BIOLOGICAL EFFECTS OF IONIZING RADIATION

Ionizing radiation in very high levels is known to increase the incidence of cancer, birth anomalies, erythema, and other problems. In low levels, these effects are either very, very small compared to natural incidences or non-existent depending on the biological model used for estimating the potential risk. Regulatory agencies assume that radiation effects observed in people exposed to very high doses can be linearly extrapolated to background levels. This model is called the "linear no-threshold theory" because the modeled effects are linear with dose and no threshold is assumed. The linear model most likely over-estimates harmful biological effects because it does not fully account for the body's ability to repair damage.

Additional Web Sites:
Radiation and Life http://www.uic.com.au/ral.htm
University of Michigan Web site http://www.umich.edu/%7Eradinfo/ select Introduction to Radiation, then links to Radiation and Nature, Radiation and Risk, or Radiation Reassessed.

Background Radiation Sources

Radioactivity is present throughout the universe, with the radiation doses varying significantly from place to place. The average annual dose to people in the Miami Valley is about 300 mrem. Across the U.S., doses range from about 100 mrem/year to about 1000 mrem/year. In each person's body, about 15,000 ionizations per second occur from background radiation sources.

Average Annual Doses from Natural Sources in the Miami Valley

	mrem	mSv
Cosmic Radiation	30	0.3
Terrestrial Radiation (e.g. uranium & thorium in the soil)	30	0.3
Radon	200	2.0
Isotopes in the body (e.g., ^{40}K, ^{210}Po, ^{14}C, ^{3}H)	40	0.4
Total average background dose in the Miami Valley	300	3.0
Variation of background in the USA	100 - 1000	1.0 - 10

Average Annual Doses from Man-Made Radiation Sources

Medical	60	0.6
Consumer Products	5	0.05
Smoking (1 pack a day, dose to lung primarily from ^{210}Po in the tobacco)	8000	80

Cosmic Radiation. The dose from cosmic rays increases with altitude. At sea level the annual dose is about 26 mrem (0.26 mSv). For each 2000-meter increase in altitude, the dose doubles. For example, Denver citizens (at 1600 meters) receive about 50 to 60 mrem each year from cosmic radiation. Moving closer to the earth's polar region (i.e., changes in latitude) will increase dose by about 10% compared to equatorial regions. Cosmic radiation to astronauts in earth orbit or outer space can significantly contribute to their dose. In orbit, astronauts can receive about 10 to 100 times the dose people on the surface receive. A solar particle event (i.e., solar flare) can expose an unshielded astronaut to a very high, perhaps life-threatening, dose of several hundred rem. The radiation from solar flares is strongly attenuated by the earth's atmosphere so that they have a minor affect on people at the earth's surface.

For further reading on cosmic radiation:

1) National Council on Radiation Protection and Measurement, Ionizing radiation exposure of the population of the United States, NCRP Report No. 93, Bethesda, MD 1987
2) Mettler, F.A. and Moseley, R.D., *Medical Effects of Ionizing Radiation,* Grune and Stratton, 1985
3) National Council on Radiation Protection and Measurement, Guidance on radiation received in space activities, NCRP Report No. 98, Bethesda, MD 1988

Terrestrial Radiation Sources *(e.g., uranium, thorium, and radium in the soil and building materials)*. The dose from these sources depends on the geography of the local area. Uranium is ubiquitous in the earth's crust; however some places have higher concentrations than others. People living in the Atlantic and Gulf coastal plains receive about 16 mrem (0.16 mSv) each year, while those residing in the Rocky Mountains receive about 65 mrem (0.65 mSv) yearly. Some places in the world have high concentrations of natural radioactivity resulting in very high doses to the local population. Tens of thousands of people in Ramsar, Iran; Kerala, India; Guarapari, Brazil; parts of China and many other places live where the soil contains monazite (a sand that is rich in thorium) and other naturally radioactive minerals. Denizens in Ramsar, Kerala, and Guarapari experience terrestrial yearly radiation doses up to 26 rad (260 mGy), 3.5 rad (35 mGy), and 3.5 rad (35 mGy), respectively. People living in these areas have been extensively studied. Epidemiological investigations have shown that cancer incidence in these areas are not statistically different from nearby populations who have much lower radiation doses and similar socioeconomic conditions.

For further reading on terrestrial radiation:

1) National Council on Radiation Protection and Measurement, Ionizing radiation exposure of the population of the United States, NCRP Report No. 93, Bethesda, MD 1987
2) Mettler, F.A. and Moseley, R.D., *Medical Effects of Ionizing Radiation,* Grune and Stratton, 1985
3) Terrestrial Gamma Activity in the U.S.: http://energy.cr.usgs.gov/radon/dds-9.html
4) Global Annual Terrestrial Doses: http://www.taishitsu.or.jp/radiation/index-e.html

Radon. Uranium and thorium are primordial (meaning they were present when the earth was formed) radioactive elements. They are present throughout the earth's crust. Some types of rock are rich in these elements. Uranium (^{238}U) eventually decays to radium (^{226}Ra, half-life 1600 years), and subsequently to radon (^{222}Rn, half-life 3.82 days). As an inert gas, radon diffuses through the soil to the atmosphere, where it can accumulate in buildings, particularly in the lower levels. Radon is relatively innocuous; however, it decays to lead (^{210}Pb) in a matter of minutes by emitting several alpha particles from elements in the decay sequence. The elements of this decay sequence are called radon daughters (or progeny). The alpha particles from the radon daughters can irradiate the respiratory tract.

The radon daughters from ^{226}Ra contribute the greatest doses to the lungs of people. Thorium (^{232}Th) also decays to radon (^{220}Rn, half-life 55 seconds, also called thoron) by a similar decay series. The very short half-life of thoron prevents it from diffusing very far before it decays to thoron progeny. Therefore the dose from thoron is often inconsequential in homes compared to radon (^{222}Rn).

The predominant concern from radon is lung cancer. The U.S. EPA claims radon as the second leading cause of lung cancer, following smoking, which accounts for 85% to 90% of this disease. This position by the EPA is mainly based on miners who were exposed to radon levels far greater than those observed domestically. The comparison of miner epidemiological data with that of the general public is complicated because the percentage of miners who smoked was greater than the general population and their breathing atmosphere often included other potential carcinogenic agents, such as silicates, heavy metals, diesel fumes, soot, and vapors from explosives. Epidemiological studies in residential areas are hampered by the low incidence of lung cancer in nonsmokers and excluding important potential confounding factors, such as second-hand smoke, urban living, respiratory diseases and injury, occupational and hobby pulmonary carcinogens, diet, and inhalation of illegal drugs.

Radon testing in homes can be performed by the owner or contracted out to a licensed firm. The EPA has set the action level for radon concentration in the home at 4 pCi/L (148 Bq/m^3). Remedial actions can be performed by licensed radon remediation firms. Both testing and remediation are voluntary. For comparison, most other industrial countries have voluntary radon action levels at 200 Bq/m^3 (5.4 pCi/L) for new buildings and 400 Bq/m^3 (10.8 pCi/L) for older buildings.

For further reading on radon:

1. National Research Council, *Health Effects of Exposure to Radon*, BEIR VI, National Academy Press, 1999
2. Cole, Leonard, *Elements of Risk: the Politics of Radon*, AAAS Press, 1993
3. National Research Council, *Health Effects of Radon and Other Internally-Deposited Alpha-Emitters*, BEIR IV, National Academy Press, 1988
4. Distribution of radon in the United States http://energy.cr.usgs.gov/radon/rnus.html
5. EPA Radon Web Page http://www.epa.gov/iaq/radon/
6. The Geology of Radon http://energy.cr.usgs.gov/radon/georadon.html
7. Europe radon action levels (PDF) http://www.ssi.se/english/RadonGustav.PDF

Isotopes in the body.
There are many isotopes naturally present in everyone with potassium-40 (^{40}K, half-life 1.3 x 10^9 years) giving the largest dose. Potassium is a common metal on earth and an essential electrolyte in the body. About one in 10,000 atoms of potassium are ^{40}K. The dose from ^{40}K depends on intakes by individuals. Another isotope, ^{210}P (half-life 138 days), is proportional to lean body mass. Minor constituents include ^{3}H and ^{14}C, which are produced in the upper atmosphere.

For further reading on terrestrial radiation:

1) National Council on Radiation Protection and Measurement, Ionizing radiation exposure of the population of the United States, NCRP Report No. 93, Bethesda, MD 1987
2) Mettler, F.A. and Moseley, R.D., *Medical Effects of Ionizing Radiation,* Grune and Stratton, 1985

Medical Exposures.
The value of 60 mrem/year from medical and dental exposures is a population average. The dose to individual patients varies depending on the medical exam. The following are typical doses from routine radiological procedures. The Entrance Skin Exposure is dose to the skin closest to the x-ray tube. The Marrow Dose is the average dose to the bone marrow, a primary organ of concern.

Typical Doses from Diagnostic X-ray Procedures

X-ray Exams	Entrance Skin Exposure (mrem)	Marrow Dose (mrem)
Chest	10	2
Skull	200	10
Lumbar spine	300	60
Abdomen	400	30
CT (pelvis)	4000	100

Consumer Products.
Many consumer products have elevated concentrations of radioactivity that contribute to each of our personal doses throughout life. Anything rich in potassium, such as bananas and salt substitutes, has elevated concentrations of ^{40}P. Most smoke detectors in people's homes use small sources of ^{241}Am to make the detector functional. A flight from New York to Los Angeles can expose a passenger to 4 mrem of cosmic radiation. Some other sources of radiation exposure include phosphate fertilizers, fossil fuel, fall out, building materials (such as gypsum board, stone, brick, and granite). The average dose to members of the general public is about 10 mrem (0.1 mSv) a year from all of these sources. Most people receive one mrem or less from TV set each year.

Tobacco Smoke.
Tobacco leaves concentrate ^{210}Pb and ^{210}Po. The lungs of one pack-a-day smokers receive about 8 rem (80 mSv) a year.

BIOLOGICAL EFFECTS FROM LOW DOSES OF RADIATION
Radiation is a form of energy. Just as sunlight, electricity, kinetic energy (speed), and potential energy (altitude) are dangerous in large amounts, so is radiation. In low levels these forms of energy are considered either inconsequential or beneficial. Radiation is the only form of energy to which effects at high levels are assumed to proportionately apply at low levels.

Ionizing radiation (e.g., beta particles, alpha particles, neutrons, gamma rays) has sufficient energy to ionize surrounding atoms. Ionization is a process of removing one or more electrons from an atom. The ionization process can lead to biological damage when DNA, the controlling molecule of a cell, is affected. When damaged, the DNA molecule can repair itself, lead to the cell death, or mutate. The most likely outcome for low doses is repair. Mutations can lead to cancer. Cancer caused by radiation is no different than that caused by other carcinogens. Radiation is not the only agent that can cause mutations in DNA. Some other mutagens are chemicals, heat, and ultraviolet light. One parameter of DNA damage is single strand breaks to the DNA molecule. In every cell, every day, about 150,000 single strand breaks naturally occur from chemical and physical processes, primarily related to oxygen and thermal effects. One rem of radiation would add an estimated 20 single strand breaks - an inconsequential amount.

Radiation is known to increase the incidence of cancer in high doses. At low doses, much controversy surrounds the premise that radiation increases cancer incidence. The controversy dwells on the fact that the natural incidence of cancer to unexposed populations is much greater than any contribution from ionizing radiation. For example, in a population of 10,000 people, about 20%, or 2000 people, will die of cancer. If that population was exposed to 1 rem of ionizing radiation, about 4 to 8 additional cancer deaths would be calculated from high dose projections. The variation is so large that any effect from radiation would not be distinguishable from natural incidence.

Agencies regulating ionizing radiation assume that high dose effects can be proportionately extrapolated to low doses. This model is called the linear, no-threshold (LNT) model because the risk of cancer is assumed to be directly proportional to dose and the end point for biological effects is considered zero rem. The LNT model applies a conservative assessment of risk from radiation exposure and simplifies risk calculations. Several other models of risk from radiation exposure have been proposed from the scientific community:

Sub-linear model: Assumes that the end point for biological effects is zero rem. The number of projected cancers with this model still increases with dose, but at a much lower rate than the LNT model.

Threshold model: Assumes radiation has no effect up to a certain dose (say, 5 to 20 rem). After that dose, excess cancers from radiation exposure may be observed.

Hormesis model: Assumes that radiation in high doses increases the incidence of cancer; however doses up to some point, perhaps 10 rem, are beneficial to the person.

As mentioned in the background section above, terrestrial radiation doses vastly differ across the face of the earth. Populations in very high dose regions have been compared with other populations living in areas of much lower doses. Epidemiological investigations have shown that cancer incidence between these areas of high and low doses are not statistically different.

For further reading on low dose biological effects:
Health Effects of Exposure to Low Levels of Ionizing Radiation - BEIR V (1990) http://www.nap.edu/openbook/0309039959/html/
Radiation and Life http://www.uic.com.au/ral.htm
Radiation Reassessed http://whyfiles.news.wisc.edu/020radiation/index.html
Radiation: Facts vs. Fears http://www.acsh.org/publications/priorities/1102/rad.html
Low Level Radiation Health Effects http://cnts.wpi.edu/_uploads/documents/live/ps41.pdf
Radiation Effects Research Foundation - Effects on Atomic Bomb Survivors http://www.rerf.or.jp/eigo/titles/radtoc.htm
Are X-rays Safe? http://www.medinfo.ufl.edu/other/cameron/rads.html

GENETIC AND IN UTERO EFFECTS

Genetic effects constitute radiation damage to a descendant resulting from modification of genetic material in a parent. Genetic changes have been observed in plants and animals following very high doses. Follow-up studies of the population of Hiroshima and Nagasaki atomic bomb survivors have not seen statistically significant effects, such as stillbirths, neonatal deaths, malformations, birth weight, infant mortality, leukemia, mutation rates, or cytogenetic analyses.

Congenital abnormalities and malformations are practically nonexistent in fetuses exposed *in utero* to fetal doses of about 5 rad or less. The risk of childhood cancer from prenatal exposure in this dose range is small compared to other risks normally associated with pregnancy.

For further reading on genetic and *in utero* effects:
Mettler, F.A. and Moseley, R.D., *Medical Effects of Ionizing Radiation,* Grune and Stratton, 1985
National Research Council, Committee on the Biological Effects of Ionizing Radiation (BEIR V), Washington, DC, National Academy Press, 1990

BIOLOGICAL EFFECTS FROM LARGE DOSES OF RADIATION

Large, acute doses of radiation can produce serious injury, such as skin burns and cataracts, to exposed persons. The severity of these direct effects increases with dose. These effects are not seen in doses consistent with ALARA levels or dose limits. For example, almost all persons exposed to an acute whole body dose of 500 rad (5 Gy) will experience some degree of bone marrow depression. Practically no one receiving a lower dose of about 50 rad (0.5 Gy) would incur bone marrow depression.

Although any accident or malicious act scenario can include large, acute doses of radiation, such scenarios are very unlikely due to engineering and administrative controls employed in each facility. Source users made knowledgeable through training are more likely to act safely. Open beams from analytical or accelerator radiation-producing devices produce very intense x-ray or particle beams, which over a very brief exposure time can deliver doses sufficient to cause direct effects. Frequent exposure to intense levels of radiation can cause biological damage. These devices also produce bremsstrahlung, which needs to be shielded. Operators are issued dosimeters to monitor their radiation doses. All operators must use practices to keep their doses as low as reasonably achievable (ALARA). As a precautionary measure, individuals using these devices should be able to recognize direct biological damage from radiation.

Skin Burns

Exposure of extremities to an open, high-intensity x-ray beam can result in severe radiation burns in a matter of seconds. Radiation burns (erythema) are the principal hazard associated with the use of analytical x-ray equipment or particle accelerators. These burns heal poorly, and on rare occasions have required amputation of fingers or surgery to remove affected flesh. The burn symptoms may require from one to several weeks to develop, depending on the dose.

It usually takes doses of 300 rad (3 Gray) or to produce a visible reddening of the skin (called erythema). Doses of about 1500 rad (15 Gray) produce serious burns with blistering. When doses reach 3000 rad (30 Gray) very serious burns requiring skin grafts or amputation may result. Table 1 shows the results the potential damage exposure to the high-intensity beam can cause.

Table 1: Skin Burns Produced by X Rays

Description of Tissue Damage	Dose Required	
	rad	Gray
Perceptible reddening of skin	300	3
Dry desquamation of skin	1000	10
Wet desquamation and blistering	1500	15
Ulceration and necrosis of skin or flesh	3000	30

Cataracts

Opacities of the lens of the eyes (cataracts) require an acute dose of 200 rad (2 Gy) to the lens. The latent period for cataract formation ranges from 6 months to 35 years, with an mean of 2-3 years. A single dose of 750 rad (7.5 Gy) will cause cataract formation in everyone exposed.

For further reading on high dose effects:

Mettler, F.A. and Moseley, R.D., *Medical Effects of Ionizing Radiation,* Grune and Stratton, 1985