Radiation Sources, Levels and Radiation Hormesis

SUPERVISED READING

Kyle Howard | PHY 473H5F | November, 20th, 2019

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Part I: What is Radiation

Radiation is everywhere, in the air, in the earth and in the stars. Radiation is the emission or transmission of energy in the form of waves or particles through space or in some material. For the purposes of this paper we will look at two forms of radiation we encounter often in everyday life, electromagnetic radiation and particle radiation.

Electromagnetic radiation is defined by subatomic particles being accelerated by an electric field causing movement, which in turn creates oscillating electric and magnetic fields which travel perpendicular to each other. The wave produced travels in a packet, a photon as seen in figure 1.1).

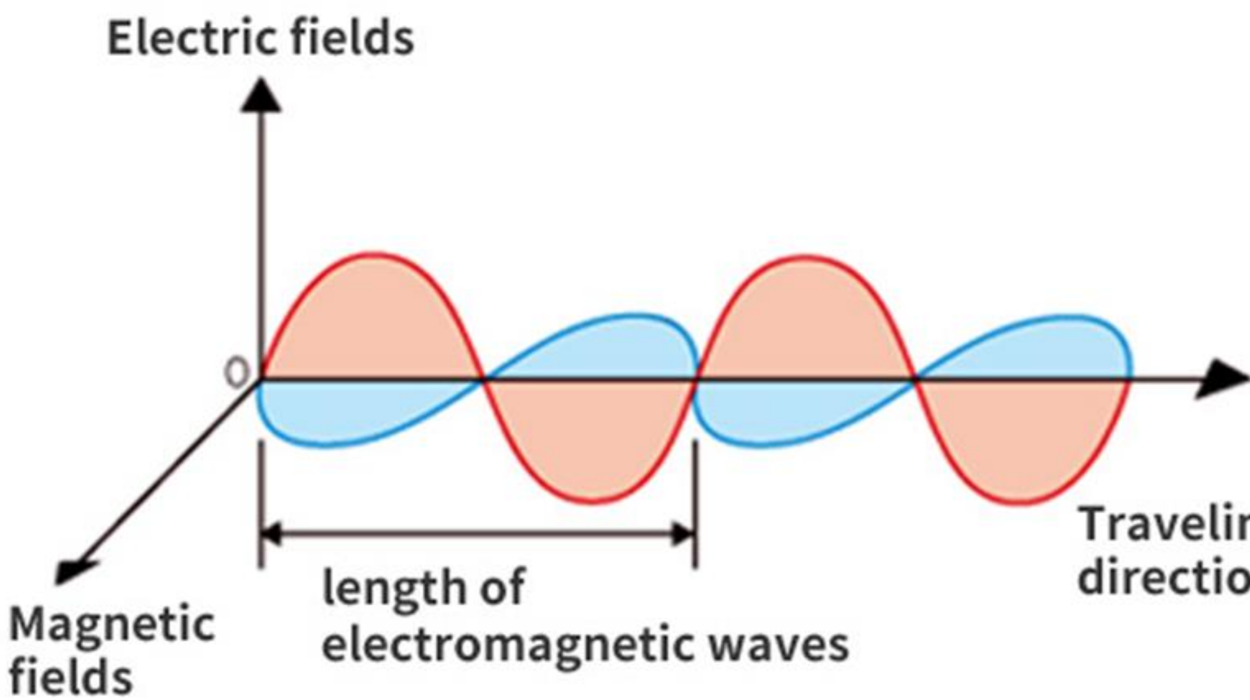


Figure 1.1) A propagating electromagnetic defined by its oscillating waves https://www.toyo-chem.com/en/products/electronics/column/emishield.html

The wavelength of a wave similar to the one in figure 1.1 is an important feature, denoted by (λ), the wavelength of an E.M wave dictates the distance between peaks. The number of peaks over a given time is known as frequency, and the resulting spectrum of frequencies creates the Electro Magnetic Spectrum (figure 1.2).

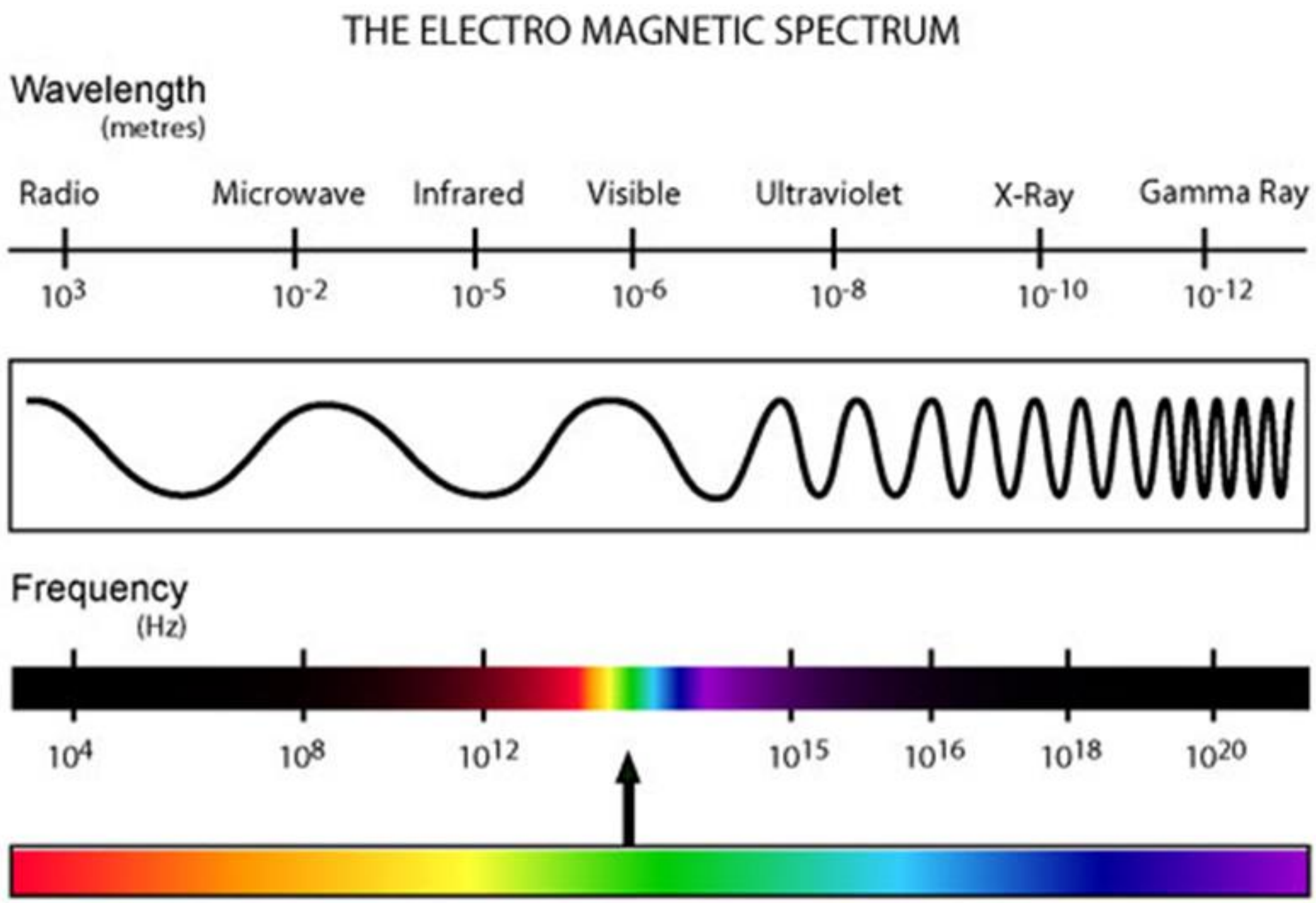


Figure 1.2) The spectrum of radiation, ranging from low energy radio waves to high energy gamma rays.
http://butane.chem.uiuc.edu/pshapley/GenChem2/A3/3.html

The lower end of the spectrum is defined by low frequency waves produced by low energy events an example of this is radio waves being produced from the earths molten core[33]. From our figure we see that an increase in frequency results in an increase of associated energy which can be potentially harmful to humans.

The second form of radiation we will look at is particle radiation. This form of radiation is produced when an unstable nucleus emits (radiates) a particle. These particles are electrically charged and come in many types, such as; protons, alpha particles, photons, neutrons and subatomic particles like mesons and muons. Particle radiation occurs in high energy events and are commonly seen in nature caused by astrological events and solar phenomenon such as solar flares. Although these events are far from home, controlled instances of particle radiation are also produced through nuclear fission to create energy within nuclear power plants[34].

The nucleus of an atom (where particle radiation is produced) is where protons and neutrons are stuck together by the Strong Nuclear Force[35]. An isotope of an atom such as Uranium is defined by the number of extra, or lack of neutrons. This creates an unstable atom that can eject a particle from its nucleus, and in doing so decays into another type of atom (figure 1.3). The time it takes for an atom to decay into its daughter atom is known as half-life.

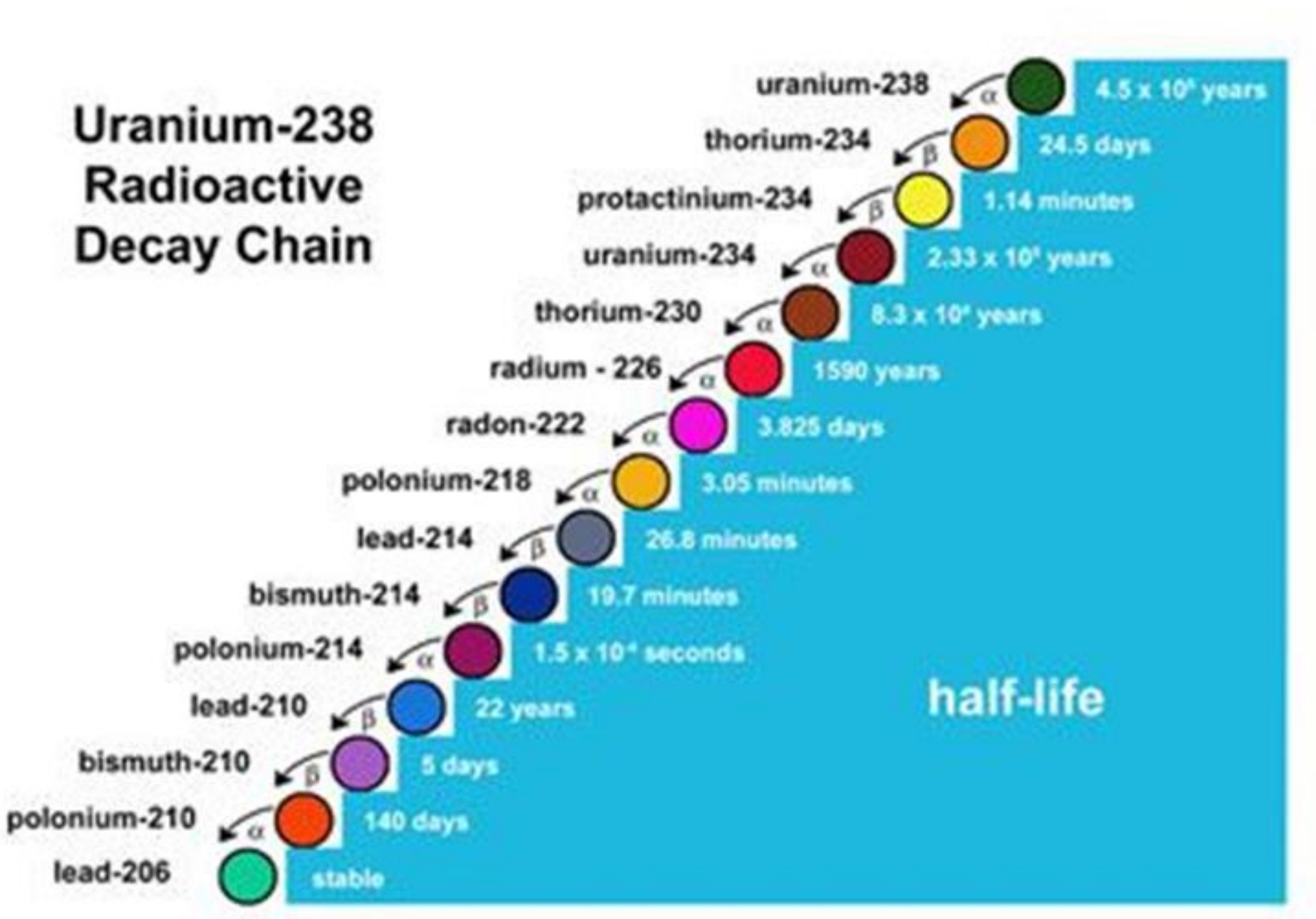


Figure 1.3) The Uranium-238 Radioactive Decay Chain. Here the parent atom is unstable and ejects a particle, decaying into a new atom. https://geoinfo.nmt.edu/resources/uranium/what.html

1.1. Non-Ionizing Radiation

Non-Ionizing radiation consists of the low frequency wavelengths found within the E.M spectrum, specifically between radio waves and ultraviolet rays[1]. These forms of radiation are commonly produced by sunlight, LED lights, low powered lasers and cell phone towers. Although Non-Ionizing radiation doesn't penetrate tissues in living organisms, it can cause skin and eye damage, the same way we get sun burns on a sunny day[2]. Typically, the higher energy the E.M wave has the more damage it can cause over a short time. The sun burn example is caused by UV or ultra violet rays that your skin can protect against in short exposures. Alternatively, radio waves never cause enough acute damage to cause serious harm.

1.2. Ionizing Radiation

Ionizing radiation is the form of radiation that carries enough energy to detach electrons from atoms or molecules, ionizing them. Common forms of ionizing radiation include x-rays and gamma rays (figure 1.2) or emitted particles like the alpha or beta particle (figure 1.4). Unstable elements which create ejected particles and emit ionizing radiation are called radionuclides. Ionizing radiation can be extremely detrimental to living tissues if enough of it is present at once or over time as it can break D.N.A chains and cause replication errors which lead to cancers[36].

Ionizing radiation is created in multiple processes as in figure 1.4 but we are more interested in the radiation sources themselves: alpha decay, beta decay, X-rays and gamma rays[4] as seen in figure 1.4.

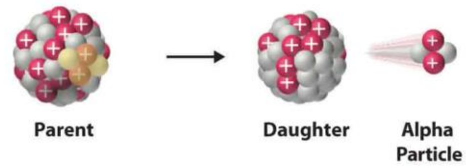
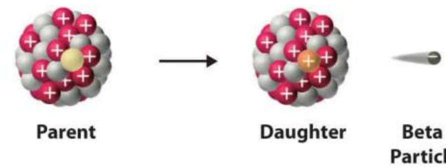
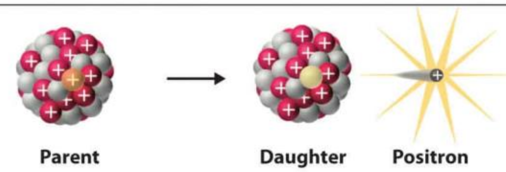
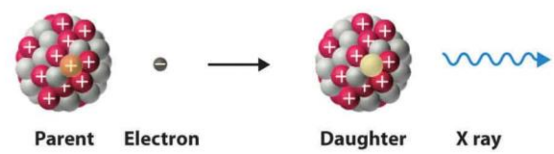
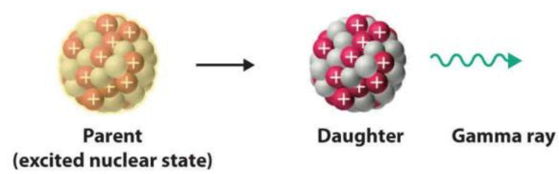
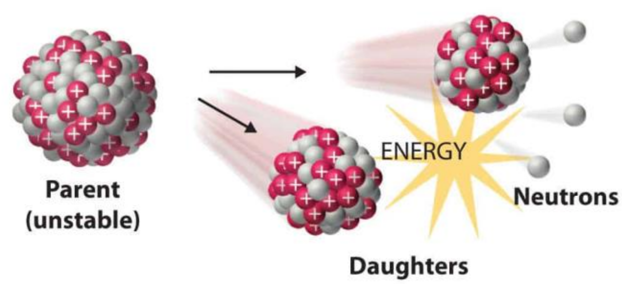
Decay Type	Radiation Emitted	Generic Equation	Model
Alpha decay	${}^{4}_{2}\alpha$	${}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}X' + {}^{4}_{2}\alpha$	
Beta decay	${}^{0}_{-1}\beta$	${}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}X' + {}^{0}_{-1}\beta$	
Positron emission	${}^{0}_{+1}\beta$	${}^{A}_{Z}X \longrightarrow {}^{A}_{Z-1}X' + {}^{0}_{+1}\beta$	
Electron capture	X rays	${}^{A}_{Z}X + {}^{0}_{-1}e \longrightarrow {}^{A}_{Z-1}X' + \text{X ray}$	
Gamma emission	${}^{0}_{0}\gamma$	${}^{A}_{Z}X^{*} \xrightarrow{\text{Relaxation}} {}^{A}_{Z}X' + {}^{0}_{0}\gamma$	
Spontaneous fission	Neutrons	${}^{A+B+C}_{Z+Y}X \longrightarrow {}^{A}_{Z}X' + {}^{B}_{Y}X' + C\,{}^{1}_{0}n$	

Figure 1.4) A table labelling ionizing radiation types, generic equations and model. The two most common types are alpha decay and beta decay. https://www.nuclear-power.net/nuclear-power/reactor-physics/atomic-nuclear-physics/radioactive-decay/

1.2.1. Alpha Decay

Alpha decay is a process that an atom will undergo to become more stable. As the alpha particle is being ejected from the parent atom, the atom will loose two protons and two neutrons (helium) which is called the Alpha particle. As the atom loses two protons the atom changes from one element to another (figure 1.3). Although the emitted particle is considered ionizing, alpha particles are not able to penetrate human skin making them less dangerous then other forms of ionizing radiation[6].

1.2.2. Beta Decay

Similar to Alpha decay, Beta decay is a process in which the atom undergoes to become more stable. Here either a neutron can transform into a proton, in the process ejecting an electron or a proton may transform into neutron ejecting a positron. In both cases the ejected particles are considered ionizing radiation and can penetrate the top layer of human skin.

1.2.3. X-rays and Gamma rays

Unlike alpha and beta decay where a particle is ejected from the nucleus, x-ray and gamma ray radiation is energy that is released from a decaying event within the particle. These energy waves are the highest energy wavelengths out there, having the ability to easily penetrate human skin and bone and many denser substances like concrete. Both emissions are created during nuclear explosions and are commonly used in medicines. This form of ionizing radiation is the most dangerous and severe, being able to penetrate skin and bones can allow these emissions to cause deep tissue damage which can lead to cancers.

1.3. Sources of Radiation

As we know radiation is everywhere and can come in different forms, some helpful and some harmful. Radiation sources can be broadly broken into natural sources and non-natural sources, both types impact our everyday lives from food to life saving medical equipment.

1.3.1. Natural Sources of Radiation

According to the Canadian Nuclear Safety Commission (CNSC)[5] and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) there are four major sources of natural radiation: cosmic radiation, terrestrial radiation and intake of radionuclides through inhalation and ingestion.

Terrestrial radiation, as its name suggests comes from the earth. Specifically, natural deposits of radioactive materials such as uranium, potassium and thorium found throughout the earth's crust emit radiation as they decay over time.

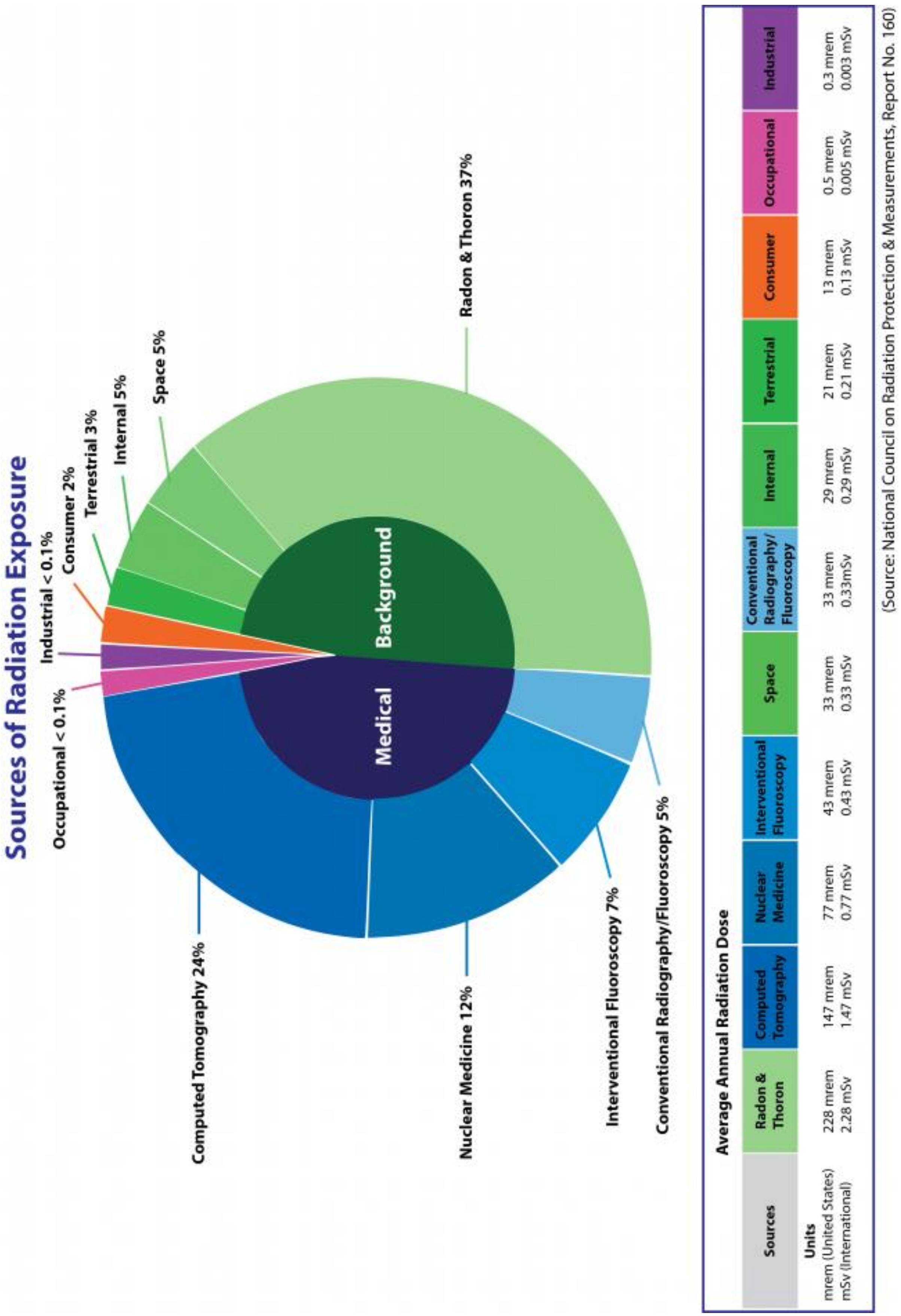
Cosmic radiation appears everywhere beyond earth's outer atmosphere. Ionizing radiation from the sun and other large-scale cosmic events such as supernova sometimes makes its way through the earth's atmosphere reaching humans, contributing to our natural radiation exposure.

Inhalation of natural radiation varies greatly depending on location. Radioactive gases such as radon and thoron are gases that will escape from the earth, are denser than air and can accumulate in stagnant areas of buildings with poor circulation. Because of this radon gas is the largest contributor to radiation exposure in humans especially if left to collect in stagnant areas over time.

Ingestion of radiation is exposure to radiation in the foods we eat and the water we drink. Potassium-40 is the main source of internal irradiation. Drinking water is especially susceptible to contamination as radionuclides from minerals are dissolved into water which people then consume[7].

1.3.2. Non-Natural Sources of Radiation

Any artificial source of radiation created by humans through various process's are considered to be artificial. Non-Natural sources of radiation account for 48 % of overall radiation doses within the United States according to EPA[8]. The largest sources of Non-Natural radiation are mostly caused by medical equipment, although industrial, occupational and consumer industries also contribute as sources.



Sources	Radon & Thoron	Computed Tomography	Nuclear Medicine	Interventional Fluoroscopy	Space	Conventional Radiography/ Fluoroscopy	Internal	Terrestrial	Consumer	Occupational	Industrial
Units mrem (United States) mSv (International)	228 mrem 2.28 mSv	147 mrem 1.47 mSv	77 mrem 0.77 mSv	43 mrem 0.43 mSv	33 mrem 0.33 mSv	33 mrem 0.33mSv	29 mrem 0.29 mSv	21 mrem 0.21 mSv	13 mrem 0.13 mSv	0.5 mrem 0.005 mSv	0.3 mrem 0.003 mSv

(Source: National Council on Radiation Protection & Measurements, Report No. 160)

Figure 1.5) This image taken from The EPA website displays Natural and Non-Natural sources of radiation and labels each source with the percentage of overall radiation contribution. The chart represents the average U.S dose and source.

The methods in which radiation is used in the medical field is vast but can be broadly split into different medical methods such as Computed Tomography, Nuclear Medicine, Interventional Fluoroscopy and Conventional Radiography/Fluoroscopy. Many of these methods can be described as radiology which use radiation to produce images of a patient's internal organs to help diagnose diseases.

Industrial sources of radiation include smoke detectors, nuclear gauges and Nuclear Power plants. Nuclear power plants often produce little radiation, most of it occurring in the form of nuclear waste which is produced after nuclear fuel rods are spent and then disposed of[34]. Very rarely a nuclear power plant can face a meltdown, a situation where the fuel rods over heat due to insufficient cooling. These meltdowns including The Fukushima Daiichi nuclear disaster, the Chernobyl disaster and the Three Mile Island accident in Pennsylvania produced massive amounts of radiation which will reside in the surrounding environment for thousands of years.

1.3.3. Background Radiation

Background radiation is a measure of the level of ionizing radiation present in the environment at a specific location in time, not due to any deliberate introduction of radiation sources. Background radiation consists of all stray radiation that is created through Natural and Non-natural processes discussed in the previous sections. Background radiation varies drastically from place to place, but to scientifically determine the amount of background radiation and the related radiation sources, the measurement of radiation must be discussed.

1.4 How Radiation is Measured

Radiation measurement is crucial to understanding radiation and associating it with a significant value for comparisons and tests. Radiation is measured using various different tools (Geiger counter, NaI Scintillation Detector, Liquid Scintillation Detector) that measure different quantities, these quantities of radiation are known as units.

1.3.4. Units of Radiation

The following table will organize and describe the various units used to measure ionizing radiation and radiation dose. Each unit has a specific use in measurements which is briefly described in the description of Table 1.1.

Table 1.1: Units of radiation and radiation dose

https://www.radiologyinfo.org/en/glossary/glossary1.cfm?gid=369

Unit	Description	Equivalent Value
Rem/ roentgen	The unit equivalent of absorbed dose of radiation while considering biological effectiveness of ionizing radiation. Rem is equivalent to dose of rad multiplied by Q (quality factor). Q changes with type of ionizing radiation.	Rem = Rad x Q
Rad (Radiation absorbed dose)	A unit of absorbed dose of radiation and a measure of amount of energy deposited in tissue.	1 Rad = 100 ergs/ gram tissue
Sievert (Sv)	A unit equivalent of absorbed dose equal to 100 rems.	1 Sv = 100 rem Sv = Gy x Q
Gray (Gy)	A unit of absorbed dose of radiation equal to 100 Rad.	1 Gy = 100 Rad
Curie (Ci)	The historical measurement of radioactivity, equal to the radioactivity of one gram of pure radium-226.	1 Ci = 37 billion dps = 37 billion Bq
Becquerels (Bq)	The standard internationally accepted unit of radioactivity equal to one disintegration per second (dps)	1 Bq = 27 pCi
Disintegrations per second (dps)	Number of subatomic particles (alpha particles) or photons (gamma rays) released from the nucleus over one second.	1 dps = 1 Bq

From Table 1 we see that units of radiation are dependent on the type of measurement being performed. Most medical studies as we will see use the Sievert and millisievert (1 / 1000 of a Sievert) as a measurement of radiation. This unit of measurement is used in a biological framework rather than a physical one and will be important in understanding how radiation effects living tissue.

Part II: Canada and Radiation

2.1 Guidelines and Regulations

All of Canada's nuclear activities are regulated by the Canadian Nuclear Safety Commission (CNSC), this includes nuclear power, nuclear research facilities and numerous nuclear materials used in medicine, uranium mines and radioactive sources from oil extraction[5]. The CNSC is a subsidiary of the Ministry of Natural Resources and reports to the Parliament of Canada.

Radiation dose limits are set through the standard guides of the International Commission on Radiological Protection (ICRP) and will also use guides from the International Atomic Energy Agency (IAEA). The ICRP is an independent non-government, international organization that creates general guidelines to follow for radiation safety. The organization was founded in 1928 during an International X-ray and Radium Protection Committee meeting in Stockholm Sweden and today is based out of Ottawa Ontario Canada. The ICRP and Canada use the Linear No-Threshold model of radiation dose-risk to assess potentially dangerous radiation levels[28] (See part 4 for more detail). The Regulation and guidelines are used to protect workers from radiation, this included medical occupations, mining occupations and nuclear power occupations.

The CNSC define Radiation Dose Limits as the following:

ALI *or* ***annual limit on intake*** *means the activity, in becquerel, of a radionuclide that will deliver an effective dose of 20 mSv during the 50-year period after the radionuclide is taken into the body of a person 18 years old or older or during the period beginning at intake and ending at age 70 after it is taken into the body of a person less than 18 years old. (LAI ou limite annuelle d'incorporation)[29]*

The guidelines are used to ensure that workers and members of the public are not exposed to more then a given amount of radiation which can be seen in table 2.1.

Table 2.1) Taken from the CNSC website[29]

For context the CNSC which follows the guidelines of the ICRP suggest that per year a member of the public should only be exposed to 1 mSv annually.

	Column 1	Column 2	Column 3
Item	Person	Period	Effective Dose (mSv)
1	Nuclear energy worker, including a pregnant nuclear energy worker	(a) One-year dosimetry period	50
		(b) Five-year	100
2	Pregnant nuclear energy worker	Balance of the pregnancy	4
3	A person who is not a nuclear energy worker	One calendar year	1

2.2 Canadian Levels of Radiation and Exposure

Radiation levels and exposure can fluctuate from location to location, many of these variables were covered in part 1. Primarily the differences in radiation are caused by inhalation of radioactive materials such as radon, nuclear materials that occur naturally in the environment and altitude. Altitude plays a factor in background radiation as higher locations have less atmosphere to block incoming cosmic rays and increase background radiation[38]. Areas of noticeably high levels of radiation are Ramsar Iran, Guarapari Brazil and Karunagappalli India[30]. For example, in Ramsar the naturally occurring limestone in the area which is often used as a building materials is moderately radioactive. This results in an external dose of 6 mSv per year, which is six times higher than the ICRP recommended limit exposure for the public[31]. The CNSC has several official definitions for Radiation dosage and defines a radiation dose as:

"When ionizing radiation penetrates the human body or an object, it deposits energy. The energy absorbed from exposure to radiation is called a dose. Radiation dose quantities are described in three ways: absorbed, equivalent, and effective."[32]

The CNSC considers the total dose of background radiation to be a cumulative of the following sources: cosmic radiation, terrestrial radiation, doses from inhalation and doses from ingestion. The following table 2.2 is taken from the official CNSC website and displays radiation data form location across Canada

Table 2.2) Taken from the CNSC website[29]

Sources and Average Effective Dose from Natural Background Radiation in Selected Canadian Cities

Canadian City	Total (mSv/y)	Cosmic radiation (mSv/y)	Terrestrial background (mSv/y)	Annual inhalation dose (mSv/y)	Radionuclides in the body (mSv/y)
CANADA	1.8	0.3	0.2	0.9	0.3
Charlottetown	1.8	0.3	0.2	0.9	0.3
Edmonton	2.4	0.5	0.3	1.3	0.3
Fredericton	1.8	0.3	0.3	0.9	0.3
Halifax	2.5	0.3	0.3	1.5	0.3
Iqualuit	1.9	0.5	0.2	0.9	0.3
Montreal	1.6	0.4	0.3	0.7	0.3
Ottawa	1.8	0.4	0.2	0.9	0.3
Québec City	1.6	0.4	0.2	0.7	0.3
Regina	3.5	0.4	0.3	2.4	0.3
St-John's	1.6	0.4	0.2	0.7	0.3
Toronto	1.6	0.4	0.2	0.8	0.3
Vancouver	1.3	0.5	0.1	0.4	0.3
Victoria	1.8	0.5	0.1	0.9	0.3
Whitehorse	1.9	0.5	0.2	0.9	0.3
Winnipeg	4.1	0.4	0.2	3.2	0.3
Yellowknife	3.1	0.4	1.4	0.9	0.3
Sources: Gratsky et al., 2004, UNSCEAR 2008, Geological Survey of Canada					

As briefly discussed at the beginning of this section, background radiation varies greatly from location to location based on environmental and human activities. From table 2.2 Winnipeg has the highest total background radiation of all other locations in Canada, this is attributed to annual inhalation of radioactive fumes, such as radon gas. An article from the Winnipeg Free Press reported that in 2010 seven percent of homes had radon levels over the national guideline of 200 becquerels, having levels between 200 and 600 becquerels. Similar trends can be seen from other locations in Canada where annual inhalation accounts for most of the total annual dose of background radiation.

Canada's background radiation levels are slightly below the worldwide dose average of 2.4 mSv per year, totaling in around 1.77 mSv per year.

Aside from background exposures to radiation deses from artificial sources are present as well. CNSC claims that commercial and industrial sources of radiation account for 0.6 mSv of our annual radiation exposure and X-rays and other medical instruments account for another 1.2 mSv per year. Consumer products such as tobacco and smoke detectors contribute another 0.1 mSv of radiation exposure per year.

In total natural background radiation accounts for nearly 60% of the Canadian annual dose for radiation. It is important to note that the effects caused by natural or man-made radiation have no difference as both are the same form of radiation.

Part III: Radiation Exposure and The Dose Response Model

Radiation was not always associated with its ability to cause severe illnesses in humans. It wasn't until 1927 that Hermann Joseph Meller published research suggesting ionizing radiation impacted genetic health and caused an increase in cancer risks. However, by the time these effects were understood many publicly available radioactive substances had entered the market. It was Marie Curie who protested many of these therapies, unfortunately it was in 1934 that Marie Curie died of aplastic anemia, a condition believed to be caused by long-term radiation exposure[10].

It has been over 80 years since the death of Marie Curie since then modern medicine and physics has led to a better understanding of the effects of radiation on the human body and the creation of the radiation dose response model. To understand this dose-risk relationship of radiation on humans we must look to see how the human body reacts to high doses of ionizing radiation and why a model describing the effects of low dose radiation is necessary.

3.1 High Dose Radiation Exposure

The effects of high dose radiation exposure are well understood, especially in comparison to the effects of low dose radiation. High dose radiation is a dose potent enough to lead to physical illness and tissue damage such as Acute Radiation Syndrome[11], cancers and skin damage. Typically, illness's such as these are not only dependent on dose but length of exposure to the dose as well.

3.1.1 Acute Radiation Syndrome

Acute radiation syndrome (ARS) is an acute illness caused by a high dose of ionizing radiation administered over a short period (usually minutes). People who have suffered from ARS include victims of the Hiroshima and Nagasaki atomic bombs and the first responders of the Chernobyl power plant incident in 1986. According to the Centers for Disease Control and Prevention there are required conditions for ARS, they are the following.

- Radiation dose must be large (greater than 0.7 Gy or 70 rads)
    - Mild symptoms can appear at 0.3 Gy or 30 rads

- Dose is usually external
    - Radioactive materials within the body have rarely cause ARS
- The radiation is penetrating (Ionizing)
    - This includes X-rays, Gamma rays and emitted neutrons
- The dose is administered over the entire body or most of it
- The dose is delivered over a short time

There are many symptoms and stages that are associated with ARS but the main syndromes are as follow.

- Bone Marrow Syndrome (exposure ~0.7 Gy).
    - The penetrating radiation causes bone marrow damage and possible hemorrhaging. Survival rate decreases with associated dose.
- Gastrointestinal Syndrome (exposure ~10 Gy).
    - The amount of radiation causes destructive changes to the gastrointestinal tract and bone marrow which causes infection and dehydration. Risk of death is high and can occur two weeks after dose.
- Cardiovascular Syndrome (exposure ~50 Gy).
    - The cardiovascular system begins to shut down and pressure within the cranial vault increases from the influx of fluid content caused by edema and meningitis.

Associated to these symptoms are the stages of which the syndromes begin to appear in a patient.

- Prodromal Stage
    - Nausea, vomiting and diarrhea occur minutes to days after exposure.
- Latent Stage
    - A patient will feel fine and look healthy for a few hours or days.
- Manifest Illness Stage
    - Symptoms depending on the radiation dose appear and last from hours to months
- Recovery or Death
    - Depending on the initial dose recovery can take from a few weeks to several years

3.1.2 Cancers

Cancer is the name that refers to a collection of diseases that generally refer to the abnormal and unstoppable dividing of cells in the body[12]. Typically, when the human body needs cells, that cell will divide to create a cell and when that cell becomes old or damaged it will die. When a cancer develops this process begins to break and old and damaged cells will continue to live and new cells will be created when they are not needed. These extra cells can continue to divide and form tumors that become malignant, which means they can invade normal surrounding cells and can be transported throughout the body through the lymph system or blood. There are risk factors that can contribute to the likelihood of a cancer starting in the body, these factors include Tobacco use, alcohol use, diet and in the interest of this report radiation.

Sources of radiation linked to causes in cancer include Radon, Medical application, Occupational and Accidental. This excerpt from '*Cancer is a Preventable Disease that Requires Major Lifestyle Changes*' published by *Preetha Anand, Ajaikumar B. Kunnumakara, Chitra Sundaram et, al* describe the sources as such:

"Cancers induced by radiation include some types of leukemia, lymphoma, thyroid cancers, skin cancers, sarcomas, lung and breast carcinomas. One of the best examples of increased risk of cancer after exposure to radiation is the increased incidence of total malignancies observed in Sweden after exposure to radioactive fallout from the Chernobyl nuclear power plant. Radon and radon decay products in the home and/or at workplaces (such as mines) are the most common sources of exposure to ionizing radiation. The presence of radioactive nuclei from radon, radium, and uranium was found to increase the risk of gastric cancer in rats. Another source of radiation exposure is x-rays used in medical settings for diagnostic or therapeutic purposes. In fact, the risk of breast cancer from x-rays is highest among girls exposed to chest irradiation at puberty, a time of intense breast development. Other factors associated with radiation-induced cancers in humans are patient age and physiological state, synergistic interactions between radiation and carcinogens, and genetic susceptibility toward radiation." (Preetha Anand, Ajaikumar B. Kunnumakara, et al, 2008)

Although radiative sources of cancer are estimated to account for only 10% of all cancer sources, these are sources not freely controllable by the individual.

The mechanisms that allow cancer to begin in the body are stochastic, meaning the probability of a cancer occurring increases with the dose of radiation. The form of cancer, where it originates and the speed at which it spreads are not functions of radiation. This relationship is the opposite of ARS which increases in severity and fatality the larger the dose. Cancer will begin with one cell that is damaged by ionizing radiation, specifically from the DNA of that cell. The DNA that is affected by the radiation is completely random, some strands can repair themselves before replication errors are made but others are not so lucky[14]. The damage caused to DNA which is believed to be the leading source of cancer in cells is known as the double-strand breaks (DSB). These DSB remove the ability to regulate gene expressions of the cell and cause replication errors, the rate of DSB was measured to be 35 DSB per Gy[15]. Luckily cells can repair these breaks before replication can occur but 25% of these breaks go unfixed. Highly damaged cells usually end up with the cell dying or being unable to replicate, these effects associated are associated to ARS. It is lighter radiation exposure that leaves the cell just damaged enough to reproduce that results in a cancer. These 'lighter' levels of radiation will be discussed more thoroughly in section 4.

3.2 The Linear no-threshold Model

As we talked about in the previous section high doses of radiation can be destructive to living organisms and ARS can cause serious and permeant damage over short periods of time, these biological effects happen in the high exposure area of radiation. It appears as the dose of radiation decreases so too do the stochastic probabilities of contracting a cancer as less cells are damaged and fewer DSB occur within the effected cells. Figure 3.1 presents The Linear no-threshold (LNT) model of predicting cancer incidence to relative dose.

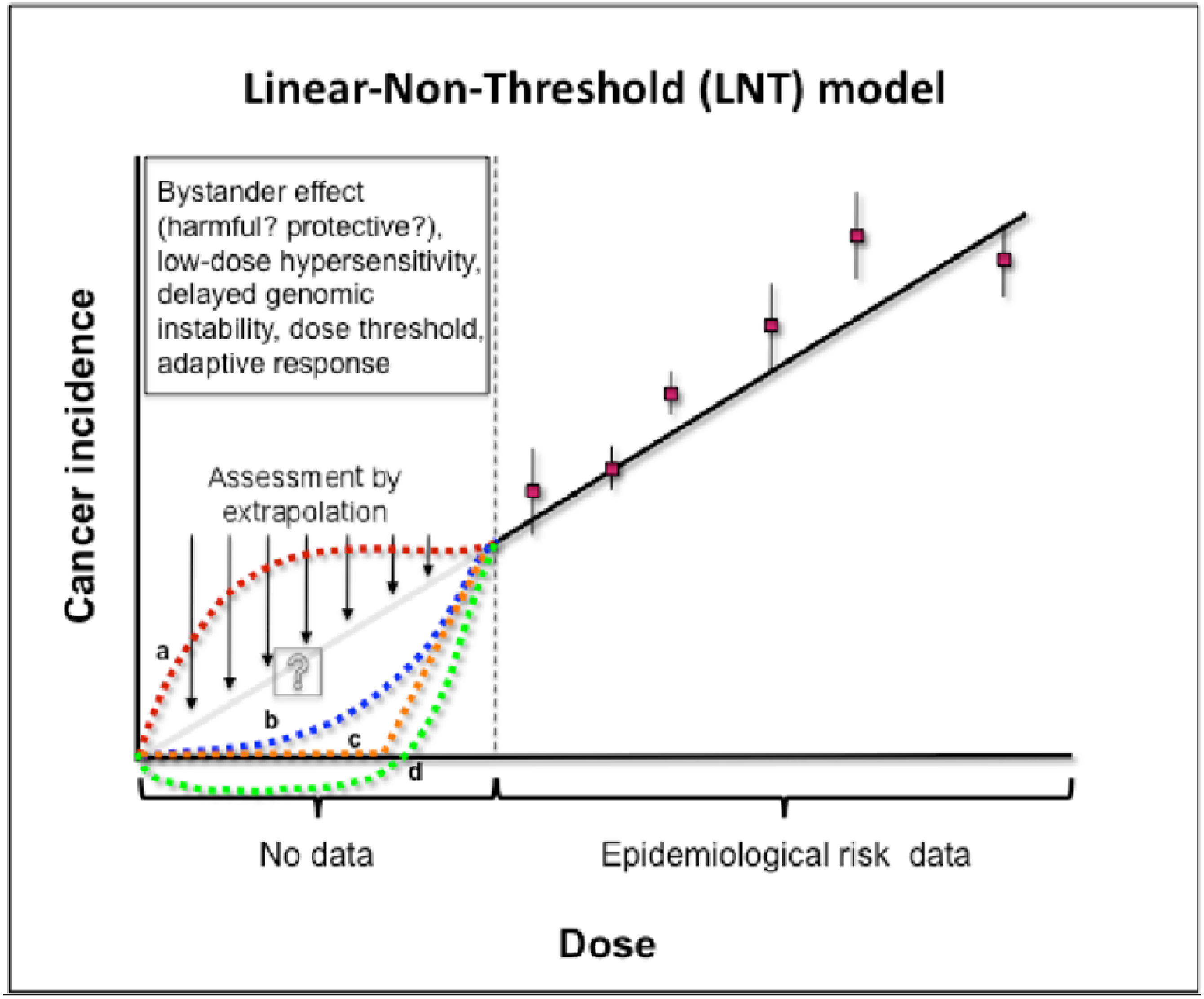


Figure 3.1) The y-axis represents cancer incidence; the x-axis represents relative does. Red points are taken from epidemiological data points. The no data region of this graph are where projected models of this curve are predicted. They are in order; A: supra-linearity, B: linear quadratic, C: dose threshold and D: Hormesis. https://www.researchgate.net/figure/Fig-3-Linear-Non-Threshold-LNT-model-and-uncertainties-in-extrapolation-of_fig3_221902556

The atomic bombings of Nagasaki and Hiroshima were the first time in history that nuclear weapons were used, the two bombings resulted in 120,000 deaths. Many more would succumb to radiation sickness related deaths in the coming weeks and a whole generation would be plagued with radiation related cancers[16]. The living population is the single largest data pool of individuals exposed to roughly the same amount of ionizing radiation at the same time. The result gave scientists and doctors the ability to work with a large enough data set to produce a model that predicts cancer risks to the ionizing radiation received. This is what led to the creation of the LNT. Even more data was used to further increase the legitimacy of the model after the 1986 Chernobyl incident where some 200,000 people were immediately and many more in surrounding countries were affected[17]. The LNT model suggests that at any incremental dose of radiation, even background radiation has some chance of causing cancer within the individual. The LNT model is accepted by the International Commission of Radiological Protection and regulators around the world as the guide to reference for human radiation exposure[18]. Also bound to this model is that many small exposures to radiation is equivalent to one larger dose of equal dose value. Because of its epidemiological supported data at the high dose range, the LNT model is used to determine low dose stochastic health outcomes by extrapolation and not scientifically proven data. This has essentially led to a research gap and the rise of alternate scientific models that challenge the LNT, the most important and interesting of which is the Radiation Hormesis Hypothesis.

Part IV: Radiation Hormesis

4.1 The Low Dose Region and Other Models

As we discussed in the last section, the effects of high dose radiation on humans is well understood through the data available on individuals that have been exposed by high levels of ionizing radiation. The LNT model uses these data points to extrapolate data into the lower dose region of radiation. This creates a linear trend line, where dose of radiation is proportional to the risk of contracting a cancer. This linear trend suggests a few things, namely that if an individual's exposure to radiation is zero, so too is their chance contracting a cancer. Also, that any minuet exposure to radiation will have an associated chance of cancer risk. In figure 4.1 we see some proposed models that claim to represent the dose response curves of potential cancer risks. It is important to note that all the suggested models begin and end in the same place, suggesting zero radiation has no impact on cancer formation. At higher doses all models converge into the LNT model.

It is difficult to measure the relationship between cancer risk and radiation dose at such low levels (notably the 10 mSv and below range) since these are levels of radiation that are just above background radiation, are variable in everyday life and effect everyone. As mentioned before since radiation is accountable for only 10% of cancer cases, this small window of low dose radiation can easily be misinterpreted by another more likely cause of the cancer. Being able to discern the cause of cancer has proven to be difficult as the exact cause of many cancers cannot be pinpointed by a single event. The baseline cancer rate is already high and the risk of developing cancer can fluctuate up to 40% due to individual life styles[21] . Since radiation exposure is variable due to environmental differences, it is difficult to isolate low dose exposure events, this is important to note moving forward as all the low dose models are conjectures based of extrapolations of data, making this research gap in particular, highly controversial.

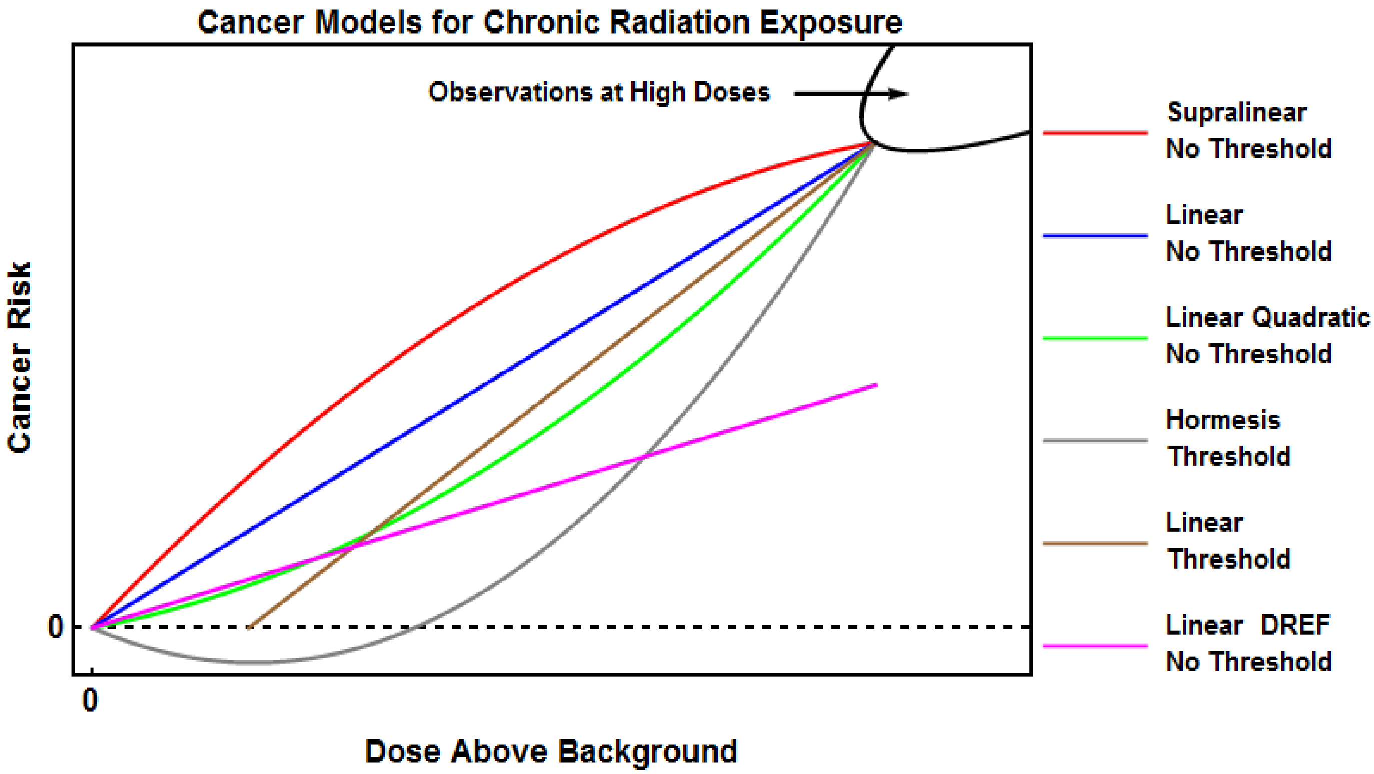


Figure 4.1) A closer look at the suggested models of low dose radiation exposure compared to relative cancer risk. The most important models are in blue: LNT, Red: Supralinear and Gray: Hormesis. https://en.wikipedia.org/wiki/Linear_no-threshold_model

Not much is known about the Supralinear no threshold model, what can be taken from figure 4.1 is that it suggests that at low doses of radiation, risk of cancer increases, with an inflection point somewhere between no radiation dose and high radiation dose. From what can be found in the scientific community neither the LNT model or hormesis agrees with the Supralinear model. This model does however conform to the anti-nuclear movement beliefs that all radiation has a negative impact on humans, possibly making this model more of a political statement rather than a scientific one.

The extrapolated LNT method is currently what is accepted in the scientific community and the model used by organizations to determine risk factors of radiation on humans. Of all the models the LNT model seems to be the most conservative in its display of potential risk factor. It also is the simplest and arguably most intuitive explanation for the dose to risk function. This model also proves to be the safest in practice, considering all levels of radiation to be dangerous, suggesting anyone who is exposed to any levels of radiation should be properly protected. Politically some believe that this interpretation is still a harsh exaggeration of the effects of low dose radiation.

The Linear Quadratic no-threshold model is a more liberal interpretation of the dose response curve, from figure 4.1 the curve in green represents the Quadratic LNT model. The model is defined by a quadratic function, something of the form $F(D)=\alpha\cdot D+\beta\cdot D^2$ where (D) is the dose and (α, β) are determined by human exposure data. This model does not go with out its flaws, as it has been suggested that this model does not 1) accurately explain observed data, 2) was derived from in vitro experiments opposed to in vivo experiments, 3) does not consider radioresistant cells such as stem cell response and 4) creates a simplified model not representative of the truth[19].

These models have something to offer while explaining the dose response curve of radiation exposure to cancer risk, but the most controversial and supported model is Radiation Hormesis.

4.2 What is Radiation Hormesis

Radiation hormesis is the hypothesis that low doses of ionizing radiation not only have a zero-risk chance associated to cancer risk but are beneficial in stimulations multiple process in the cell that reduce cancer risk. This is an impressive statement to make, to understand what this looks like, let us look back to figure 4.1, the gray line (Hormesis Threshold) has a concave shape associated to it. The section of this model that dips below the zero-cancer risk line is known as hormesis. The term hormesis is used in other fields of research as well, it is typically used to refer to an adaptive response of cells and organisms to a moderate (usually intermittent) stress[20]. This adaptive response is positive and numerous in mechanisms. This has an interesting feature, namely that these hormesis effects are only present when ionizing radiation is introduced into the model similar to the medical benefits that vaccinations provide.

4.3 Cellular Effects of Radiation Hormesis

If radiation hormesis is to be believed, then the effects of low dose radiation far out way the negative cancer risk effects shown by other low radiation dose models. Using L. E Feinendegen's 2005 paper on The Evidence for beneficial low-level radiation effects and radiation hormesis as a guide, we will look at the scientific benefits of radiation hormesis and how, if this model is correct, can revolutionize how we view radiation and our understanding of the physiological effects of radiation on humans. (The following section has many medical and biological terms, if you are unfamiliar with these terms check the glossary where definitions can be found.)

4.3.1 Damage Prevention

Depending on the cell type, after irradiation detoxification of reactive oxygen species (ROS) begins within the cell. ROS are a reactive molecule type that is created when a cell is hit with ionizing radiation, these ROS can damage DNA, RNA and proteins and can lead to cell death[22]. This process has been seen to promote enzyme activities in mice that can lead to higher cell defenses preventing damage in the future.

4.3.2 Damage Repair

Protection against high radiation dose induced chromosomal alteration increased after cells were conditioned by low dose low linear energy transfer (LET) radiation and lasted for 3 days. This protection was also provided against other DNA damaging agents. The exposed cells received 30% less damage compared to the non-conditioned cells and varied between cell types. This adaptive damage repair response was seen to enhance DNA repair rate in human fibroblasts when conditioned within a 1 mGy to 500 mGy range.

4.3.3 Damage Removal by Apoptosis

Apoptosis is a form of programmed cell death that occurs in organisms, a process that may be induced after high dose irradiation through a process of intracellular and intercellular signaling. Low dose induced apoptosis can allow pre-damaged cells to be replaced with new healthy living cells. Tests done on rat cells show that the induction of apoptosis requires a certain level of existing DNA damage, which can be caused by irradiation.

4.3.4 Stimulation of Immune Response

Little is known of the stimulated immune response, but it is suggested that the removal of damaged cells induced a strengthened immune response and a reduction in cancer metastases to less than one third of the control group. Low doses of 0.2 Gy triggered these response mechanisms.

4.3.5 Reduction of Carcinogenesis

Protective responses within cells may initiate a reduction in spontaneously occulting cancer cells. When tested on mice cells the single low LET dose of radiation significantly delayed the appearance of cancer cells appearing later in life. Although a protective mechanism may be present it also appears that their may be a threshold case where these cancers only arise after a minimal dose is reached. In either case the introduced dose indicates either a threshold or a reduced rate in cancers forming.

4.3.6 Low dose Induced Changes in Gene Expression

All the previous described mechanisms were able to occur through the process of induced change in gene expression. When human skin fibroblasts were exposed to 20 mGy of radiation, more than 100 genes changed their expression within 2 hours of the dose. The gene group included stress responses and were completely different then parallel cultures that were exposed to much higher doses of radiation suggesting the low doses of radiation give way to uniquely different changes in gene expressions.

4.4 Radiation Hormesis Vs. The LNT Model

Radiation hormesis stands in stark contrast to the current and widely accepted LNT model of the dose to risk response relationship. If the mechanisms of radiation hormesis are to be believed, then cultural and political views on radiation would be changed entirely. Hormesis suggests that low dose radiation is beneficial to the body which is contradictory to the LNT model that suggests any amount of radiation has an associated risk to cancer. If radiation hormesis is accepted by the scientific community, it could give way to complete reform of current radiation exposure legislation and ultimately improve public opinion of radiation. To consider radiation hormesis as a legitimate model we will compare it to the current mainstream LNT model and discuss the pros and cons of both.

4.4.1 Positives of The LNT Model

The LNT model was constructed the atomic bomb survivor cancer mortality data which is reputable and has a large sample size, good things to have when creating a model. Although the low dose regain of the LNT model is largely extrapolated, it does fall in line with the higher region trend. Policy makers have adopted this idea, creating safety regulations based of the idea that any amount of radiation can cause cancer. This 'rather safe then sorry' approach does benefit radiation workers as it creates stricter radiation safety laws that will protect people regardless of exposure level.

4.4.2 Drawbacks of the LNT Model

Controversy does surround the LNT model dating back to 1946 where some believe the creator of the model Hermann Joseph Muller ignored an early study that did not support the LNT model[23]. Afterall the low dose region is extrapolated data, which can be a pro in terms of flushing the model out but cannot be assumed to be true scientifically. It is also suggested that the LNT model was chosen as a model at a time when the world had rightful fears of radiation, following the 1986 Chernobyl accident the LNT model was used to justify that children during this time would be born with higher rates of health defects[24]. Following the accident studies looked at millions of birth data from EUROCAT and determined no significant impacts due to the Chernobyl incident were found[25]. By the early 2000's more articles were starting to come out that challenged the LNT model and its legitimacy [26][27] suggesting that its inarguable high radiation dose model was not so easily extrapolated into the lower dose regions.

4.4.3 Positives of Radiation Hormesis

As more studies in the medical community are conducted on low dose exposure to radiation, more evidence is seen to be in favor of the hormesis model. Some analysis of the atomic bomb survivor mortality rate no longer support the LNT hypothesis but is now becoming more consistent with the radiation hormesis model, which suggests that low dose levels of radiation (< 100 mSv) can produce beneficial effects like those discussed in section 4.3. Radiation hormesis coincides with the belief that human evolution has been assisted through radiation opposed to being hindering by it. Since cosmic radiation has been present since the beginning of the universe radiation hormesis could be the explanation many have been looking for to explain evolutionary functions in biology. The data used to express the hermetic curve may not be as abundant as the data used to create the dose-risk relation at higher radiation doses, but the data collected is specific and well documented unlike the LNT low dose model. This can also be used to ease public fears of radiation which could spearhead new legislation that would allow more work to be done with nuclear technology such as the implementation of new nuclear power facilitates.

4.4.4 Drawbacks of Radiation Hormesis

Radiation hormesis is very difficult to prove in humans as the effects of low ionizing radiation levels are too small to be measured against normal cancer rates. Many organizations consider this model to be unproven and lack enough supporting data. This model is a considerable risk to take if not fully understood as many nuclear workers and even the general public could suffer if it is discovered low levels of ionizing radiation are connected to cancer risks especially over long periods of time. Many of the experiments that claim to have observed hormesis have done so in a lab environment and it is not yet known if hormesis can occur outside the laboratory or in human cells.

Part V: The Future of Radiation Hormesis and Conclusions

Radiation hormesis and its promise of medical benefits have the potential to revolutionize the medical field and change the public perspective of radiation and its effect on humans. New methods of therapy could create new pathways for treating and preventing radiation caused cancers and provide massive insights to human cell biology. Changing the perception of low-level radiation exposure would eliminate stigmas that have plagued the nuclear industry for decades and could usher in a new era of nuclear industry and new-found support in nuclear energy.

As of now radiation hormesis continues to gain interest in the scientific community to close the low-level radiation exposure research gap. The current research being done in hormesis is largely based on animal cells in a hermetic lab environment. As hormesis continues to be explored the next step is to begin conducting tests in human cells, this will prove to be a difficult task to over come as many regulations are in place that prevent human testing. If human testing can be achieved in the near future, then more data can be curated to provide evidence to whether or not radiation hormesis truly exists. Until then radiation hormesis is a promising but unproven hypothesis that has the potential to change everything.

Appendix

Feinendegen, L. E. (2005). Evidence for beneficial low-level radiation effects and radiation hormesis. *The British journal of radiology*, *78*(925), 3-7.

This paper by L E Feinendegen analyze the effects caused to cellular DNA at the low dose spectrum of radiation absorption. Findings from the paper show that damage done to DNA is primarily from non-radiation sources and double stand breaks (DSB) occur 1000 times higher due to endogenous process compared to radiogenic ones. Feinendegen claims that the probability of adaptive cell protection out weighs that from the damage caused to cells at the >200 mGy low linear energy transfer (LET) irradiation. In short, the list of adaptive properties includes damage prevention, damage repair, damage removal through apoptosis, stimulation of immune response, protection and cell cycle, reduction in carcinogenesis and low-dose induced changes in gene expression. At higher absorbed doses DNA damage apoptosis and terminal cell differentiation continue to function where as the other properties do not. The linear-dose-risk function appears to be invalid and should include both a linear and non-linear trend in the low-dose spectrum.

Luckey, T. D. (1980). *Hormesis with ionizing radiation* (p. 222). Boca Raton: CRC press.

The paper *Hormesis with ionizing radiation* is a hypothesis formed by T. D Luckey. In this paper Gerald .A Shlapper reviews the piece and examines its plausibility. Hormesis with ionizing radiation is the positive stimulation of an organism's response through low-level dosages of ionizing radiation. This openly denies the linear extrapolation of known harmful doses of radiation to zero. Examples are presented that indicate ionizing radiation may be essential to life but lack convincing evidence. Difficulties with radiation are discussed the fact that exposures showing radiation as a harmful agent are 10 to 10^4 times greater than any of those used in studies of radiation stimulation and the technical issues of measuring radiation and low levels. Most of the data arguing the positive effects of low dose radiation is from plants although some are gathered from vertebrates. Luckey makes the point that many areas of study have not looked at low dose leaving a research gap. The paper lacks data on higher forms of vertebrate species and lacks statistical analysis. Since this paper is a review of another paper it is difficult to find real data in the form of experimental and research data. Since the review goes into detail of the structure of the paper it has been beneficial to understanding how the conversation for Radiation hormesis should be formatted for my personal paper.

Scott, B. R. (2008). It's time for a new low-dose-radiation risk assessment paradigm—one that acknowledges hormesis. *Dose-Response*, *6*(4), dose-response.

The paper by B . R. Scott looks at the current linear-no-threshold (LNT) risk assessment protection protocol and speculates that the LNT method should adopt a nonlinear hormetic risk curve. Scott discusses the inaccuracies of the LNT model such as the low-dose and dose-rate effective factor (DDREF) that when implemented dismisses the possibility of a hormesis effect. With hormesis, low doses of radiation protect against cancer, leading to a negative slope in the low-dose region for the dose-response curve. High doses, however, inhibit protection causing risk to then increase as dose increases. This yields what has often been called a U- or J-shaped dose-response curve. Classes of radiation-associated hormesis are discussed such as Radiation conditioning hormesis (small dose or mild dose over time activate protective process that suppress damages from large doses), Radiation hormesis (A small radiation dose or a moderate dose given at a low rate activates protective processes and reduces the level of biological harm to below the spontaneous level.) and Radiation post-exposure conditioning hormesis (large dose radiation is reduced as a result of subsequent small radiations dose). Tricks that favour LNT is discussed such as dose lagging (reducing dose to account for lost dosage), eliminating the hormetic zone via averaging over dose groups and constraining the slope of the cancer risk dose response curve to be always positive. In summary there is abundant information related to radiation associated hormesis but dismissal based on epidemiological tricks alter expected results.

Vaiserman, A. M. (2010). Radiation hormesis: historical perspective and implications for low-dose cancer risk assessment. *Dose-Response*, *8*(2), dose-response.

After introducing a historical introduction of the development of radiation hormesis Vaiserman introduces the LNT model of radiation carcinogenesis, the model which cancer risk increases linearly with radiation dose increase. This model is the standard model for determining radiation risk in humans. The slope change at low doses and dose rates is typically implemented using the DDREF or dose and dose rate effectiveness factor which does not account for hormetic responses. Using retrospective radiologist's cancer mortality study, nuclear workers study, diagnostic x-ray examinations, radio therapy, background radiation studies and Japanese atomic bomb survivors' study Vaiserman concludes that the LNT model does not accurately represent the relationship between carcinogenesis and radiation dosages. Furthermore, low doses and dose rates of radiation may be of benefit rather than detriment.

Hooker, A. M., Bhat, M., Day, T. K., Lane, J. M., Swinburne, S. J., Morley, A. A., & Sykes, P. J. (2004). The linear no-threshold model does not hold for low-dose ionizing radiation. *Radiation research*, *162*(4), 447-452.

The paper published by Hooker et. Al argues that the LNT hypothesis does not accurately depict changes in biology at low levels of radiation dosage. To emphasise this, they examined chromosomal changed in mice caused by ionizing radiation. Looking at the chromosomal changes in DNA is a good tell to see if damage was done by the radiation. Mice were exposed to radiation doses as small as 1 μGy and observed three responses. (1) Inductions of inversions were found at ultra low doses, (2) a reduction below endogenous inversion frequency at low doses and (3) an induction of inversions again at higher doses. These results do not fit the LNT hypothesis. Although the drawbacks of the study are that doses were acutely given, and the lack of human testing may still not give clear understanding to the hormesis effect in larger mammals.

Doss, M. (2013). Linear no-threshold model vs. radiation hormesis. *Dose-response*, *11*(4), dose-response.

The atomic bomb survivor cancer mortality data has been used to justify the LNT model for estimating carcinogenic effects at low dosage of radiation. An updated analysis of the atomic bomb survivor mortality rate no longer supports the LNT hypothesis but is now becoming more consistent with the radiation hormesis model. Evidence of radiation hormesis is looked at through atomic bomb survivor data where the shape of the dose-response curve is significantly non linear. More over significant reduction in cancer mortality rates in the dose range of 0.3Gy to 0.7Gy were found. Although it would be against modern day radiation safety standards which are founded upon the LNT hypothesis it may be beneficial to test radiation hormesis as an alternative for reducing cancers. Major changes would need to take place to test radiation hormesis on humans such as (1) recognition of the importance of adaptive response by advisory committees and reversal of their current recommendations to use the LNT model for radiation safety, (2) changes in the governments' radiation safety regulations recognizing adaptive response, and (3) allaying of concerns among the scientists and the public regarding low dose radiation through increased dissemination of information on the invalidity of the LNT model and the evidence for radiation hormesis. Low dose radiation may improve outcomes in cancer patients by cure of early stage cancers and to reduce second instances of cancers.

Key Words Glossary

- **Acute Radiation Syndrome (ARS)**
  - an acute illness caused by irradiation of the entire body (or most of the body) by a high dose of penetrating radiation in a very short period of time.
- **Alpha particles**
  - Particles consisting of two protons and two neutrons tightly bound together. They are emitted from the nucleus of some radionuclides during a form of radioactive decay.
- **Apoptosis**
  - The death of cells which occurs as a normal and controlled part of an organism's growth or development.
- **Canadian Nuclear Safety Commission (CNSC)**
  - The Canadian Nuclear Safety Commission is the federal regulator of nuclear power and materials in Canada.
- **Cancer**
  - A group of diseases involving abnormal cell growth with the potential to invade or spread to other parts of the body. These contrast with benign tumors, which do not spread.
- **Cancer Metastasis**
  - The spread of cancer cells to new areas of the body, often by way of the lymph system or bloodstream. A metastatic cancer, or metastatic tumor, is one that has spread from the primary site of origin, or where it started, into different areas of the body.
- **Carcinogenesis**
  - The initiation of Cancer Formation.
- **Cosmic Radiation**
  - High-energy protons and atomic nuclei which move through space at nearly the speed of light.
- **DNA**
  - Deoxyribonucleic acid is a molecule composed of two chains that coil around each other to form a double helix carrying genetic instructions for the development, functioning, growth and reproduction of all known organisms.
- **Dose Risk Relationship**
  - The relationship between radiation exposure and the relative risk of contracting a cancer, often presented as a plot of Risk Vs Dose.

- **Double Strand Break**
    - A strand break in DNA which is a result to DNA being exposed to radiation. Can cause genetic mutations.
- **Electromagnetic Radiation**
    - Radiation including visible light, radio waves, gamma rays, and X-rays, in which electric and magnetic fields vary simultaneously.
- **Enzymes**
    - Biological molecules (typically proteins) that significantly speed up the rate of virtually all chemical reactions that take place within cells. They are vital for life and serve a wide range of important functions in the body, such as aiding in digestion and metabolism
- **EUROCAT**
    - A European organization that describes itself as "a network of population-based registries for the epidemiological surveillance of congenital anomalies, covering 1.5 million births in 20 countries of Europe."
- **Fibroblasts**
    - A type of biological cell that synthesizes the extracellular matrix and collagen, produces the structural framework (stroma) for animal tissues, and plays a critical role in wound healing. Fibroblasts are the most common cells of connective tissue in animals.
- **Gene Expression**
    - The process by which information from a gene is used in the synthesis of a functional gene product. These products are often proteins, but in non-protein coding genes such as transfer RNA (tRNA) or small nuclear RNA (snRNA) genes, the product is a functional RNA.
- **Hormesis**
    - Any process in a cell or organism that exhibits a medically positive response to exposure of an amount of a substance or condition. Within the hormetic zone, there is generally a favorable biological response to low exposures to toxins and other stressors.
- **In Vitro**
    - In vitro (meaning: in the glass) studies are performed with microorganisms, cells, or biological molecules outside their normal biological context.

- **In Vivo**
  - Studies that are in vivo are those in which the effects of various biological entities are tested on whole, living organisms or cells, usually animals, including humans, and plants, as opposed to a tissue extract or dead organism.
- **Isotope**
  - Isotopes are variants of an element which differ in neutron number, and consequently in nucleon number. All isotopes of a given element have the same number of protons but different numbers of neutrons in each atom.
- **Linear Energy Transfer**
  - The amount of energy that an ionizing particle transfers to the material traversed per unit distance. It describes the action of radiation into matter. It is identical to the retarding force acting on a charged ionizing particle travelling through the matter.
- **Linear No Threshold Model**
  - The dose response model in which the risk of inducing a cancer in an irradiated tissue by low doses of radiation is proportional to the dose to that tissue
- **Lymph System**
  - A network of tissues and organs that help rid the body of toxins, waste and other unwanted materials. The primary function of the lymphatic system is to transport lymph, a fluid containing infection-fighting white blood cells, throughout the body.
- **Neutrons**
  - A sub-atomic particle with no net electrostatic charge, with a very similar mass to a proton. Neutrons are present in almost all atomic nuclei except for Hydrogen.
- **Photons**
  - A tiny particle that comprises waves of electromagnetic radiation and are electric fields traveling through space. Photons have no charge, no resting mass, and travel at the speed of light.
- **Proteins**
  - Proteins are large size molecules (macromolecules), polymers of structural units called amino acids.
- **Protons**
  - A subatomic particle with a positive charge found in the atomic nucleus.

- **Radiation**
  - The emission of energy as electromagnetic waves or as moving subatomic particles, especially high-energy particles which cause ionization.
- **Radiology**
  - The medical discipline that uses medical imaging to diagnose and treat diseases within the bodies of both humans and animals.
- **Radionuclides**
  - A radionuclide is an atom that has excess nuclear energy, making it unstable. This excess energy can be used in one of three ways: emitted from the nucleus as gamma radiation; transferred to one of its electrons to release it as a conversion electron; or used to create and emit a new particle from the nucleus.
- **Reactive Oxygen Species**
  - Reactive oxygen species are chemically reactive chemical species containing oxygen. Examples include peroxides, superoxide, hydroxyl radical, singlet oxygen, and alpha-oxygen.
- **RNA**
  - Ribonucleic acid (RNA) is a polymeric molecule essential in various biological roles in coding, decoding, regulation and expression of genes.
- **Strong Nuclear Force**
  - One of the four known fundamental interactions, with the others being electromagnetism, the weak interaction, and gravitation. It is responsible for holding most ordinary matter together through binding neutrons and protons together within the nucleus.
- **Terrestrial Radiation**
  - Long wave electromagnetic radiation emitted by naturally radioactive materials on Earth including uranium, thorium, and radon.

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