form of either particles or waves. Both alpha decay and beta decay release particles (alpha particles, and either positrons or beta particles, respectively). Both methods release ionizing radiation. Gamma radiation is a form of ionizing radiation that produces a chemical change in the substance through which it passes.

This chapter included mathematical extensions into how to calculate the amount of gamma radiation a substance will absorb, as well as a foray into the historical progression of units of measurement and their relationships. Somatic damage is any damage caused by radiation to the human body other than to the reproductive organs. Genetic damage is radiation damage caused to the reproductive organs.

Terms of Interest:	
absorbed dose	microcephaly
absorption coefficient (µ)	neutrino
biologically equivalent dose	non-ionizing radiation
dose rate	quality factor (QF)
gamma radiation	radiation absorbed dose (rad)
genetic damage	relative biological effectiveness (RBE)
gray (Gy)	roentgen (R)
incident intensity (I0)	roentgen equivalent, man (rem)
metastasis	sievert (Sv)
somatic damage	