RADIATION—
RISKS AND REWARDS

Michael D. Sevilla

Radiation from gamma rays, x-rays, and high-energy particles . . . they conjure up in the public mind frightening images of death and cancer. Scientists have investigated the effects of radiation now for over 100 years and while much is known about the biological effects of radiation there still continues controversy about the risks of low radiation doses in cancer induction. This article is meant to fill in some background on the history of radiation and to give an overview of what are the likely risks of radiation from the environment as well as radiation exposure from medical tests.

Short History.

In 1895 William Conrad Roentgen found that a simple Crooks tube[1] was emitting a strange radiation he called x-rays that pierce through matter. Within two years of Roentgen's discovery there was widespread medical use of x-rays for visualizing bone structures. The inner human anatomy was never before seen so readily in a living patient. Below is an early example of

[1] A Crook's tube is a forerunner of today's TV tube. Television tubes also produce x-rays that are absorbed by the thick glass at the front of the tube. Early TV tubes emitted significant amounts of radiation.

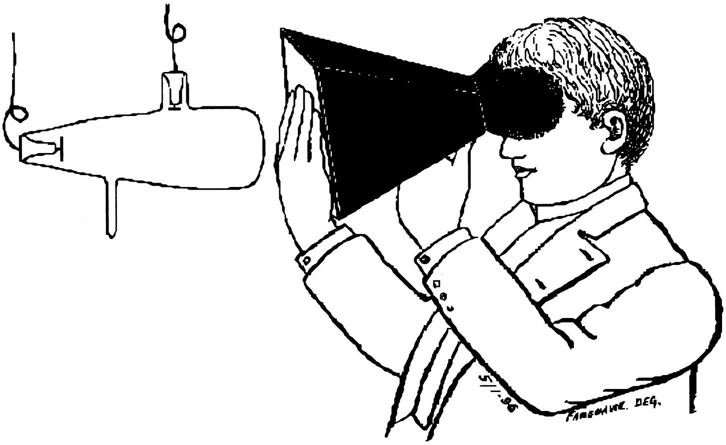

Figure 1: First x-ray tube and fluoroscope from 1896. From "Something about X Rays for Everybody" by E. Trevert 1896 , Bubier Publishing, Lynn, MA.(reprinted by Medical Physics Publishing Corp. Madison, WI, 2000)(www.cc.emory.edu/X%2DRAYS/century.htm).

a x-ray device commonly employed in 1896 that gave an image of the bone structure of the hand on a fluorescent screen.

Legitimate medical uses of x-rays have helped patients since that time but not without a cost in the early years. Since nothing was known of the biological effects of the radiation, as may be gathered from the use of the device above, little protection was taken against the radiation with some tragic consequences for a number of early x-ray practitioners. With experience, safeguards such as proper shielding for the x-ray technicians became the norm. But the frivolous use of radiation continued. In the 50's I recall as an eight-year-old sneaking into the corner shoe store on the way home from school to have a look at my feet in the fluoroscope that allowed me to see the image of the bones in my feet right in my shoes. Wiggling my toes was so impressive that I returned a number of times. Then the small doses we encountered in such imaging of our feet were considered inconsequential.

Shortly after Roentgen's discovery of x-rays Becquerel discovered that a uranium-containing rock placed over a photographic film caused it to be "exposed" without light. The rock we now know was emitting high-energy alpha and beta particles from nuclear decay processes. Becquerel's experiments piqued the curiosity of Marie and Pierre Curie who, by arduous efforts, took tons of the ore pitchblende and isolated the naturally occurring radioactive element Radium. In its purified form, vials of radium actually glowed in the dark. Pierre took these vials to parties to entertain guests with the new glowing element. While the guests were amused, his playful nature had a minor cost as he carelessly left the tube in his breast pocket from which he received burns on his chest. Although the burns healed in time, there was speculation that his heavy exposure was a factor in a traffic accident in 1906 that took his life. Marie continued her experiments with radioactive elements for many years accumulating enormous doses of radiation while winning two Nobel prizes. She died at 67 from an anemia possibly induced by her long time exposure to high levels of radiation.

Up and through the 1930's there was little real fear of radiation except for the tragic early x-ray overexposures. The mysterious rays were considered by many to be a health tonic. As today there were charlatans who touted radiation as a cure-all, but even legitimate European physicians sent their arthritic patients to Radium mines to sit for hours absorbing the healing doses of the magical emanations.

Development of the A-bomb.

A sea change occurred in the public image of radiation during World War II that brought primal fear into the radiation story. Lise Meitner and Otto Hahn[2] in Berlin had earlier discovered that an isotope of a naturally occurring element, uranium, on

[2]Otto Hahn won the Nobel Prize for this discovery in 1944. Dr. Hahn was not at the awards ceremony as he was being interrogated by the British who were seeking information about the failed German effort to develop an atomic bomb.

absorbing a neutron spontaneously divides in a process coined by Meitner as "nuclear fission". Fission resulted in the release of substantial energy as well as two or more small particles called neutrons. When these neutrons were absorbed into other uranium nuclei they also undergo fission with the release of additional neutrons. The potential of this geometrically increasing natural process for releasing of vast amounts of energy was recognized quickly by Leo Slizard who patented the process in 1936. The development of the atomic bomb came within 9 years and culminated with the bombing of Hiroshima and Nagasaki in 1945. The lingering and traumatic deaths of many of the victims by radiation exposure forever changed public perception of radiation.

Yet radiation has become a crucial part of modern life. From dental x-rays, CAT scans, radioisotope testing, to x-ray machines at airports, we encounter it regularly in our daily lives. Yet the fear pervades even every day medical uses. For example MRI facilities were once called Nuclear Magnetic Resonance Imaging until numerous patients, mistakenly thinking that nuclear meant radioactive, refused to have NMRI's done. MRI's are apparently now much safer than Nuclear MRI's. The question is what are true risks associated with the use of actual radiation in everyday experiences and what is only an "NMRI"-like emotional reaction.

Primer on units of absorbed dose.

We need a few units to discuss radiation exposure. A common unit for radiation adsorbed dose is the Rad. One thousand Rads, which is a lethal dose, would raise the temperature of one kilogram of water by 0.002 °C. Clearly it is not the amount of energy that is lethal but what it does, i.e., ionize molecules by ejecting electrons. Damage to living organisms is a function not only of the dose by the type of radiation. Simply put some radiations are far more dangerous than others. Neutrons or heavier particles such as alpha particle and cosmic rays are 10 to 50 times more damaging than x-rays, gamma rays, and beta particles. Thus the dose in Rads is multiplied by the *relative biological effectiveness* (RBE) of each radiation to estimate the hazard of that radiation. This gives the REM (Roentgen equivalent man).

$$1 \text{ REM} = \text{Rads} * \text{RBE}$$

Another unit commonly used is the Curie that gives the number of individual disintegrations per second that result in rays or particles emanating from the source. One Curie is 37 billion disintegrations per second and is the number that resulted from one gram of radium. This unit describes the source of the radiation, whereas, the Rad describes the amount of the energy absorbed by an entity separated from the source.

Radiation's effects on living systems.

There is little doubt about the short-term effects of high doses of radiation on life. At doses below 100 REM few effects are noticed even though many cells are killed but the body simply produces more. At doses of 100–300 REM many rapidly dividing cells which are most sensitive to radiation (see table), are killed and this results in loss of the lining of the intestine and this leads to nausea and diarrhea (radiation sickness). At doses of 400–500 REM so many cells are killed that general weakness ensues, the immune system is compromised and death results in ca. 50% of cases by infections and debilitation. At 1000 REM, so much general damage is done to the all systems, including the vascular system that death is certain.

In general most mature cells are radioresistant; all immature cells are very radiosensitive. This is why rapidly dividing tissues such as bone marrow or others in the first column are so sensitive. Also for this reason fetuses and children are more far more sensitive to radiation than adults.

Table

Radiation Sensitive Cells	Radiation Resistant Cells
Bone marrow cells	Brain (Neurons)
Stem cell populations	Heart tissue
Mucosa lining of intestines	Large Arteries and veins
Immune response cells	Mature blood cells
Lymphocytes	Muscle cells

The sensitive molecular target in the cell is the DNA in the chromosomes. Damage to the non-DNA portion of the cell is repairable but damage to DNA can be lethal for the cell. Even so most damage even to DNA is repaired by repair enzymes which search DNA and quickly excise any damage found and replace it with a new part, e.g., a DNA base and/ or deoxyribose group. However, certain types of damage are difficult to repair. These are multiple damage sites on DNA in which both strands are damaged in several places. This type of damage occurs more often with radiations with high Relative Biological Effectiveness such as neutrons, alpha particles or cosmic rays. X-rays, gamma rays and beta particles generally produce more of the easily repaired damage. Rapidly dividing cells are more sensitive because DNA repair takes time and if cells are called upon to divide before repair this can be fatal.

The dose of 1000 REM of high-energy radiation is lethal to humans but is unnoticed by the victim during the process. This is one of the hazards of radiation. We cannot sense it, so we may blunder into radiation areas if they are not carefully monitored. Even so deaths from accidental high doses of radiation are extremely rare. The only serious loss of life in peacetime was in the Chernobyl event in Russia. Such an event is unlikely to be repeated in the US owing to additional protections and differing reactor designs. High radiation exposures are simply not a normal daily risk to the public in the US. With the fear of nuclear power or war diminishing, the concerns have shifted gradually to threats from low doses of radiation that we do encounter. So, what are the primary concerns about low doses of radiation? The concerns focus on the possibility of a low but perceptible increased cancer risk.

Let's look at what we receive from Mother Nature as background radiation to put this in perspective. Typically Americans receive between 100 and 300 mREM of radiation as background and another lesser amount from medical uses (30 mREM on average., a mREM = 1/1000 REM). Natural background radiation comes from cosmic radiation from outer space (15%), naturally radioactive isotopes of thorium and uranium in the soil and structures (20%), or other natural isotopes such as Carbon-14 and Potassium-40 in our bodies (15%), as well as Radon' a gas produced by natural decay of uranium (50%). An example of natural radiation is the entrance hall of the new Rayburn Building in Washington DC which has beautiful polished granite walls containing uranium, that are quite radioactive. For similar reasons (uranium in the soil) high background doses of over 1000 mREM/yr are found in certain parts of India with the inhabitants doing quite well, that is, those living at higher radiation backgrounds have no greater incidence of cancer than those in India living in the lowest background levels.(1)

In the US the highest background doses are for those who live at higher altitudes because cosmic ray doses increase with altitude owing to the thinner atmosphere which lowers the shielding from the radiation. Thus Denver has a higher background level (300 mREM/yr) than Michigan (100mREM/yr). Interestingly, epidemiological studies comparing populations at high background levels with those at low background levels found that those receiving the most radiation had the fewest cancers.(2) There would seem to be no causative link between background radiation levels and cancer induction. So where does the link come from?

There simply are no definitive studies for low dose effects in humans. There have been studies of nuclear workers that suggested a correlation between low doses of radiation and cancer. However, follow-up studies have called this finding into question at least for solid tumors.(3) There remains a correlation with dose for leukemia however. The most widely used source of low-dose projections comes from data from Atomic Bomb survivors of the events at high doses at Hiroshima and Nagasaki.(4) These data, extrapolated down to low dose regions and applying the so-called "linear no threshold model" support a relationship to leukemia. However there are those who believe that this model overemphasizes cancer induction and argue against the linear no threshold model as well. Others insist the data may underestimate the cancer risk at low doses. The recent evaluations of the Hiroshima-Nagasaki data possibly suggest a threshold of a few REMs, i.e., the first few REMs are not significantly cancer inducing (see Figure 2).

Figure 2 shows that there is a moderate increase of solid tumors with radiation dose and a somewhat larger increase in cancer rate for leukemia from a much lower background rate.(4) The apparent decrease in leukemia deaths for low doses has been associated with radiation hormesis (discussed below). In general men, women and children have different risk profiles. For example for leukemia, males at any age are about three times as susceptible as females, but for solid cancers females are twice as susceptible as males. Children are more at risk than adults for both cancer types. With most cancers the risks increase after time of exposure but with leukemia the highest risks are 5 years after exposure and decrease thereafter. As an example, a full body dose of 100 REM to a male of 25 years will cause about 10 excess cases 5 years later for every 10,000 receiving the dose. The same dose will cause 3 excess cases for females of the same age. 100 REM is a very high dose to receive. What are the risks at doses we come across in medical testing or chest x-rays? If we assume the linear extrapolation model then the lifetime solid cancer risk of a chest x-ray of 10 mREM is ca. 3 in one million and the lifetime risk of a medical test that gave 1 REM of dose (Thallium stress test) is 3 cases in 10,000. Are these realistic? Probably

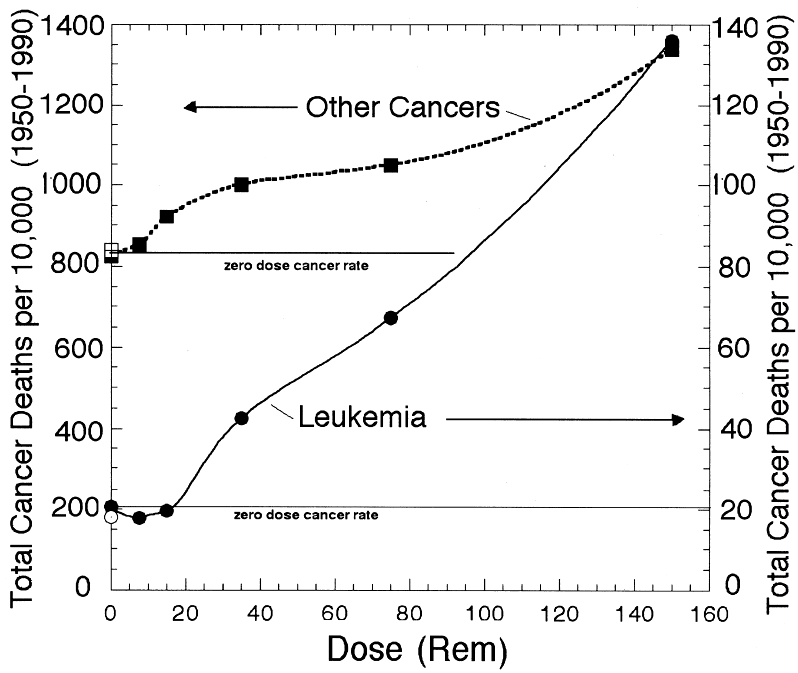

Figure 2: This figure shows a plot of the cumulative solid tumor cancer and leukemia death rates in atom bomb survivors from 1950–1990 versus the dose of radiation. The doses are averages over cohorts. Note that the right axis is for leukemia, which has a much lower natural rate than for all other cancers combined. The open symbols on the left axis are the expected background rates. Data from ref 4.

not as they actually overestimate the risks because medical tests do not generally irradiate the whole body and because the radiation at Hiroshima and Nagasaki was at high dose rates and included neutron as well as gamma radiation. Neutron radiation has a much higher RBE and this makes the atomic bomb data less representative of x-rays or gamma rays we encounter in a medical exam. Further, there may be a threshold dose up to which no harm occurs. As a consequence the risks of solid tumor promotion by low doses of radiation are small for all doses the population is exposed to including medical testing. Some risk for solid tumors does arise when a patient is exposed to hundreds or thousands of REMs used to treat cancer. But even so, considering the alternatives, the treatment is well worth the risk.

Radon—the EPA's folly?

Radon is a colorless, odorless naturally occuring gas that seeps into everyone's basement. As we pointed out, Radon accounts for about half our natural exposure to radiation. The National Research Council's Committee on Biological Effects of Ionizing Radiation (BEIR VI) addressed the risk of lung cancer from Radon and pointed out that in epidemiological studies of underground miners there was a conclusive link between lung cancer and Radon.

The estimates of the EPA and the BIER report range from 10,000 to 20,000 deaths per year from this cause. As a result of the uranium miners data, much expensive retrofitting of homes and worry has taken place. Further the EPA strongly recommends such retrofitting. Here is a sample quote from the EPA web page on Radon.

"There is no scientific doubt that Radon gas is a known human lung carcinogen. Prolonged exposure to high levels of Radon gas can cause lung cancer. Millions of homes and buildings contain high levels of Radon gas. EPA's efforts are directed at locating the homes with high levels and encouraging remediation of them."

"The Environmental Protection Agency recommends that you test for Radon and fix your home if the measured level is 4.0 picoCuries per liter (pCi/L) of air or greater. Elevated Radon levels in indoor air have been found in every state in the country. . . . For the typical home, the Radon reduction cost is usually between $700 and $1,200."

Many in Michigan have paid for these fixes. Some states require retrofitting before sale of a home.

From the EPA and NRC position one would think this a settled issue. Interestingly some epidemiological studies for residential situations (most people after all are not uranium miners) show no positive correlation between Radon levels and lung cancer.(5–7) A county by county analysis across much of the US shows the average lung cancer rate in a county *falls* with the average increasing radon concentration in homes in that county. The NRC did consider these "ecological" studies and dismissed them as not scientifically controlled since incidence of lung cancer were not associated with radon levels in the individual home. Other controlled studies do, however, suggest a correlation between lung cancer and Radon. Such controversy is typical of low dose radiation health effect studies. The decisions based on them are based on what will always be incomplete or inadequate evidence. The consensus now is that the lung cancer risks of Radon are chiefly among smokers and for the most part do not apply to nonsmokers.(8) There is an apparent synergistic effect between Radon and smoking in cancer induction. It is not known for certain why this is, but it is possible that smoke particles or dust particles of the right size are necessary to carry Radon decay particles into the lung and to later cause cancer. In any case if you don't smoke (smoking is far more deadly than Radon exposure) Radon is not likely a serious risk in your home. Smoking kills about 400,000 people per year. The effect of Radon is to increase that number by a few percent. For a smoker to continue smoking and to retrofit his or her house against Radon misses 97% of the risk. To put it succinctly, smoking kills—Radon only helps.

Radiation hormesis— Is radiation good for you?

The radiation hormesis hypothesis is that at low doses radiation can be beneficial.(9) It assumes that the reports that radiation is harmful at the lowest doses are incorrect. It is well known that radiation does stimulate cellular repair processes to repair damage caused by the radiation. The theory suggests this stimulation actually repairs and maintains the system beyond the damage caused by the radiation. Thus small amounts of radiation are suggested to be beneficial whereas beyond a certain critical dose net harm results. This is similar to drugs, which in low doses are beneficial but are often lethal in high doses.

While this is not an accepted theory, there is data that can be interpreted along these lines including the Atom Bomb survivor data (Figure 2) that would suggest small doses up to 10 REMs actually prevent leukemia. Opponents would point out data points with lower than background rates of cancer are statistically insignificant. While low doses of radiation are not yet proven to be beneficial, it is clear at this time that ascribing excess cancers to low radiation doses is also not statistically valid. Personally, I would guess that it is possible that some hormesis effects are present at low doses but the information is far too sketchy to recommend we take our daily dose of radiation for health purposes.

Any hormesis effects would likely only apply to radiations with a RBE of 1. Radiation with RBE's of 10 or higher such as cosmic rays are highly damaging even at low doses as they produce damage to DNA that is difficult to repair and this would likely overwhelm any benefits from inducing repair systems.

So the upshot is that radiation such as x-rays and gamma rays at low doses (<1 REM) are probably nothing to worry about. However, that occasional cosmic ray might just get you. So short of hiding in a mine shaft the next best thing is to live life to the fullest while our constantly irradiated bodies are still functioning and are in "glowing" health.

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