Radiation Hazards

Few issues in our uncomfortably complicated high-tech modern world are so muddled as that of *radiation hazards*. The confusion stems partly from the emotionally charged politics surrounding any subject associated with the word "nuclear" — which in turn is the result of the brutalizing terror of nuclear war that has infected the psyches of several generations of Cold War veterans — and partly from ignorance and misunderstanding of what radiation *does* and how it can be harmful — which in its own turn is the result of decades of gleeful indulgence in the thrills of grade-B sci-fi horror films. Moreover, most people seem quite content with their fantasies and "good *vs.* evil" decision-making strategies, so don't expect a deeper understanding to enhance your popularity! Nevertheless, knowledge is power and *someone* has to know what's going on, so it looks like you're it. Let me tell you what I can.[1]

Rad.1 What Hazards?

One thing we can all agree on is that radiation is bad for you, right? Well.... First we have to be careful to define what we mean by "radiation." Your fireplace *radiates* in the infrared (heat) and visible (light) parts of the electromagnetic (EM) spectrum; these forms of radiation are certainly beneficial as long as they don't get out of control. On the other hand, visible light in the form of a high-power laser can inflict damage, as can excessive heat or even microwave EM radiation. On the shorter-wavelength side of the EM spectrum, ultraviolet light can cause sunburn to the skin, while X-rays penetrate deeper and can do the same sort of microscopic damage as the still shorter-wavelength gamma (γ) rays emitted by ^{60}Co (cobalt) radioisotopes. Can we make general statements about all of these? Perhaps, "A little is good, but a lot is bad!" Sorry, nothing so simple. It is certainly true that we cannot maintain health without both heat and light, and a certain amount of "near ultraviolet" may be required for natural vitamin D production in the skin, but we probably have no biological need for microwave or radio frequency radiation; and all EM radiation from "far ultraviolet" upward in frequency (downward in wavelength) is exclusively and unambiguously bad for the individual.[2]

Why the big qualitative difference? What do ultraviolet, X-rays and γ-rays do that visible and infrared light don't? At last, a question to which there is a simple answer! They cause *ionization* of atoms and molecules inside cells, leaving behind a variety of free radicals — types of molecules that quickly react chemically with other nearby molecules. If the free radicals react with the DNA molecules in which are encoded all the instructions to our cells for how to act and how to reproduce, some of these instructions can get scrambled.

Surprisingly, this does not always happen. The simplest detectable damage to a DNA molecule is a "single-strand break," in which one of the strands of the double helix is broken by a chemical reaction with a radical. It is a testimony to the robustness of DNA that it is usually able to repair its own single-strand breaks in a few hours![3] If, however, the DNA molecule with a

[1] *Caveat!* I encourage you to distrust everything I say (and everything anyone else says) on this subject until you have seen (and believe) the data for yourself. Like most people, I am not a scholar or even an expert in the field of radiation hazards, just an amateur with strong convictions which will distort my presentation of the evidence; my only excuse for subjecting you to my opinions is that everyone else seems to be so timid about expressing any ideas on this subject that the only information you are likely to get elsewhere (without determined effort on your part) is even more politically motivated and less reliable than mine, which I acquired through informal discussions with various people who *do* have legitimate professional credentials.

[2] Whether or not genetic mutations are beneficial for the human race as a whole is a difficult question both scientifically and ethically; I will avoid trying to answer it.

[3] Whether this is because of multiple redundancy or context programming I do not know, but it sure is an impressive

single-strand break is subjected to further damage before it has a chance to "heal itself" then it may sustain a "double-strand break" (two breaks in the same strand), which it seems to be far less able to repair. Before we go on to discuss the consequences of permanent DNA damage, it is important to note that the irreparable damage usually takes place only after a large fraction of DNA molecules have already sustained temporary damage — and that the temporary damage is mostly repaired in a fairly short time. This explains why a given "dose" of radiation is less harmful when accumulated over a long time than when delivered in the space of a few hours.[4]

What sorts of bad things are liable to happen when a DNA molecule sustains irreparable damage, scrambling some part of the instruction manual for the operation of the cell it inhabits?

- **Cell Reproductive Death** [most common] — The cell containing the defective DNA may be unable to reproduce itself, so that although it may be able to function normally for its remaining natural lifetime, when it dies a natural death it will not have a new cell to replace it. Whether this causes a problem or not depends upon whether many other nearby cells have the same malady (one by itself will never be missed!) and upon the natural lifetime of that type of cell — which ranges from a few days for hair follicles, skin and mucous membrane cells to "forever" for brain cells. Obviously, the loss of reproductive capacity is meaningless for a cell that never reproduces!

- **Genetic Mutation** [most subtle] — If the cell in question happens to be a *gamete* destined for fusion with a member of the opposite sex, the resulting individual will have some scrambled instructions in the construction manual and will probably not grow up normally. In almost every case this will be fatal to the fœtus, and in almost all the remaining cases it will be detrimental to the survival of the individual, although such mutations have presumably played a rôle in evolution to date. Note however that it is strictly impossible for any individual's genetic makeup to be *retroactively* altered by radiation (like the Hulk or Spiderman or any number of cheap sci-fi horrors), as this would require the *same* accidental scrambling to take place independently in every DNA strand in the victim's body!

  For men, there are two types of genetic damage: the sperm cells themselves have an active lifetime of only a few days, after which a new generation takes over; but the sperm-producing cells are never replaced and so can never repair damage to themselves. The latter applies also to women: the female gametes (eggs) are all produced early in life and, once damaged, cannot be repaired.

  If the altered cell is "just any old cell" then usually the change is harmless — either the cell merely fails to do its part in the body until it dies or else the affected part of the DNA is irrelevant to the functioning of that cell in the first place — but occasionally the change is related to cell division itself, and then there can be real trouble.

- **Cancer** [most unpleasant] — Sometimes (very rarely) a damaged DNA molecule instructs a cell to mobilize all its resources and the resources of all its neighbours to reproduce as many copies of itself as possible. The offspring preserve the mandate, and a chain reaction takes place that "crashes the system." This runaway repro-

[4] I should add an extra *caveat* at this point: what I have said about single- and double-strand breaks and healing times is what I recall from sitting on the PhD committee of a student working on pion radiotherapy about ten years ago. I don't imagine it has been substantially revised since then, but I am not absolutely sure. If you want a more reliable witness I will be glad to direct you to local experts.

> ductive zeal of a misguided cell is what we know as CANCER, and it is the worst hazard of radiation exposure. As far as anyone knows, *any* exposure to ionizing radiation increases one's chances of developing cancer, and so we can unambiguously say that **ionizing radiation is bad for you.**

Before we go on, it is interesting to note that *all* of the most potent therapies for *treating* cancer involve either ionizing radiation or chemical reactions that cause similar DNA damage; the strategy for these "interventions" is always to cause such overwhelming DNA damage to the cancer cells that *every single cancer cell* suffers "cell reproductive death" as described above. Although there are various techniques for making the cancer cells more susceptible to the radiation or harsh chemicals than normal cells, there are inevitably many casualties among the latter. It is not unusual, for instance, to kill off (in the sense of "reproductive death") as many as 90% of the normal cells in the tissues surrounding a tumour, relying upon the fantastic healing capacity of normal tissue to bounce back from this insult. Remember, the idea is to kill 100% (!) of the cancer cells.

It provides an important perspective to realize that the radiation used to kill the cancer may deliver a "dose" to healthy tissues that is more than 10,000 times the maximum legal limit for environmental radiation exposure, and yet the increased likelihood of developing another cancer from the radiation therapy is regarded as a negligible risk relative to allowing the existing cancer to progress unchecked. Whether or not oncologists have optimized their treatment strategies is another charged issue which I will avoid, but it is clear that a large radiation dose does not necessarily "give you cancer" immediately; rather it increases your *chances* of developing cancer *in the long run*. By how much? And over how long a run? These are the quantitative statistical questions that must be answered if one is to develop a rational scheme for evaluating radiation hazards.

Rad.2 Why Worry, and When?

Unfortunately much of our public policy today seems to be based on the belief that if we could only eliminate the last vestiges of hazardous materials and dangerous practices from our society then none of us would ever get sick or die. This must be regarded as nonsense until medical science finds a way to halt or reverse the natural aging process — which might not be such a great idea.[5]

If I were exposed to radiation that virtually guaranteed that I would develop cancer within 200 years, *but no sooner than 100 years*, would I be wise to worry? What if it raised my chances of developing cancer within 20 years by 2%? My chances of developing cancer within 20 years are roughly 20% *normally*, now that we have eliminated most other mortal dangers except for heart disease. Most people would agree that I would be foolish to allow myself to be exposed to enough radiation to increase my chances of developing cancer within 10 years by 10% (unless we mean 10% *of* 10%, in which case it is a rather small increase — one must always ask for precise explanations of statistical statements!) and yet we all routinely choose to engage in activities that are as least as hazardous, such as downhill skiing or motorcycle riding. Why do we reserve such terror for one sort of hazard when we so stoically accept others of far greater risk? Which is the healthier attitude?

[5]Even if a sufficiently totalitarian regime could be instituted to forcibly prevent the population from increasing exponentially once immortality was commonplace, would such a thing be beneficial? Would life seem as precious if it were not so annoyingly *short*? Again I shall bypass the thorny issues and play the hand I am dealt.

Rad.2.1 Informed Consent *vs.* Public Policy

One answer to this question is that there are two *entirely separate* issues regarding life-threatening hazards: the first relates to *personal choice*, in which the individual has a right to decide for him/herself how much risk is justified for the sake of certain perceived benefits; the second relates to *public policy*, in which decisions may affect millions of people without their knowledge or consent. It is not unethical for me to choose to risk my life for what I conceive to be worthwhile, or even for fun (as long as I don't expect anyone else to bear the consequences); but it *is* unethical for me to subject millions of other people to the same level of risks without their consent.

Rad.2.2 Cost/Benefit Analyses

Unfortunately, this does not necessarily make the issues simpler. It does not help to conclude that any global policy decision that increases the public risk *at all* is *a priori* wrong, because of unintended consequences and complex interconnections. A nuclear power plant in New York puts local residents at some risk from possible cancer due to possible radiation exposure from possible leaks due to probable bungling and/or inadequate engineering and/or substandard construction. On the other hand, a fossil fuel plant of the same size puts a different population at risk from acid rain, ozone depletion and the Greenhouse Effect. [6] And no power plant at all increases the risk of pneumonia in the area served during Winter brown-outs — probably the worst hazard of the three in the short term, but one to which millennia of familiarity have hardened us!

The point is, *every* public policy decision creates risks. Even a decrease in bus fare, if it affects millions of people, will cause some people to die this year who would otherwise have lived longer. The questions must always be, "Is this likely to do any good? How much good? Is it likely to do any harm? How much harm? What are the relative probabilities of good and harm? How many people are likely to suffer from the harm? How many people are likely to benefit from the good?" And of course the two questions most popular with politicians, "Which people?" and "When?"

Time to duck the difficult issues again. I am satisfied to point out the questions; I have no more competence than the next person to offer answers. Suffice it to say that any sensible policy regarding radiation hazards, whether public or personal, must take into account that each of us is going to die, that our lifespan is frustratingly short no matter what we do, and that our chances of dying of cancer (radiation-induced or otherwise) are already rather high.[7] So any strategy dictated exclusively by absolute minimization of our cancer risk is somewhat silly. Still, *all other things being equal*, less (ionizing) radiation is better!

Rad.3 How Bad is How Much of What, and When?

Time to get quantitative. What kinds of radiation are there, how do we measure how much we get, and what effects can we expect from different exposures to different parts of our bodies over different times?

There are lots of kinds of radiation, from the *EM* spectrum we have already discussed to neutrons, alpha (α) particles, beta (β) "rays" (high-energy electrons) and γ-rays — all constant companions in our environment due to

[6] Also, surprisingly enough, from the *radioactivity* released from fossil fuels in combustion, which is far greater than that released by a nuclear power plant *in normal operation*.

[7] I have been assuming 30%, but that number could be out of date; I don't think it makes much difference to my arguments.

natural or man-made radioisotopes — to the utterly harmless neutrinos coming from our Sun, to beams of high-energy protons, electrons, positrons, pions, muons *etc.*, produced by accelerators like TRIUMF, to catastrophically destructive cosmic rays from which we are shielded by our atmosphere (except when we fly across country in an airliner) and so on *ad infinitum.* Everyone is constantly exposed to most of these types of radiation, accumulating an annual dose varying from a few hundred mR to several R. What are these units "R" and how can we gauge what they mean in practical terms? Time to get more technical.

Rad.3.1 Units

The basic unit of radiation dose used to be the "*rad*," defined in terms of the *energy deposited* by ionizing radiation *per unit mass* of exposed matter (*e.g.* flesh or bone):

$$1 \; rad \equiv 100 \; erg/g$$

(g means *gram* here.) More recently, for some reason this nice mnemonic unit has been officially supplanted by yet another "personal name SI unit" in honour of British physicist and radiation biologist Louis Harold Gray (1905-1965) — the "*gray*:"

$$1 \; gray \equiv 100 \; rad \equiv 1 \; J/kg.$$

Early work on radiation hazards was based on X-ray exposure[8] and the units used were always *rœntgen* (after the scientist by that name), which are about the same as *rad* for X-rays *only*, and are virtually unused today. Later it was found that even the *rad* was too simple; different *types* of radiation (*e.g.* neutrons) were found to be more (or less) destructive than X-rays for different types of tissues, so an empirical "fudge factor" called the *R*elative *B*iological *E*ffectiveness (RBE) was invented to account for these differences (averaged over all body parts, of course, which decreased its usefulness). The RBEs of γ-rays, X-rays and β-rays (fast electrons) are all 1 by definition; thermal neutrons have an average RBE of 3; fast neutrons (on average), protons and α-rays (^{4}He nuclei) all have RBEs of 10; and fast heavy ions have an RBE of 20.[9]

A new unit was then constructed by combining the RBE with the dosage in rads, namely the *rem* (*r*œntgen *e*quivalent to *m*an), defined by

$$rem \equiv \text{ RBE} \times \; rad.$$

The "R" in the preceding paragraph stands for *rem* and the "mR" for *millirem* — one thousandth of a *rem*.

Today the standard international unit for measuring "effective dosage" is the *seivert*, named after Rolf Sievert (1898-1966), a pioneering Swedish radiation physicist. Converting between *rem* and *seivert* is just like converting between *rad* and *gray*:

$$1 \; seivert \equiv 100 \; rem.$$

Now that all mnemonic content has been deleted from the names of the units associated with radiation dosage, you may expect these names to stick.[10]

Rad.3.2 Effects

All of these units are meaningless until one has some idea of how bad one of them is for you.

[8] I can remember sticking my feet into the fluoroscope at the corner shoe store and looking at my foot bones inside my new shoes; it was quite popular about 40 years ago.

[9] Actually, the RBE of neutrons varies tremendously for different tissues and is a complicated function of the neutron energy because of the energy-dependence of the neutron capture cross-sections of different elements. Neutrons are very bad.

[10] The purpose of SI units is evidently to make it as difficult as possible for intelligent laypersons to understand what "experts" are talking about. I cannot imagine a more humiliating posthumous fate than to have countless generations confused by some perfectly simple unit renamed the "*brewer*" in honour of my efforts to make some field more understandable.

Here are some rules of thumb that may be off by factors of two from one case to the next:

- **Instant Death:** It takes a monumental radiation dose to kill outright, typically something like 5000 R (50 Grays) "whole-body" — *i.e.* half a million ergs of energy deposited in every gram of your body. This amount of energy wipes out your central nervous system (CNS) immediately when delivered all at once. Needless to say, only the military mind makes a strong distinction between this and the next level down.
- **Overnight Death:** Approximately 900 R (9 Grays) whole-body will accomplish the same thing as 50 Grays but it takes about a day.
- **Ugly Death:** A somewhat lower dose, around 500 R (5 Grays) causes severe "radiation sickness" (*i.e.* nausea, hair loss, skin lesions, *etc.*) as the body's short-lived cells fail to provide new generations to replace their normal mortality ("cell reproductive death"). It is not this trauma which usually kills, however, but the complications that arise from a lack of resistance to infection, due in turn to the lack of new generations of white blood cells. If you survive the initial radiation sickness and avoid infection, you will probably recover completely in the short term; but you are very likely to develop cancer (especially leukemia) in later years (usually some 10-20 years later!) and your offspring, if any, will have a high probability of genetic mutations.
- **Sub-Acute Exposures:** From a whole-body dose of around 100 R (1 Gray) delivered in less than about a week, you are unlikely to notice any immediate severe symptoms. However, you are likely to develop leukemia in 10-30 years, and there is a significant chance of genetic mutations in your offspring. A whole-body exposure of 5 R delivered over 1 year was believed in 1970 to represent 1.8 "doubling doses" — *i.e.* it was thought to multiply your odds of developing cancer by a factor of 2.8 if maintained year after year. At that time it was also the legal exposure limit for radiation workers in the U.S.A., set by the Atomic Energy Commission (AEC) there. Presumably quite a few people received this exposure for a few years, although it is unusual for more than a small fraction of workers to receive the maximum allowed exposure. For perspective, it is noteworthy that a series of spinal X-rays is apt to give an exposure of 1–4 R locally, and that an afternoon on Wreck Beach in midsummer often produces a painful sunburn that represents 10-20 R to the skin; the resultant burn is a *bona fide* radiation burn and is just as dangerous as any other kind! In fact, the overwhelming majority of all radiation-induced cancer fatalities on Earth can be attributed directly to far ultraviolet from our favourite nuclear fusion power plant in the sky: the Sun.
- **Marginal Exposures:** The average exposure from natural sources of radiation is on the order of 300 mR per year. As of 1979 this was also the Canadian legal limit for public exposure from artificial sources. Whether an extra 300 mR makes a significant difference epidemiologically in the incidence of cancer depends almost entirely on what one considers significant; however, it is a fact that the statistical difference between populations that have received such an exposure "artificially" and those who have not is smaller than the statistical differences between populations with different eating habits, who live in different regions, who have different types of jobs, *etc.* This is partly because of the wide variety in the amount and type of *natural* radiation exposure.

Before we go on to discuss *sources* of radiation, it is important to note that different organs or body parts have dramatically different resistance to radiation. The *hands*, in particular, are able to withstand radiation doses that would kill if the whole body were subjected to them! The *lens of the eye* and the *gonads* are considered to be the most vulnerable and should be protected first.

Rad.4 Sources of Radiation

In 1972 a detailed survey was made of average annual whole-body doses to the U.S.A. population from various sources. Occupational and miscellaneous artificial exposures averaged about 1-2 mR/y (remember, some people got enough to make up for the vast majority who got none!); global fallout from nuclear testing made up about 6 mR/y; medical exposures (X-rays, radiotherapy, *etc.*) were good for nearly 100 mR/y; and natural background (see below) averaged about 120 mR/y. The numbers have not changed much in the intervening years. One must conclude that for the average person there are only two significant sources of radiation exposure: medical and natural. Although this begs the question of "extraordinary cases" who receive larger exposures in accidents such as Chernobyl, it still helps to set perspectives for those examples.

Some medical and natural radiation sources are listed below. For medical examples I have shown the mean dose per exposure. It is important to note that these are only the *easily measured* forms of radiation — X-rays and γ-rays — that penetrate flesh (and detectors!) easily. More insidious and difficult-to-measure types will be discussed in the next Section.

- **Medical X-rays:** Chest, radiographic: 45 mR. Chest, photofluorographic: 504 mR. Spinal (per film): 1265 mR. Dental (average): 1138 mR.[11]
- **Cosmic Rays:** Sea level: 30–40 mR/y. Colorado: 120 mR/y. At 40,000 ft: 0.7 mR/h.[12]
- **Natural Terrestrial Radionuclides:** γ-radiation is fairly uniform in the U.S.A., ranging from 30 mR/y in Texas to 115 mR/y in South Dakota. Guess where the uranium deposits are![13]

Rad.5 The Bad Stuff: Ingested Radionuclides

The information given above would seem to indicate that medical X-rays were the worst radiation hazard around, except for natural sources we can't do much about. Unfortunately this is a distortion based on the difficulty of measuring the most dangerous kind of radiation: α-emitting radionuclides (radioactive isotopes). Many heavy elements have isotopes which naturally fission into lighter elements plus a helium nucleus, with the latter being emitted with a substantial kinetic energy as an alpha "ray." The range of most α particles is only a few cm in air and less than a mm in tissue, so the damage they cause is localized. While this may be reassuring when the isotopes are at arm's length, it can be bad news if you have breathed them into your lungs or swallowed them so that they can collect in your bones, where they can do the most damage! Since there is such a wide variety of radioactive elements with assorted chemical properties, it is wise to be aware of the specific hazards associated with each. I have neither the

[11] Note: medical X-rays are normally *localized* to the region being imaged; they are not "whole-body" and therefore are not as bad as they look. Still. . . .

[12] Note: that is per *hour* at a typical cruising altitude for a normal commercial jetliner; thus an average round-trip transcontinental flight yields a dose of 6-8 mR! The estimated average cosmic-ray dose for airline crew is 670 mR/y. Astronauts have it even worse.

[13] I don't have the numbers for the Okanagen, but I believe they are even higher than for South Dakota.

expertise nor the space to provide a comprehensive survey here, but I can mention a few of the most common culprits.

- **Radon:** All rock contains some amount of naturally occurring *radium* which gradually decays, releasing the chemically inert noble gas *radon*. Radon in turn is a radioactive element which decays by emitting a rather low energy α particle that is quite difficult to detect since it has such a short range it can't penetrate the window of a typical Geiger counter. Thus until recently there was little known about radon in our environment, even though it is generally believed that Madame Curie died from exposure to radon emitted by the radium upon which she performed her famous experiments. It is now felt by many that radon is the most widespread and dangerous of all radiation hazards, because it accumulates in the air of any building made of rock, brick or concrete (especially those with closed circulation air conditioning!) and thence in the lungs of the people breathing that air. Lungs in fact make a superb filter for the radioactive byproducts of radon, so that one of the most effective radon detection schemes is to measure the radioactivity of the *people* who live in high-radon environments. In the lung tissue, the short-ranged α particles expend all their energy where it does the most harm, raising the incidence of lung disease and cancer. Rocks from different regions have a tremendous range of radium content, so that a stone house may be perfectly safe in one city and hazardous in another.[14]

- **Potassium and Carbon:** Radioisotopes of potassium and carbon are continually created in the atmosphere by cosmic ray bombardment; these isotopes build up to a constant level in all living tissues, only to decay away in a few thousand years after death. This means that the most radioactive component in your household is probably you![15] It also provides a handy method of estimating the time since formerly living matter was alive (^{14}C and potassium-argon dating).

- **Man-made Radionuclides:** There are too many of these to make a comprehensive list here.[16] The most famous is plutonium, ^{239}Pu, the stuff of which fission bombs are made. Plutonium is both a deadly chemical poison and a nasty radioisotope. If a miniscule grain is caught in your lungs or other tissues, it may not do much damage to your body as a whole, but it exposes the tissue immediately around it to a huge dose of radiation, drastically increasing the likelihood of cancer in that tissue. Cancer is just as deadly no matter where it begins, which makes the ingestion of radionuclides the worst possible sort of radiation hazard.

It is important to note that the food chain may serve to concentrate "harmless" levels of radionuclides in (*e.g.*) sea water to a level which is worthy of our concern. Were it not for this effect, and the fact that the waste products of nuclear fission include a large variety of radionuclides with various chemical properties that naturally occurring isotopes do not exhibit, it would be a sensible strategy to dispose of radioactive waste by diluting it and spreading it far and wide in the oceans — since the net radioactivity of reactor fuel actually *decreases* in the process of digging up the uranium, burning it in a reactor and storing the spent fuel rods for 10 years until the short-lived isotopes decay away. Because of

[14] I think Vancouver is just slightly on the hazardous side; but in the Okanagen, where there are concentrated uranium ore deposits, I might choose to live in a wooden house. However, you should check out the latest data before you jump to any conclusions.

[15] Married folks who sleep together pick up a few extra mR/y from their spouses!

[16] One may feel that there are simply too many, period!

the biological concentration effect, however, it is wiser to seek safe long-term containments for radioactive waste.

Rad.6 Protection Against Radiation

By far the best shielding against radioactivity is GAUSS' LAW: the intensity of a point source falls off as the square of its distance from the observer. All localized sources are labelled with their activity *at a given distance*, for instance "10 *mr/h* at 1 *m*." If one keeps at least 10 *m* away from such a source, one will receive less than 0.1 *mR* per hour, which is not worrisome.[17] Other safety measures include lead aprons, which are effective *only* for X-rays and γ-rays, and thick concrete shielding for neutrons and high-energy charged particles (these are much in evidence at TRIUMF).

Rad.7 Conclusions

Draw your own. Please.

Just try to keep in mind that neither extreme attitude ("There's nothing to worry about." *vs* "The only acceptable risk is no risk at all.") represents much of a commitment to the public good. Radiation hazards are subtle and complex, but the benefits of major sources of environmental radiation (*e.g.* medical X-rays) are important. They often save lives by endangering them; the deciding factor must involve relative probabilities and cost/benefit analyses, which may seem cold-blooded but are essential if you really want to do as little harm and as much good as you can.

Remember, if you let someone else decide for you, then you forfeit your right to righteous indignation if you later disapprove of their decision.

[17]Needless to say, one should never *touch* a radioactive source, because $1/r^2$ can be very large as $r \to 0$.