X-Rays, CT and MIBI Scans: Ionizing Radiation and Health

Definitions:

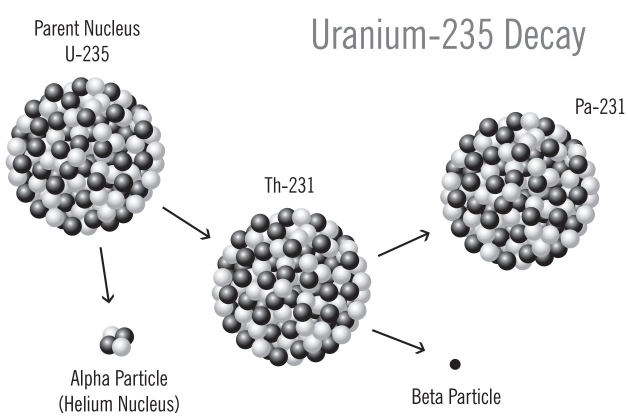
Radiation: is "the transfer of energy as electromagnetic waves or as moving particles" (*Oxford English Dictionary).*

Ionizing Radiation: radiation that has enough energy to dislodge electrons from atoms and molecules to form ions and free radicals, for example: x-rays, radioactive imaging. Examples of non-ionizing radiation include light, radio waves, microwaves, heat, electromagnetic waves of cell phones and Wi-Fi networks.

Isotopes are different kinds of atoms of the same element – just as German shepherds and collies are different breeds of the same thing, dogs. Isotopes possess the same number of protons but differ in the number of neutrons in the nucleus.

Radioisotopes are radioactive isotopes. They change into different elements or isotopes by emitting radioactivity in the form of gamma rays, beta particles or alpha particles.

Radioactive Decay: the process whereby a radioisotope gives off energy and/or particles and becomes a different element. If the new element is also radioactive, it, too, will change into a third element. A series of these changes is called a *decay chain.* A commonly medical radioisotope, technetium-99m, has a two step decay chain from Tc-99m to Tc-99 and then to stable ruthenium-99.



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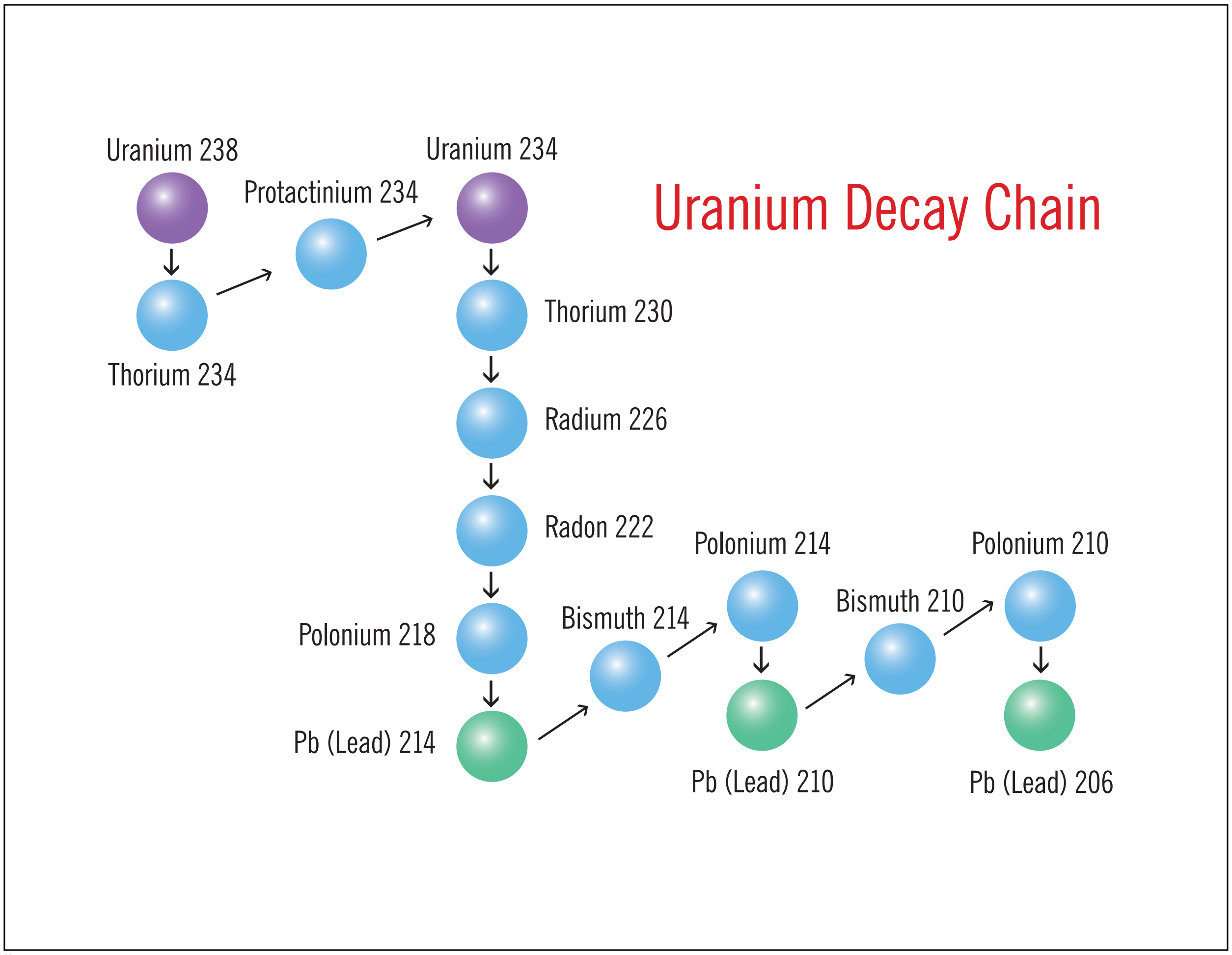
Above: First two steps of a long decay chain for U-235   Source: Michael Webb, Alchemy Design

Uranium-238 ("depleted uranium" called so only because it has no value in nuclear power plants or nuclear weapons, unlike its fissionable isotope, uranium-235) undergoes a 14 step decay chain before reaching stable lead-206.



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Half-life: The length of time taken for one half of the radioactivity in a sample of an element to dissipate. In effect, this could mean that half of the sample has become another element. For example, the half-life of caesium-131, used in radiopharmaceuticals, is 10 days so after ten days one half of the caesium has become xenon-131. Ten half-lives, 100 days, results in only 1/1024 of the original caesium-131.

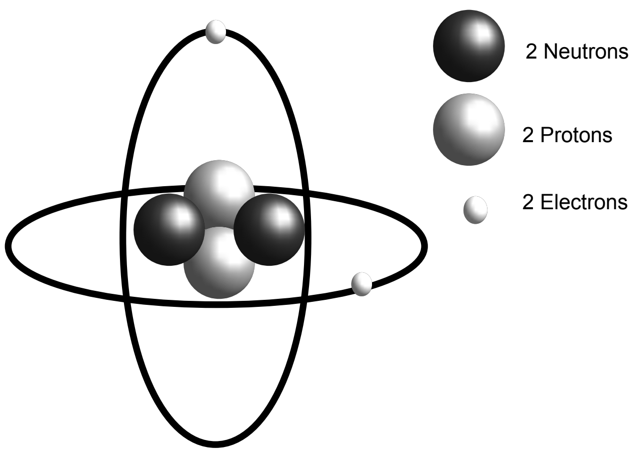
Radiopharmaceuticals: this term covers a range of drugs, chemicals or elements that are chemically bound to radioisotopes. When used for a medical examination, a radiopharmaceutical may be referred to as a *tracer*. As the ultimate "designer drugs", they are designed to be absorbed by specific cells or organs in the body and may be introduced by injection, inhalation, or ingestion. The optimum radioisotope is short-lived, delivers high energy to a specific target and decays to a stable product. For example: in the use for treatment of hyperthyroidism or thyroid cancer, iodine-131 delivers high energy beta radiation to the thyroid and decays with a half-life of eight days to stable xenon-131. Virtually none of its energy is absorbed by other cells in the body.

X-rays are short high-energy waves that are released in the form of excess energy when an electrically produced electron collides with, or has its path altered by a tungsten target. The process of production is highly controlled. Modern machines are very focussed with little scatter.

Gamma rays are very similar to x-rays in that they are also short high-energy waves. They are given off by radioisotopes during the process of radioactive decay. Radiopharmaceuticals make use of gamma radiation because the gamma-emitting substance concentrates in organs or blood and can affect photographic film.

Beta particles are electrons emitted from the nucleus of an atom during decay – as a neutron changes to a proton, it emits an electron. They have poor penetrating energy but are more dangerous when inhaled or ingested. Tritium, the radioactive form of hydrogen found naturally in extremely small amounts is a common gaseous release from nuclear power plants. It decays by beta emission.

Alpha particles: are equivalent to the nucleus of a helium atom – two protons and two neutrons. They are slow-moving and easily stopped by skin. They are considered 20x more biologically damaging than either gamma rays or beta particles when taken internally. Uranium-238 and radium-226 decay by alpha particle emission to thorium-234 and radon-222 respectively.



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Electron capture: an electron from an atom's circulating electrons is pulled into the nucleus. Gamma rays are released as a proton in the nucleus becomes a neutron; the atom becomes the next lower element in the periodic table. Palladium-103 is one such radioisotope sometimes used for prostate cancer. Its decay product is stable rhodium-103.

History:

In 1895, x-rays were discovered by Wilhelm Conrad Roentgen, a professor of physics in Bavaria, when he was experimenting with electrons. He made the first x-ray immortalizing his wife's hand and her wedding ring. Physicians were quick to jump on the bandwagon of a technology that would differentiate bones from soft tissue. The first x-ray department was opened a year later in Glascow, Scotland. It was inevitable that the first side-effects were reported; in the same year, an Austrian doctor reported that he had severely burned a patient's back.

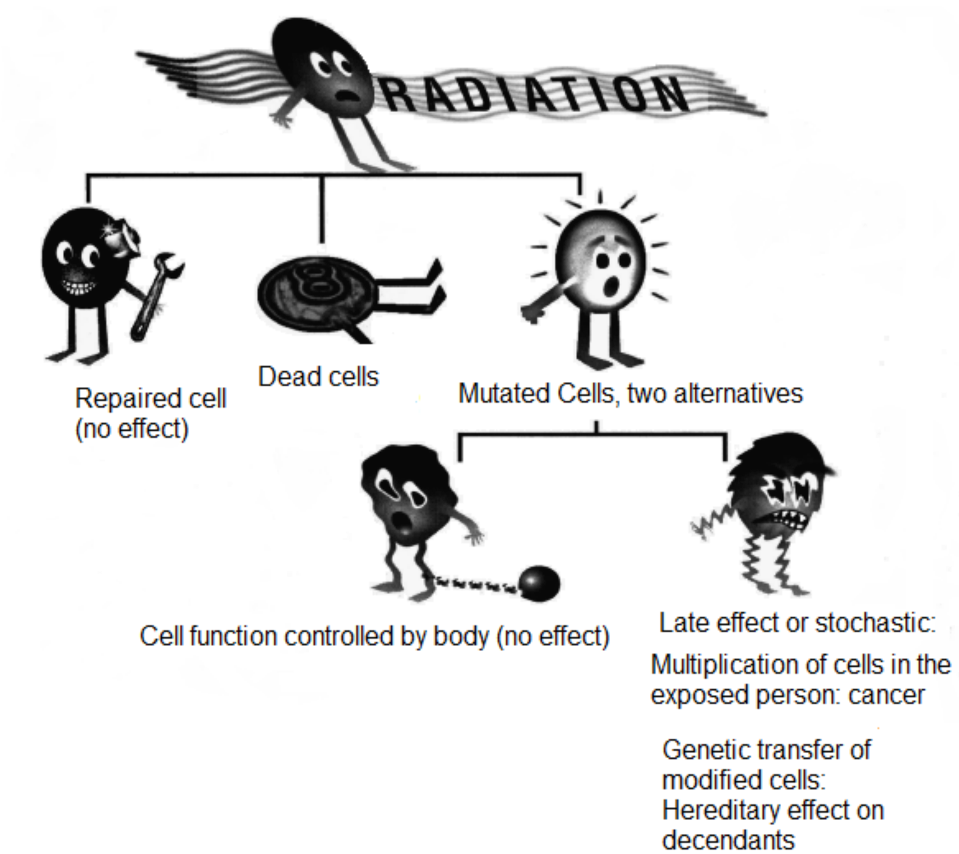
A meeting of the International Congress of Medical Electrology (electricity had only recently been discovered as well) and Radiology was held in 1902 to discuss the usefulness of these two modalities and their side effects. Dr. William Rollens, a dentist who had burned his hands using x-rays on patients experimented with guinea pigs to draw up a list of precautions for their use. It included recommendations governing the distance from the x-ray tube, the shielding of parts of the body of no interest to the purpose of the x-ray and the protection of the technician. It would be decades before shielding and protection for workers would become common practice.

By 1905, the known side-effect of reddened skin was called "radiation dermatitis", burns that healed poorly or not at all. In 1934, the first regulations governing exposure were established as "tolerance levels" – if reddening of the skin didn't occur, exposure was below the tolerance level. In 1936, a monument was erected in Hamburg, Germany to commemorate the thousands of people and hundreds of medical staff who had perished as a result of x-ray exposure. However, the medical profession was so enamoured with the diagnostic tool that, after decades of mishaps including damage done to victims on the battlefield, it took the work of two researchers, Dr. Alice Stewart in the UK in the 1950's and Dr. Rosalie Bertell in the USA in the 1960's to change their unquestioning acquiescence in ordering chest x-rays. These two researchers, one a family physician, the other an epidemiologist, established the link between a single chest x-ray on a woman in pregnancy and an increased risk of leukemia in the offspring. In the mid-1970's patient shielding became standard practice and x-rays during pregnancy severely limited.

Radiotherapy was used as early as 1896 when a medical student in Chicago reported using x-rays to reduce the size of a cancerous nodule of the breast. Fifteen years of trial and error – many seriously injured patients and use of radiotherapy for everything from hypertrichosis to plantar's warts and cancerous tumours – passed before an Austrian physician suggested that using fractionated doses over several days would result in less tissue damage. By 1922, this was common practice. The production of cobalt-60 in cyclotrons made it widely available in the 1950's, replacing x-rays and radium-226 for tumours.. Even so, while the patients were often cured, the side effects were lifelong scarring and erosive dermatitis.

Effects of ionizing radiation on a cell:

Exposure of a cell to ionizing radiation (x-rays, etc) usually results in damage that can be repaired by the cell but a cell can also be killed or changed (mutated). The path of a single x-ray through a body can be followed by following the ions formed. The mutated cells may have no effect upon the body but they may also have been damaged so that they become cancerous. DNA, RNA and mitochondrial function may be altered to affect development of eggs and sperm and passed on to future generations.



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Medical uses of radioactivity:

1) External:
   a) X-rays – machine generated ionizing radiation.
   b) CT (CAT) scans – Computerized (or "computed") axial tomography is a series of x-rays taken at different levels through a body part like slices of bread and computer-manipulated to form a three dimensional image.
   c) External radiotherapy – radiotherapy is generated by linear accelerators that focus high-energy x-rays at tumours preferentially destroying cancer cells. Older units targeted tumours with gamma rays from cobalt-60 but were limited by the energy that could be generated. They continue to be used in low-resource settings.

2) Internal:
   a) Scanning materials and devices:
      i) Gallium scans – The earliest and most widely applied radiopharmaceutical was a gallium-67 salt (citrate or nitrate) making use of a short half-life of 3.26 days and ease of production in a cyclotron. As it decays to zinc-67, it emits gamma rays which were picked up by photographic film before the advent of gamma cameras and computers. Gallium behaves like ferric iron and concentrates in areas of inflammation. It has mostly been supplanted by other tracers but the fact that it can be absorbed by both dead and alive white blood cells

gives it special value in identifying places where they accumulate such as lymphomas, osteomyelitis and abscesses.

ii) PET scans – Positron emission tomography scans show how the body works. A simple gamma camera detects gamma rays and a computer generates a three-dimensional image in contrasted colours. The most commonly used radioisotope is fluorine-18 with a half-life of 1.83 hours produced in cyclotrons close to the hospitals. It decays to stable oxygen-18. The ease with which fluorine can be bound to sugar molecules makes it useful to examine places where rapid metabolism occurs.

iii) SPECT scans – Single photon emission computed tomography scans use moving gamma cameras in order to provide the three-dimensional image. The image is less specific but cheaper to produce. For intracranial examination, technetium-99m is attached to exametazime, a molecule that crosses the blood-brain barrier.

iv) MIBI scans using the radioisotope technetium-99m have special use in parathyroid and heart scans. MIBI is short for methoxyisobutylisonitrile which is picked up by actively metabolizing mitochondria. Two scans are usually performed, an early scan and one after a "wash-out" period.

v) MUGA scans: Multi-gated acquisition scans also involve the use of technetium-99m in this case attached to a pertechnetate ion which binds to red blood cells. Typically sixteen images are taken using the contractions of the heart to trigger (gate) the pictures.

b) Brachytherapy – (from Greek "brachys" meaning "short distance") the radioactive source is implanted directly into or close to the tumour itself. Ideal elements for brachytherapy deliver a high dose in a short period of time minimizing the effect upon healthy cells. The first implantable radiotherapeutic materials were alpha particle emitters like radium-226.

i) Permanent brachytherapy: small "seeds" of the radioactive element are placed into the tumour - Iridium-192 which decays by strong gamma and beta emission is commonly used for prostate cancer but other elements, caesium-131, iodine-125 and palladium-46 have also been used.

ii) Temporary brachytherapy: The radiopharmaceutical is delivered by catheter, needle or applicator inserted into the body cavity or interstitially. Doseages may be high, low or delivered intermittently. Iridium-192 (which decays by electron capture to platinum-192) is a radioisotope frequently used.

Putting Ionizing Radiation Exposure in Perspective[v]:

We are often asked about the effect of various tests or interventions on the human body:

Airport passenger scan	0.0001 mSv
Hand or foot x-ray (single view)	0.005 mSv
Watching TV (4 hrs / day)	0.01 mSv/yr

Bitewing dental x-ray	0.03 mSv
Air travel (round trip Toronto, ON to Vancouver, BC)	0.05 mSv
Chest x-ray (one film)	0.1 mSv
Nuclear medicine thyroid scan	0.14 mSv
Dental Panoramic	0.15 mSv
Pelvic x-ray	0.7 mSv
Mammogram (four views)	0.7 mSv
Thoracic spine x-ray	1.0 mSv
Lumbar spine x-Ray	1.5 mSv
Nuclear medicine lung scan	2.0 mSv
Background radiation (Average Cdn)	2.5 mSv
Nuclear medicine bone scan	4.2 mSv
Nuclear cardiac diagnostic test	10 mSv
Abdominal CT scan	10 mSv
PET studies (average)	14 mSv
Smoking 20 cigarettes/day	53 mSv/yr

The consensus of the Biological Effects of Ionizing Radiation VII (BEIR VII)[vi] was that no level of radiation is safe and that the risk of cancer, auto-immune diseases, teratogenesis and genetic alterations increases with dose.

Hazards/Concerns about Ionizing Radioactivity:

When the ionizing radiation of x-rays or gamma rays pass through a body, no radioactivity remains in the body but a trail of damaged structural proteins, enzymes and nucleic acids mark their passage. The damage done is cumulative, the probability of genetic defects, cancers, and life-shortening effects increases over a person's lifetime. By and large, the greatest body burden of ionizing radiation for North Americans is the result of medical diagnostic or therapeutic uses. The exact contribution of the hundreds of above ground nuclear tests, nuclear power plant planned or accidental releases of radioactivity, and wastes and tailing exposures is unknown.

Radiotherapy has its risks. Although the intention is to avoid irradiation of healthy cells, some will inevitably be exposed to radiation. The possibility exists that one of these cells will mutate and lead to a secondary cancer. One study estimated that 8% of secondary cancers are caused by radiotherapy.[vii] This is very difficult to calculate because the same risks present for the first cancer may still exist (for example, smoking) and will vary with amounts of radiation exposure, parts of the body exposed and the age of the patient. In 2011, researchers at McGill reviewed more than eighty thousand patient charts and concluded that the risk of cancer from low-dose imaging techniques increased 3% for every 10 mSv of radiation received.[viii]

A further concern is the variety of decay products from radioisotopes used in radiopharmaceuticals. Although the tracers may decay rapidly to a stable element, their progeny may not. While fluorine-18 used in cardiac imaging decays to oxygen-18 which is stable, technetium-99m decays to technetium-99 which is also radioactive and has a half-life of 211,000 years.

Finally, the science of nuclear fission was shrouded in secrecy through the development of the nuclear bombs that fell on Hiroshima and Nagasaki. The commission established to study the Japanese people started amid suspicion and coercion by the conquering US but, in spite of very suspicious findings, their findings have been used to establish safe levels of exposure for the succeeding sixty-five years! In 1959, after strong-arm tactics by the International Atomic Energy Commission, the World Health Organization signed away its right to investigate the effects of ionizing radiation on population health. Five renowned scientists and whistle-blowers for the US Atomic Energy Commission or US Department of Energy, Drs. John Gofman, Karl Morgan, Thomas Mancuso, Alice Stewart, and Jay Gould at different times have concluded that the effect of environmental irradiation on human health has been great – and compare the state of corporate and government interests upon public perception to the public awareness of tobacco fifty years ago[ix]. Several thousand physicians, members of International Physicians for Prevention of Nuclear War from 64 countries agree.

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[i] Dale Dewar, Florian Oelck, "From Hiroshima to Fukushima to You", Between the Lines, Toronto, 2014, p28
[ii] Ibid. p32
[iii] Ibid. p25
[iv] Adapted by F. Oelck from Grenier, Gilles W. (2006). Lignes Directrices Pour Le Depistage De La Contamination Et La Decontamination Des Personnes Lors D'une Urgence Nucleaire. As posted online at: <http://www.urgencenucleaire.qc.ca/documentation/decontamination_perspdf>[May 10th, 2011].
[v] Modified based on Society of Nuclear Medicine, "Beneficial Medical Uses of Radiation," www.molecularimagingcentre.org/index.cfm?PageID=7083>; American Dental Association, "Oral Health Topics," www.ada.org/2760.aspx., Neil Savage, "X-ray Body Scanners Arriving at Airports," spectrum.ieee.org/biomedical/imaging/xray-body-scanners-arriving-at-airports.
[vi] "Health Risks from Exposure to Low Levels of Ionizing Radiation", The National Academies Press, Washington, DC, (2006), http://www.nap.edu/read/11340/chapter/1
[vii] "Benefits of Radiotherapy Outweigh Small Increased Risk of Second cancer," *Ecancernews*, 2011 ecancermedicalscience.com/news-insider-news.asp?itemid=1660
[viii] Mark J. Eisenberg, Johathan Afilalo, Patrick R. Lawler, Michal Abramhamowicz, Hugues Richard, and Louise Pilote, "Cancer Risk Related to Low-Dose Ionizing radiation from cardiac Imaging in Patients after Acute Myocardial Infarction," *Canadian Medical Association Journal* 183 (March 8, 2011): 430-436.
[ix] Jay M. Gould, Benjamin A. Goldman, "Deadly Deceit, Low-Level Radiation High-Level Cover-up", Four Walls Eight Windows, New York, 1991.